ATLAS CP violation and rare B decays

V.Nikolaenko
IHEP Protvino
on behalf of the ATLAS collaboration
2 September 2015

LHCP2015, 31.08. – 05.09.2015,
St.Petersburg, Russia

Outlook

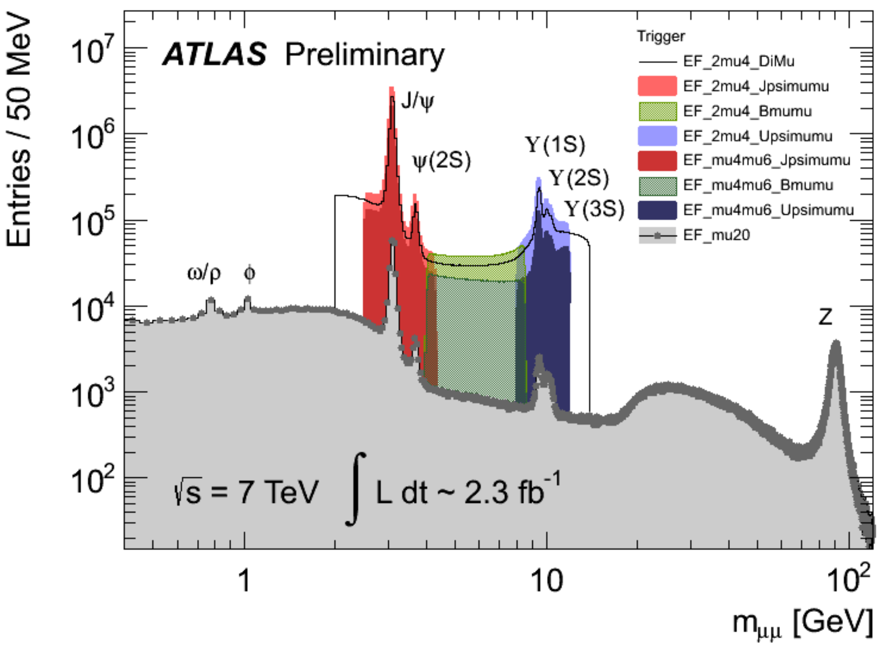
- Introduction
- Measurement of CP-violation parameters in $B_s \rightarrow J/\psi\phi$ decay

  $\Delta\Gamma_s$ and ϕ_s from Flavour-tagged time-dependent analysis

- Analysis of 2012 data
- Combination of results from data at 7 and 8 TeV
- Limit on BR(B_s(5366)$\rightarrow \mu^+ \mu^-$) decay
- Determination of f_s/f_d ratio
- Summary

Introduction

- B-physics results are based on statistics acquired mainly with di-muon triggers.
- Requirements on muons p_t mostly 4 GeV/c (for small fraction of events with high instantaneous luminosity increased to 6 GeV/c)



No preference for di-muon mass close to B_s(5366) mass was applied.

B_s time evolution parameters

- Like the K^0 meson, B_s meson can be produced in CP-even or CP-odd state with different lifetimes. $\Delta\Gamma_s$ is a difference between inverse lifetimes. CP-odd state has a longer lifetime than the CP-even one, the relative difference is ~13-17%.
- Observed $(b\ \bar{s}) \leftrightarrow (\bar{b}\ s)$ **oscillations** **via box diagrams with intermediate u, c, t $q\bar{q}$ pairs in t-channel and possibly New Physics.** The mass difference between heavy (B^H) and light (B^L) CP-eigenstates leads to measured oscillation frequency Δm_s - $17.77\ ps^{-1}$.
- CP-violating phase ϕ_s manifests itself in interference terms between mixing and decay amplitudes

B_s time evolution and $B_s \to J/\psi\phi$ decay

- In SM, phase $\phi_s \approx -2\beta s_s$, where β_s is angle in Kobayashi-Maskawa triangle, $$\beta_s = \arg\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}$$ (NOT β angle in other unitary triangle,
- with d instead of s quark, see PDG!
- SM predictions: ΔΓ = 0.087±0.021 ps

  $\phi_s = -0.0363^{+16}_{-15}$ rad Phys. Rev. D, 84 (2011), p. 033005
- Measurements of ϕ_s and ΔΓ test theoretical predictions.
- The analysis of data at 8 TeV is similar for published analysis of 7 TeV data (Phys.Rev. D90 (2014) 052007) . The number of signal events at 8 TeV is greater by a factor of 3. Due to high statistics, more detailed study of acceptance, signal shape and background was performed. Also Electron tagging was applied. Finally, results at 8 and 7 TeV were statistically combined.

Partial waves in J/ψϕ analysis

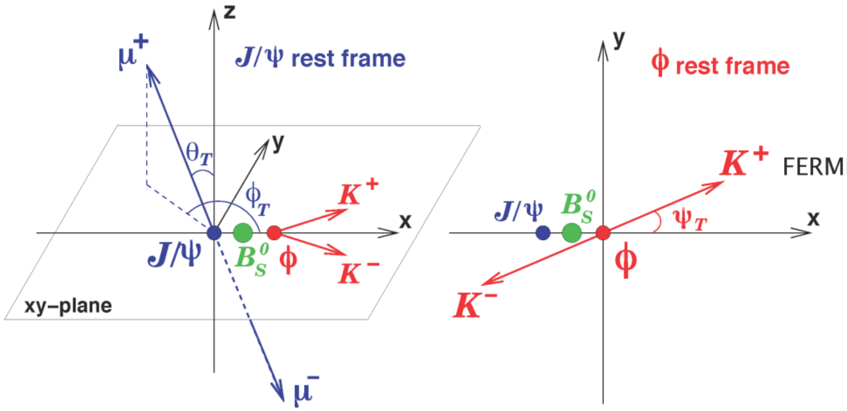
- $B_s \to J/\psi\phi \to (\mu^+\mu^-)(K^+ K^-)$ without Kaon identification
- $B_s \to J/\psi\phi$ - pseudo-scalar to vector-vector decay, waves :
- CP-even (L=0,2) and CP-odd (L=1) final states,
- added 4th wave with (KK) in S-wave, J/ψKK
- Distinguishable through time-dependent angular analysis
- Used 3 angles between final-state particles in Transversity basis
  - Multi-dimensional fit to the data; three amplitudes and strong phases extracted.

A_0 – longitudinal CP-even final state

$A_{\|}$ – transverse CP-even

$A_{\perp}$ – transverse CP-odd

$$\delta_0 = 0$$
$$\delta_{\|} = \arg[A_{\|}(0)A_0^*(0)]$$
$$\delta_{\perp} = \arg[A_{\perp}(0)A_0^*(0)]$$



FERMILAB-PUB-11-646-E

- 3 amplitudes and strong phases extracted alongside with ϕ_s and $\Delta\Gamma_s$
- 4-th amplitude A_s and phase δ_s for J/ψKK (CP-odd) also determined from the fit.

Event selection in 2012 data analysis

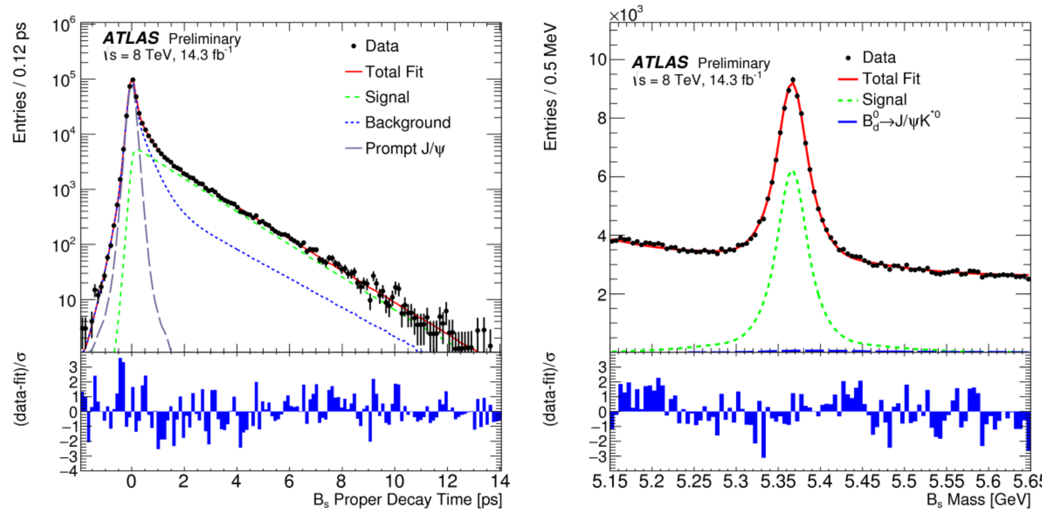
- Events selected from $\mu^+ \mu^-$ pairs using 14.3 fb^{-1} data acquired at $\sqrt{s}$ = 8 TeV.
- 2 other opposite sign tracks with p_t > 1 GeV/c and $|\eta|<2.5$ taken with Kaon mass.
- Retain pairs consistent with ϕ : 1008.5 < $m(K^+ K^-)$< 1030.5 MeV.
- 4-track Vertex Fit, using J/ψ mass constraint, χ^2 /NDF < 3.
- Primary vertex selected with smallest 3D-impact parameter.
- Proper decay time:

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

with B_s World Average mass M_B

- 376 K B_s candidates in range: 5.150 – 5.650 GeV
- 75100 ± 400 B_s signal candidates extracted from the fit

22670 ± 150 in 2011 data

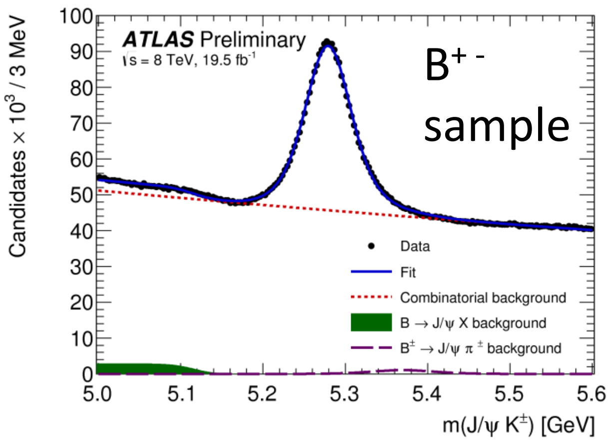


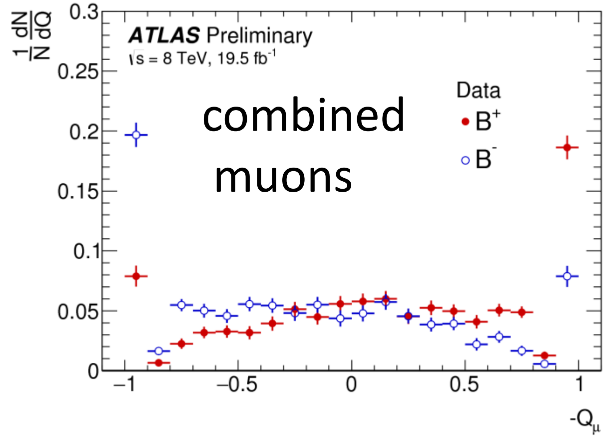
No decay time cut applied in analysis

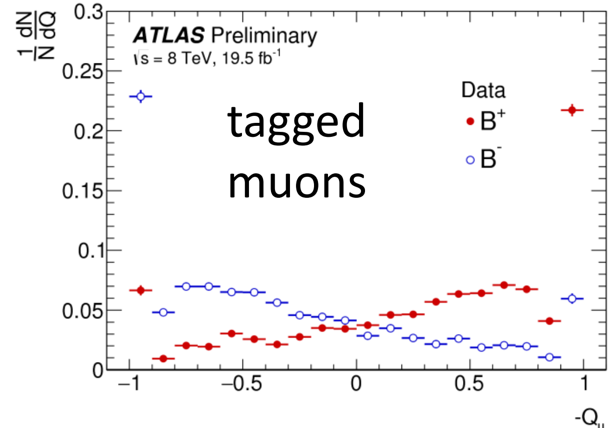
b-quark charge tagging

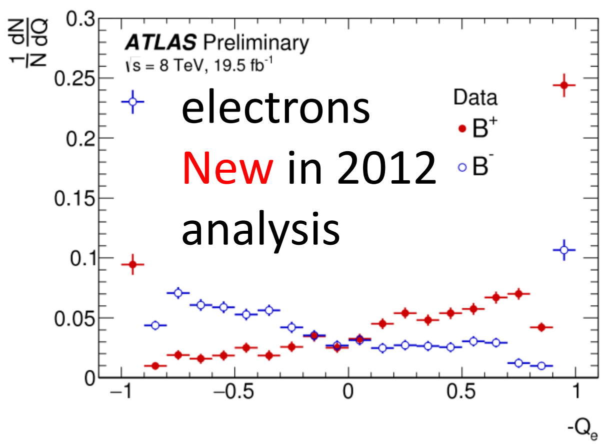
- Identification of b or anti-b quark in B_s at the production time improves precision of ϕ_s measurement and helps with sign ambiguities
- Information from opposite side tagging used, i.e. leptons and/or jet charge from decay of 2nd B-hadron in the event
- Methods were calibrated on B^{+-} candidates in data

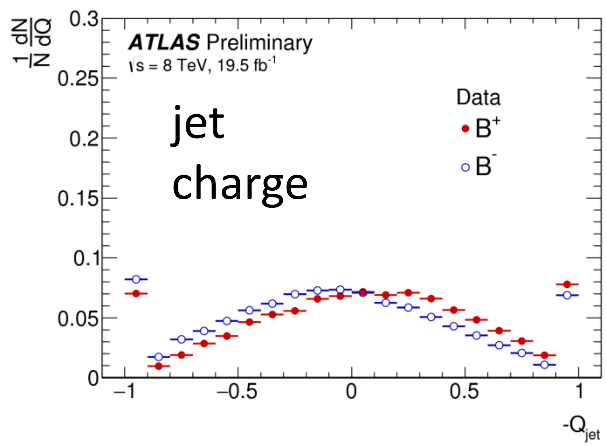
B^{+-} sample











Tagger	Tagging power [%]
Combined muon	0.92±0.02
Electron	0.29±0.01
Tagged muon	0.10±0.01
Jet charge	0.19±0.01
Total	1.49±0.02

Fit model – signal component

- Unbinned likelihood fit: 9 physics parameters

$$\ln \mathscr{L} = \sum_{i=1}^{N} \{w_i \ln(f_s \cdot \mathscr{F}_s(m_i, t_i, \sigma_{t_i}, \Omega_i, P(B|Q)) + f_s \cdot f_{B^0} \cdot \mathscr{F}_{B^0}(m_i, t_i, \sigma_{t_i}, \Omega_i, P(B|Q)) + (1 - f_s \cdot (1 + f_{B^0}))\mathscr{F}_{\mathrm{bkg}}(m_i, t_i, , \sigma_{t_i}, \Omega_i, P(B|Q))\}$$

- Observables:
  - $m(J/\psi KK)$, τ, $\sigma(\tau)$
  - $\Omega = (\theta_T, \psi_T, \phi_T)$
  - Tagging probability

Signal components: Mass – Triple Gaussian; Lifetime – 2 Exp ·Gaussian (per-candidate error) Angular functions; Tagging probability distribution (PDF)

Scaling factor was applied to per-event timing errors from the Vertex fit.

It was estimated from negative tail in distribution, due to absence of lifetime selection in Trigger.

With 4 decay channels -> 4 diagonal + 6 non-diagonal Angular & Lifetime functions, an example:

AMPL	$O^{(k)}$ f(t)	$g^{(k)}(\theta_T, \psi_T, \phi_T)$
$(1/2)\lvert A_0(0)\rvert^2$	$(1+\cos(\phi_s))\exp(-\Gamma_L^{(s)} t) + (1-\cos(\phi_s))\exp(-\Gamma_H^{(s)} t) \pm$ $\pm 2\exp(-\Gamma_s t)\sin(\Delta m_s t)\sin(\phi_s)$	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$

oscillating term with $\sin(\phi_s)$ arises due to Tagging , other terms with $\cos(\phi_s)$

Angle ϕ_s is small -> terms with $\sin(\phi_s)$ significantly improves precision of ϕ_s measurement

Time and angular functions for $B_s \to J/\psi\phi$

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

Fit model – background components

- Unbinned likelihood fit: 9 physics parameters

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

- Observables:
  - m(J/ψKK), τ, $\sigma(\tau)$
  - $\Omega = (\theta_T, \psi_T, \phi_T)$
  - Tagging probability

B_d component :

Mis-reconstructed $B_d \to J/\psi K^{*0}$

Mass: Landau shape from MC

Lifetime: Exp · Gaussian
(per candidate errors)
(slope fixed to PDG lifetime)

Angular distributions: taken from
3D-fits to MC

Combinatorial BG component

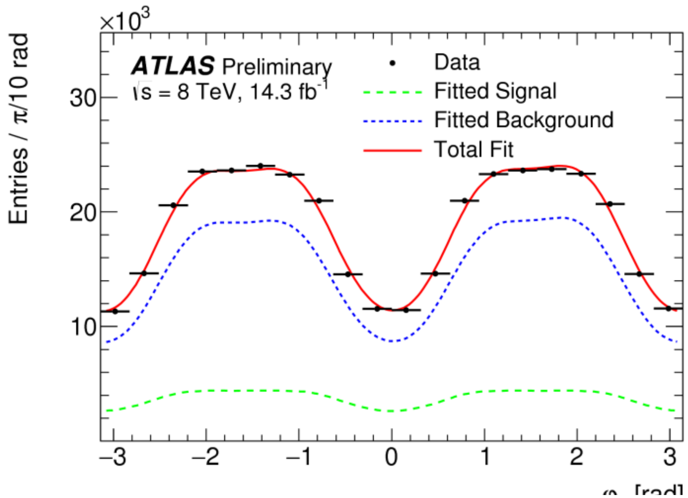
Mass: Exp function

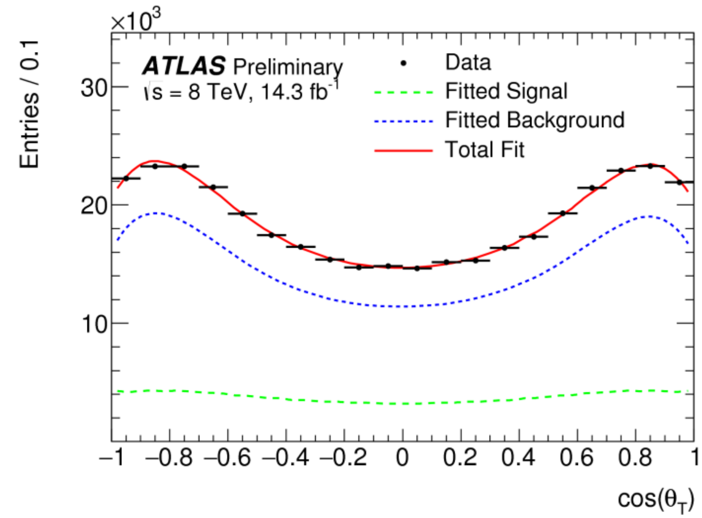
Lifetime: Prompt Exp(±t), and 2 Exp(t>0)

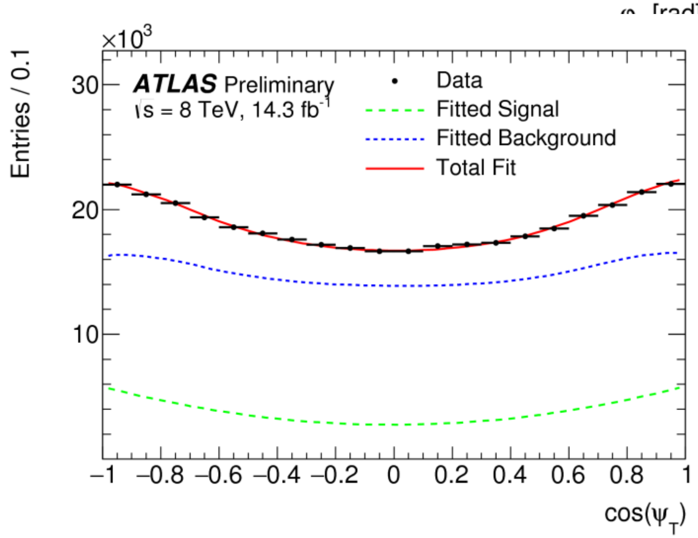
Angular distributions: Spherical harmonics
from side-bands regions

"Punzi" terms – accounting for differences between Data and MC in Tagging Efficiency and lifetime uncertainties,
Determined from the data

Angular fit projections







- θ is the angle between p(μ^+) and x-y plane in the J/psi meson rest frame

- ϕ is the angle between the x-axis and the projection of $p_{xy}(\mu^+)$, the projection of the μ^+ momentum in the x-y plane, in the J/ψ rest frame

- ψ is the angle between p(K^+) and –p(J/ψ) in the ϕ meson rest frame.

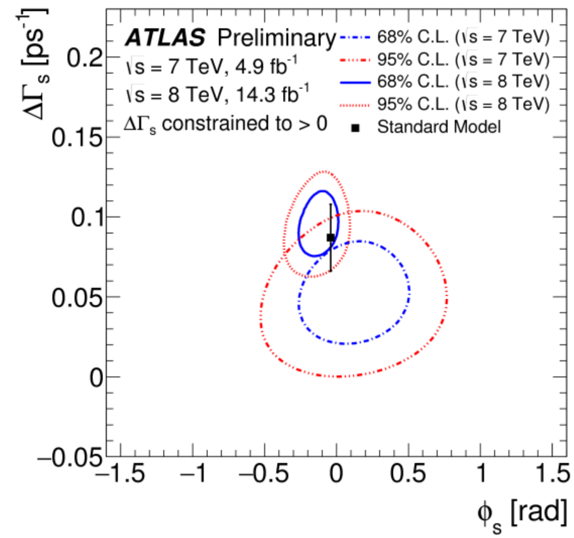
- sample

Systematic uncertainties in physics parameters

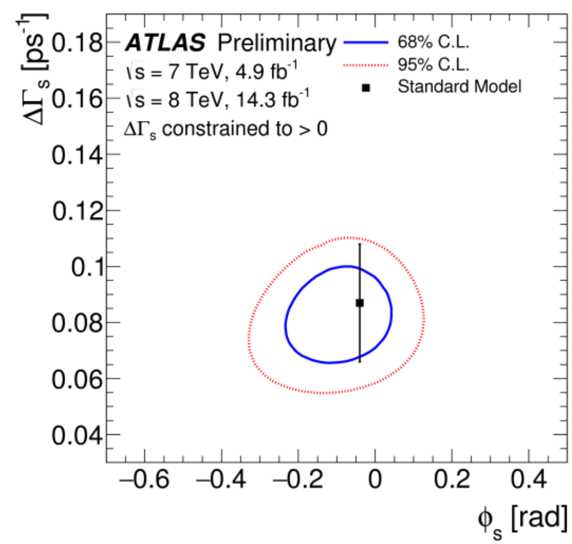
	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_\perp$ [rad]	$\delta_\parallel$ [rad]	$\delta_\perp - \delta_S$ [rad]
Tagging	0.026	0.003	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.001	0.238	0.014	0.004
Acceptance	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.003	$<10^{-3}$	0.001	0.004	0.008	$<10^{-3}$
Background angles model:									
Choice of p_T bins	0.02	0.006	0.003	0.003	$<10^{-3}$	0.008	0.004	0.006	0.008
Choice of mass interval	0.008	0.001	0.001	$<10^{-3}$	$<10^{-3}$	0.002	0.021	0.005	0.003
B_d^0 background model	0.008	$<10^{-3}$	$<10^{-3}$	0.001	$<10^{-3}$	0.008	0.007	$<10^{-3}$	0.005
Fit model:									
Default fit	0.001	0.002	$<10^{-3}$	0.002	$<10^{-3}$	0.002	0.025	0.015	0.002
Mass Signal model	0.004	$<10^{-3}$	$<10^{-3}$	0.002	$<10^{-3}$	0.001	0.015	0.017	$<10^{-3}$
Mass Background model	$<10^{-3}$	0.002	$<10^{-3}$	0.002	$<10^{-3}$	0.002	0.027	0.038	$<10^{-3}$
Time Resolution model	0.003	$<10^{-3}$	0.001	0.002	$<10^{-3}$	0.002	0.057	0.011	0.001
Total	0.036	0.007	0.003	0.006	0.001	0.013	0.25	0.05	0.01

Results at 8 TeV and Combination

- Results from 8 TeV measurement:
  - ϕ_s = -0.119 ± 0.088 (stat.) ± 0.036 (syst.) rad
  - $\Delta\Gamma_s$ = 0.096 ± 0.013 (stat.) ± 0.007 (syst.) ps^{-1}
  - Correlation (ϕ_s , $\Delta\Gamma_s$) = 0.110



- Combination of results:
  - Statistical combination
  - Best Linear Unbiased Estimate (BLUE) of 7 TeV and 8 TeV results
  - Minimizes the variance in the estimators



$B_s \to J/\psi\phi$ combined results

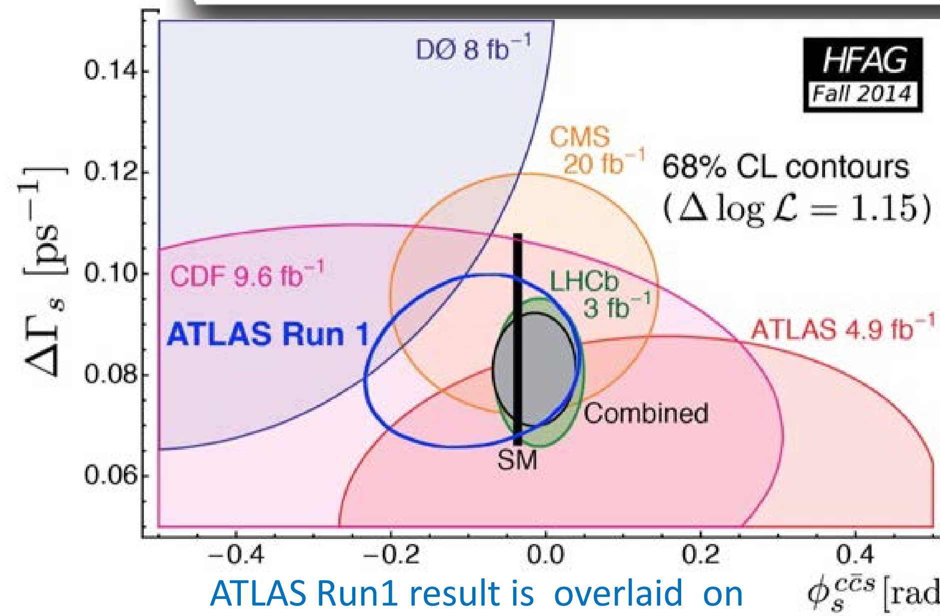
- Preliminary measurement of the time-dependent flavoured-tagged CP asymmetry parameters in decays $B_s \to J/\psi\phi$

Parameter	Value	Stat.	Syst.	
ϕ_s	-0.094	0.083	0.033	rad
$\Delta\Gamma_s$	0.082	0.011	0.007	ps^{-1}
Γ_s	0.677	0.003	0.003	ps^{-1}
$\lvert A_{\parallel}(0)\rvert^2$	0.227	0.004	0.006	
$\lvert A_0(0)\rvert^2$	0.515	0.004	0.002	
$\lvert A_S(0)\rvert^2$	0.086	0.007	0.012	
$\delta_\perp$	4.13	0.34	0.15	rad
$\delta_\parallel$	3.16	0.13	0.05	rad
$\delta_\perp - \delta_S$	-0.08	0.03	0.01	rad

- 14.3 fb^{-1} from 8 TeV
  - statistically combined with previous result at 7 TeV 4.9 fb^{-1}
    Phys.Rev. D90 (2014) 052007
- CP-violating phase, ϕ_s,
  - consistent with other experiments and SM predictions

    $\phi_s = -0.0363^{+16}_{-15}$ rad

    $\Delta\Gamma_s^{(SM)} = 0.087 \pm 0.0021\ ps^{-1}$

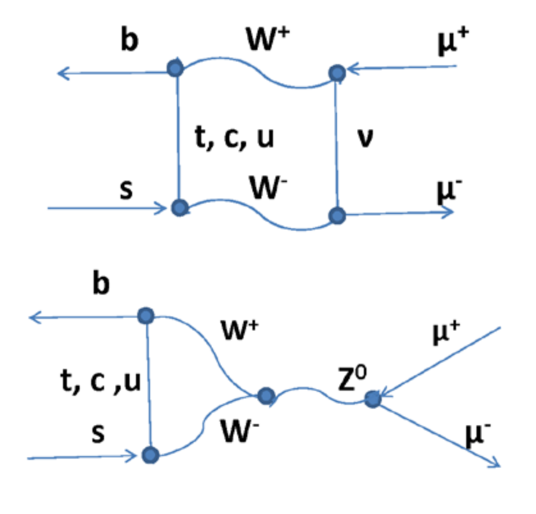


ATLAS Run1 result is overlaid on combination of other measurements

$B_s \to \mu^+\mu^-$ decay

- Decays $B_s^0 \to \mu^+ \mu^-$ and $B^0 \to \mu^+ \mu^-$ are suppressed in SM
- Recent predictions in SM:
  - $BR(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \cdot 10^{-9}$
  - $BR(B^0 \to \mu^+ \mu^-) = (1.06 \pm 0.09) \cdot 10^{-10}$

C.Bobeth et al., PRL 112, 101801 (2014)



- Combined result from LHCb and CMS:
  - $BR(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \cdot 10^{-9}$
  - $BR(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \cdot 10^{-10}$

Nature 522 (2015) 68

ATLAS result on 4.9 fb^{-1} data at 7 TeV:

G.Aad et al., PL B713 387

- $BR(B_s^0 \to \mu^+\mu^-) < 19 \cdot 10^{-9}$ at 90% C.L.

Analysis on full Run 1 data is going to be completed soon !

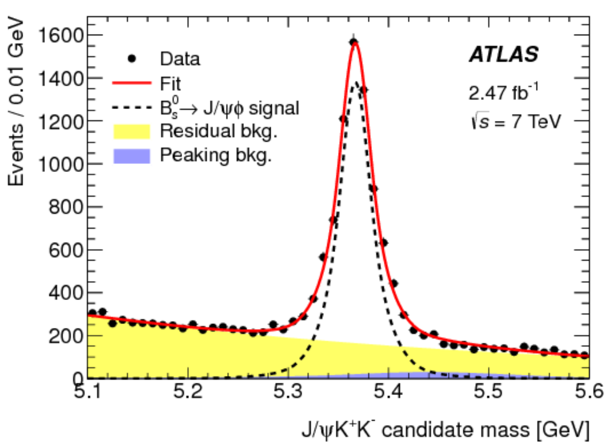
Determination of ratio of b-quark fragmentation functions f_s/f_d

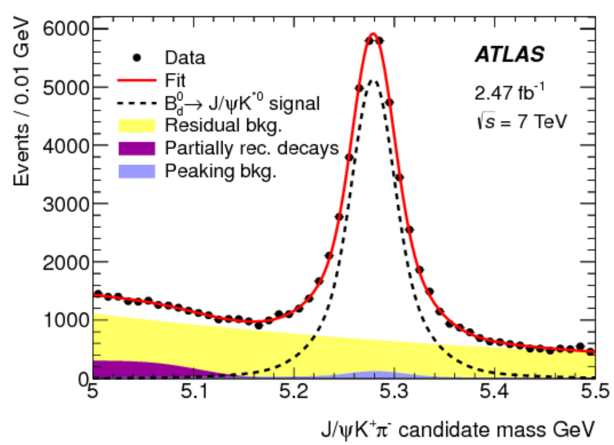
- Used exclusive decays $B_s \to J/\psi\phi$ and $B_d \to J/\psi K^{*0}(890)$ at $\sqrt{s}$=7 TeV, integrated luminosity 2.47 fb^{-1} e-Print: arXiv:1507.08925
- With 6640±100±220 $B_s \to J/\psi\phi$ and 36290±320±650 $B_d \to J/\psi K^{*0}$ decays,

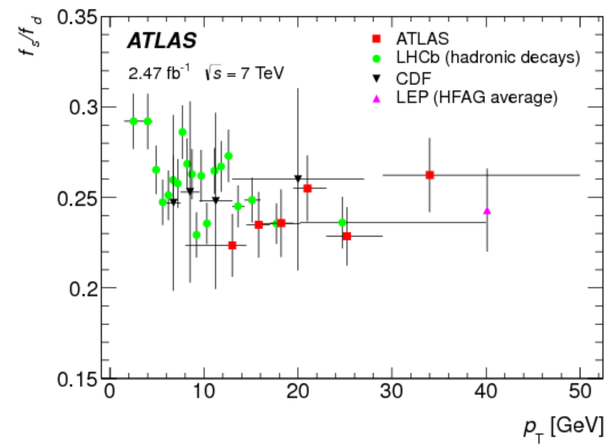
f_s/f_d = 0.240±0.004(stat.)±0.013(syst.) ±0.017(br.) at p_T > 8 GeV/c.

used $BR(Bs_s \to J/\psi\phi)/BR(B_d \to J/\psi K^*)$ ratio from X.Liu et al. PRD 89 (2014) 094010

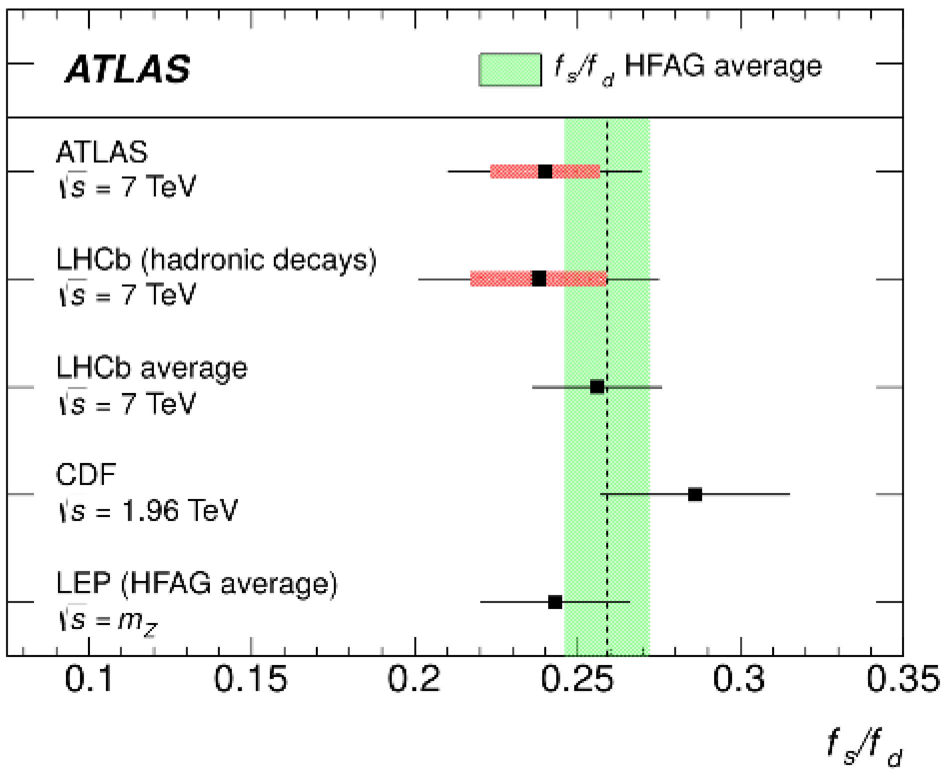
This result is consistent with previous measurements. It is also useful for measurement of the $BR(B^0 \to J/\psi\ \mu^+ \mu^-)$.







Compilation of measurements of b-quark fragmentation functions f_s/f_d



Summary

- - ATLAS can provide precise measurements in B-decays, which are relevant for searches of effects beyond SM
- - CP-violating phase ϕ_s and decay width difference $\Delta\Gamma$

  - **analyzed 2012 data**
  - **statistical combination 2011+2012 (4.6+14.3 fb^{-1})**

    $\boldsymbol{\phi_s = -0.094 \pm 0.083(stat.) \pm 0.033(syst.)}$ **rad**

    $\boldsymbol{\Delta\Gamma = 0.082 \pm 0.011 \pm 0.007\ ps^{-1}}$

  - consistent with SM predictions and other experiments
- - $B_s \rightarrow \mu^+\mu^-$ analyzed 2011 data, full Run 1 result expected soon
- - The ratio of b-quark fragmentation functions measured at p_T > 8 GeV/c

  $\boldsymbol{f_s/f_d = 0.240 \pm 0.004(stat.) \pm 0.013(syst.) \pm 0.017(br.)}$
- - $B_d \rightarrow K^{*0}\mu^+\mu^-$ analysis on full Run 1 is ongoing
- Statistical errors dominate in measurements, we expect better precision from Run 2 due to modifications in ATLAS (IBL) and significantly more statistics.

References

- ATLAS:
- Flavor tagged time-dependent angular analysis of the $B_s \rightarrow J/\psi\phi$ decay and extraction of $\Delta\Gamma_s$ and the weak phase ϕ_s in ATLAS, Phys. Rev. D90 (2015) 5, 052007, arXiv:1407.1796
- Limit on $B^0_s \rightarrow \mu^+\mu^-$ branching fraction based on 4.9 fb^{-1} of integrated luminosity, ATLAS-CONF-2013-076

  http://cds.cern.ch/record/1562934
- Search for the decay $B^o_s \rightarrow \mu\mu$, Phys. Lett. B713 (2012) 387, arXiv:1204.0735
- LHCb
- Precision measurement of CP violation in $B_s \rightarrow J/\psi K^+K^-$ decays,
- Phys.Rev. Lett. 114 (2015) 041801, arXiv:1411.3104

References

- LHCb & CMS:
- Observation of the rare $B^0_s \to \mu^+\mu^-$ decay from combined analysis of CMS and LHCb data, Nature 522 (2015) 68, and ref. therein
- CMS
- Measurement of the CP-violating weak phase ϕ_s and the decay width difference $\Delta\Gamma$using the $B_s \to J/\psi\phi(1020)$ decay channel, Tech.Rep. CMS-PAS-BPH-13-012, CERN, Geneva, 2014
- arXiv:1507.07527 submited to PL B

Backup slide: Correlation matrix between $B_s \rightarrow J/\psi\phi$ decay parameters

	ϕ_s	$\Delta\Gamma$	Γ_s	$\|A_{\|\|}(0)\|^2$	$\|A_0(0)\|^2$	$\|A_s(0)\|^2$	$\delta_{\|\|}$	δ_{tr}	$\delta_{tr}-\delta_s$
ϕ_s	1.000	0.094	-0.072	0.028	0.028	0.048	0.062	-0.016	-0.009
$\Delta\Gamma$		1.000	-0.377	0.113	0.145	0.068	0.012	0.012	-0.012
Γ_s			1.000	-0.126	-0.043	0.172	-0.026	-0.009	0.019
$\|A_{\|\|}(0)\|^2$				1.000	0.326	0.081	0.095	0.024	-0.018
$\|A_0(0)\|^2$					1.000	0.220	-0.008	0.006	0.012
$\|A_s(0)\|^2$						1.000	-0.042	-0.002	0.050
$\delta_{\|\|}$							1.000	0.165	0.016
δ_{tr}								1.000	0.010
$\delta_{tr}-\delta_s$									1.000

PRELIMINARY