Measurement of Φ_s, $\Delta\Gamma_s$ and Lifetime in $B_s \to J/\psi\,\Phi$ at ATLAS and CMS

Claudio Heller
Excellence Cluster Universe
LMU München

For the ATLAS and CMS Collaborations

Beauty 2013
14th International Conference on B-Physics at Hadron Machines
April 12th 2013, Bologna

Content

- CMS: Measurement of the B_s lifetime difference
  CMS-PAS-BPH-11-006

NEW!

- Flavor tagged time dependent angular analysis of the $B_s \rightarrow J/\psi\ \Phi$ decay and extraction of $\Delta\Gamma_s$ and weak phase ϕ_s in ATLAS
  (update of JHEP 12 (2012) 072)

Motivation

- Test predictions of the Standard Model
- $B_s \rightarrow J/\Psi\Phi$ is one of the channels that had the potential to show larger CP violation than predicted by the SM
- Measurement of the decay width difference $\Delta\Gamma_s$ provides constraints on the ratio $\Delta\Gamma_s/\Delta m$ which is free of most theoretical uncertainties

The neutral B_s system

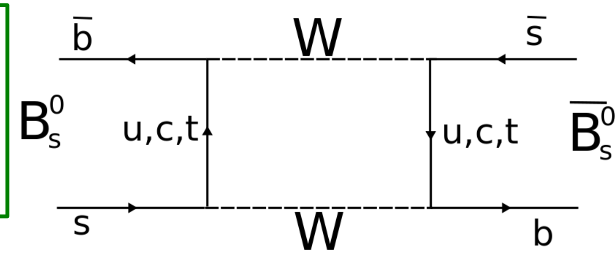
- flavor eigenstates

$$|B_s^0\rangle = (\bar{b}\, s)$$
$$|\bar{B}_s^0\rangle = (b\, \bar{s})$$

oscillation and mixing

$$i\frac{d}{dt}\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} = \left[\begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix} \right] \begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix}$$

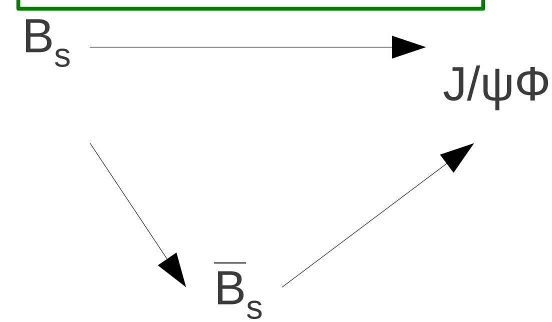
mass matrix — decay matrix



- This leads to two mass eigenstates (heavy and light) with difference of lifetime of O(10%) expected

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

- mass difference $\Delta m = m_H - m_L \approx 2|M_{12}|$
- mixing phase $\phi_s = \arg(-M_{12} / \Gamma_{12}) \approx -0.0368$ ← SM
- decay width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(\phi_s)$

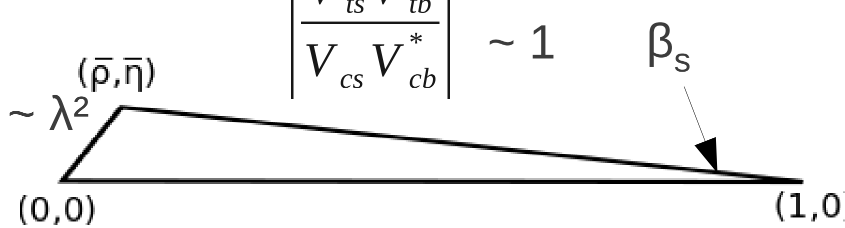


CP violation in the decay $B_s \to J/\psi\, \phi$

- CP violation occurs through the interference of mixing and decay
- SM describes CPV with a single complex phase in the CKM matrix

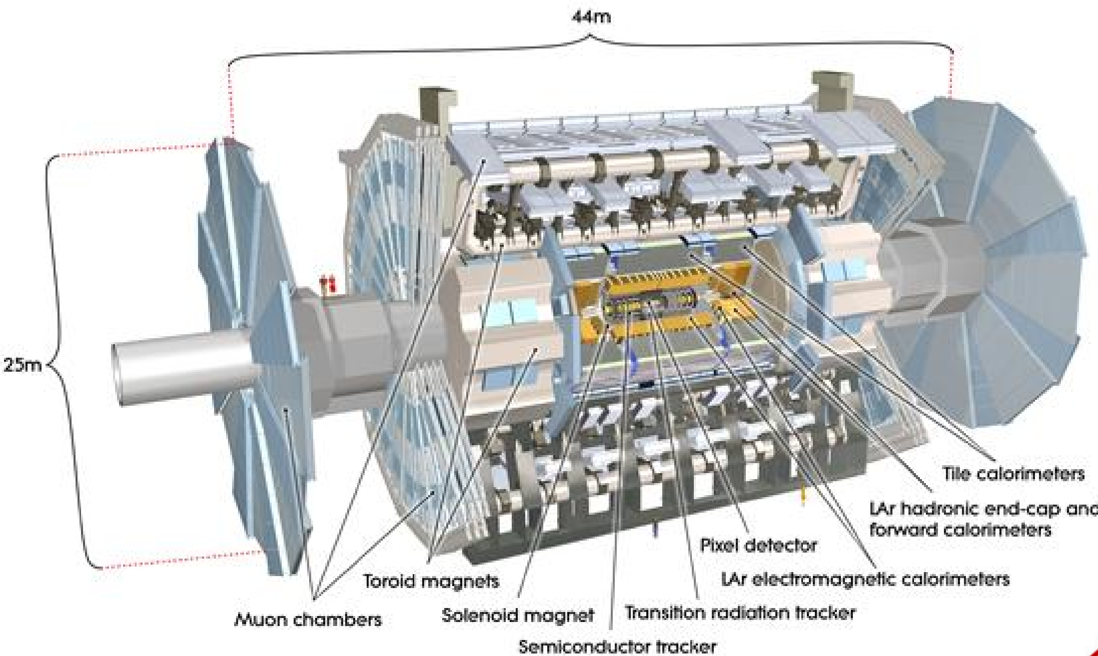
$\phi_s \simeq -2\,\beta_s$,with $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$

$$\left|\frac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*}\right| \sim \lambda^2 \qquad \left|\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right| \sim 1$$



pseudoscalar (B_s) → 2 vector mesons (J/ψ Φ)
angular analysis is performed to disentangles CP states

The ATLAS and CMS Detectors



ATLAS

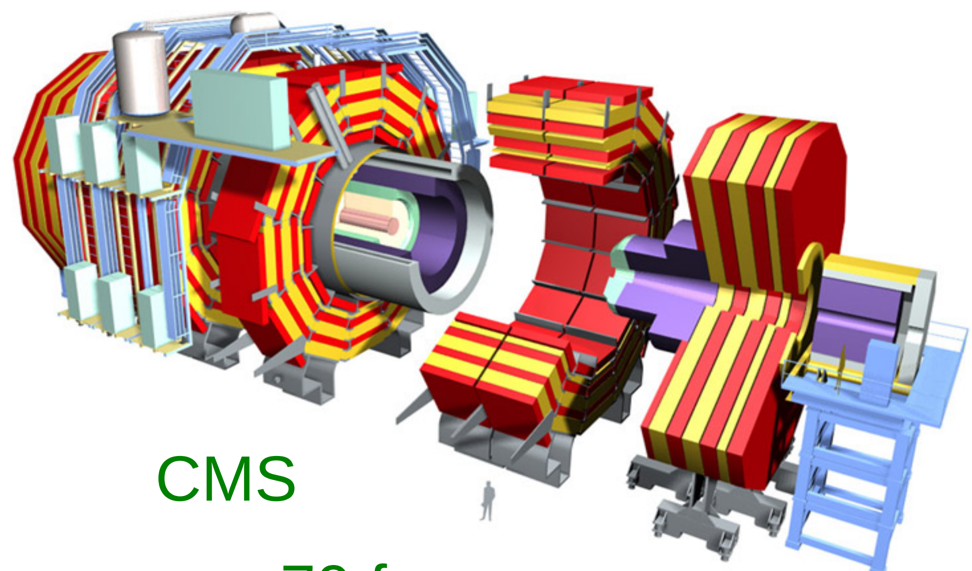
σ_τ ~ 100 fs

$B_s \rightarrow J/\psi\ \Phi$ analysis uses measurements provided by

- inner tracking detectors
- muon spectrometers

ATLAS and CMS provide good performance for B-physics:

- good p_T and vertex resolution
- high muon purity



CMS

σ_τ ~ 70 fs

Analysis Overview

J/ψ Triggers

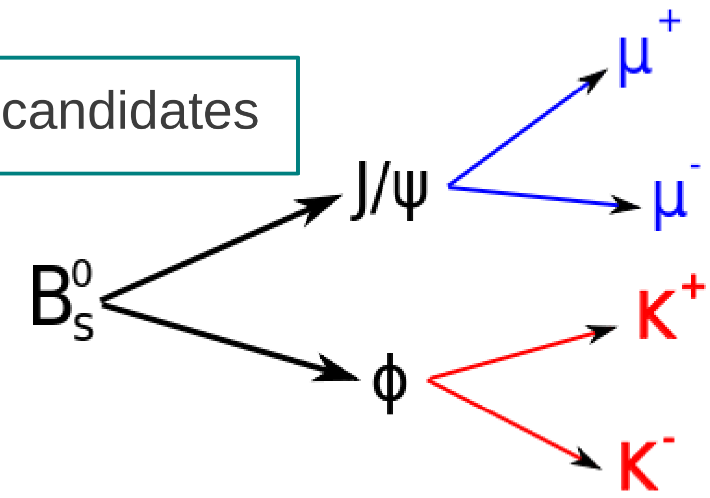
↓

Reconstruction of $B_s \rightarrow J/\psi\phi \rightarrow \mu^+ \mu^- K^+ K^-$ candidates

↓

Selection Cuts

↓



Simultaneous fit of mass, lifetime and angular distribution

- B_s mass fit to separate signal and background
- Time dependence of the decay
- Angular separation of CP eigenstates

CMS Analysis

- $5.0 \pm 0.1\ fb^{-1}$ collected in 2011 at $\sqrt{s}$ = 7 TeV
- 19,200 B_s candidates in the mass range *5.24 - 5.49 GeV* with proper decay length between *0.02 – 0.3 cm*
- Mass, decay time and three decay angles of the selected B_s candidates enter the fit
- Five-dimensional unbinned maximum likelihood fit of $\Delta\Gamma_s$, Γ_s, $|A_\perp|^2$, $|A_0|^2$, $\delta_{||}$
- $|A_{||}|^2 = 1 - |A_\perp|^2 - |A_0|^2$
- Assumption of no CP violation: mixing phase Φ_s fixed to 0 in the fit
- Untagged analysis: all B_s candidates have equal probability to be particle or anti-particle
- S-wave component assumed to be negligible

Event Selection / Reconstruction

J/ψ trigger:

- $\mu^+ \mu^-$ pair with $p_T(\mu^+ \mu^-) > 6.9$ GeV
- common decay vertex with transverse decay length significance $L_{xy}/\sigma_{Lxy} > 3$
- invariant mass *2.8 – 3.35 GeV*
- Distance of closest approach < *0.5 cm*

J/ψ candidates:

- Each muon: $p_T(\mu) > 4$ GeV, $|\eta| < 2.2$
- Dimuon mass within 150 MeV of J/ψ

Φ candidates:

- Pair of oppositely charged tracks with $p_T(K) > 0.7$ GeV
- invariant mass with within 10 MeV of Φ

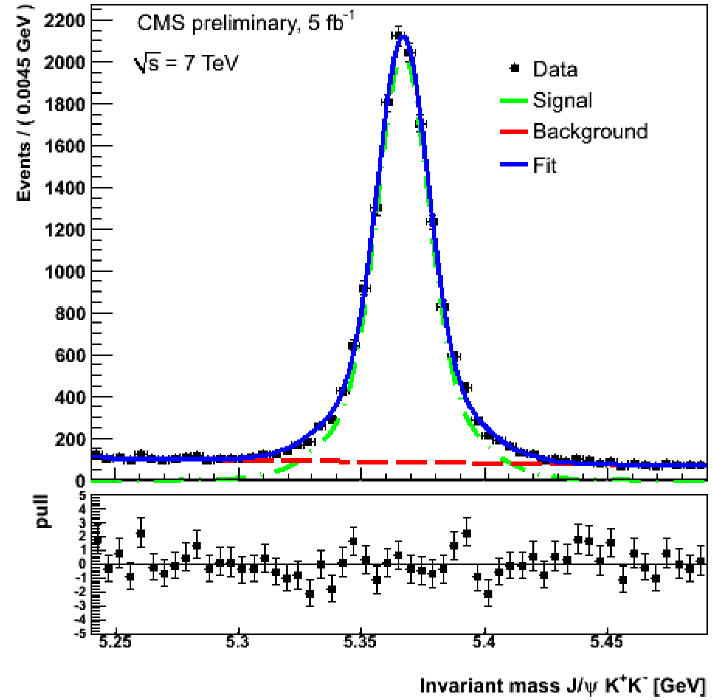
B_s candidates:

- Combination of J/ψ and Φ with invariant mass between *5.2 - 5.65 GeV*
- χ^2 vertex fit probaility larger than 2 %

Components of the Likelihood Function

$$\mathcal{L} = L_{\text{signal}} + L_{\text{background}}\,,$$
$$L_{\text{signal}} = (f(\Theta, t; \alpha) \otimes G(t, \kappa, \sigma(t))]) \cdot M(m) \cdot \epsilon(t)\epsilon(\Theta)$$
$$L_{\text{background}} = b(\Theta, t, m)\,,$$

- Signal model
  - time and angles: differential decay rates
  - *M(m)*: sum of two Gaussians
  - proper decay time efficiency
  - angular efficiency
- Background model
  - mass: exponential
  - proper time: two Gaussians and two exponentials
  - angles: series of Legendre polynomials for $cos(\theta_T)$ and $cos(\psi_T)$ and a sinusoidal distribution for φ_T



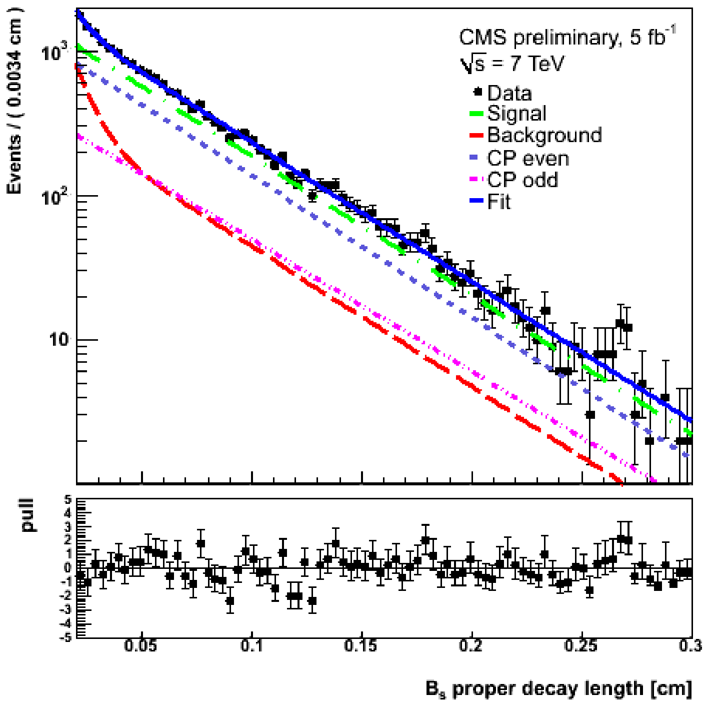
Proper decay time efficiency is calculated from MC simulation as the ratio between selected signal events and generated events. Threshhold of ct(B_s) > 0.02 cm ensures stable and high efficiency.

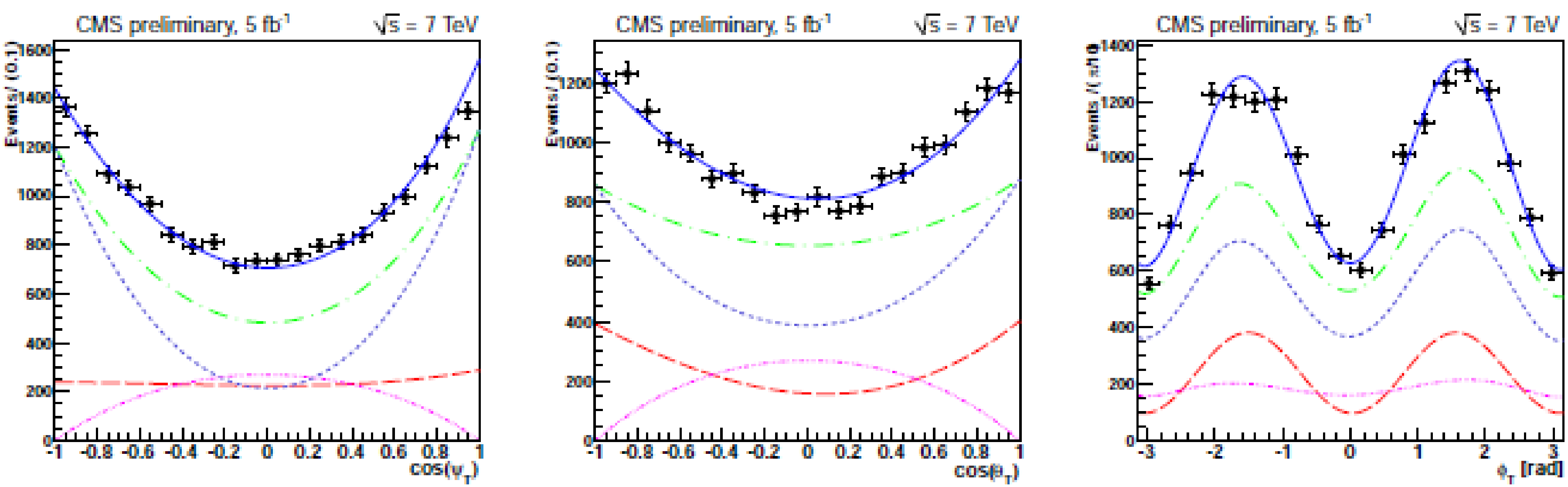
Angular efficiency is determined from MC simulation. Angles are parametrized separately using Legendre polynomials. Correlations are neglected.

Fit Technique

Fit is performed in several steps

- Mean and narrower width of the two Gaussians are determined in a mass fit and kept fix for further steps.
- Parameters of the background angular model are fitted on data sideband distributions and kept fix for further steps.
- Mass lifetime fit on data with no selection on decay length significance is performed to determine a calibration scale factor for the proper decay time resolution
- Extended likelihood fit is performed taking into account signal and background PDFs





Result and Systematic Uncertainties

$$\Delta\Gamma_s = 0.048 \pm 0.024\,(\text{stat.}) \pm 0.003\,(\text{syst.})\,\text{ps}^{-1},$$
$$\tau_{B_s} = 0.04580 \pm 0.00059\,(\text{stat.}) \pm 0.00022\,(\text{syst.})\,\text{cm},$$
$$|A_0|^2 = 0.528 \pm 0.010\,(\text{stat.}) \pm 0.015\,(\text{syst.}),$$
$$|A_\perp|^2 = 0.251 \pm 0.013\,(\text{stat.}) \pm 0.014\,(\text{syst.}),$$
$$\delta_{||} = 2.79 \pm 0.14\,(\text{stat.}) \pm 0.19\,(\text{syst.})\,\text{rad}.$$

14456 ± 140 signal events

Mean B_s Mass 5366.8 ± 0.1 MeV

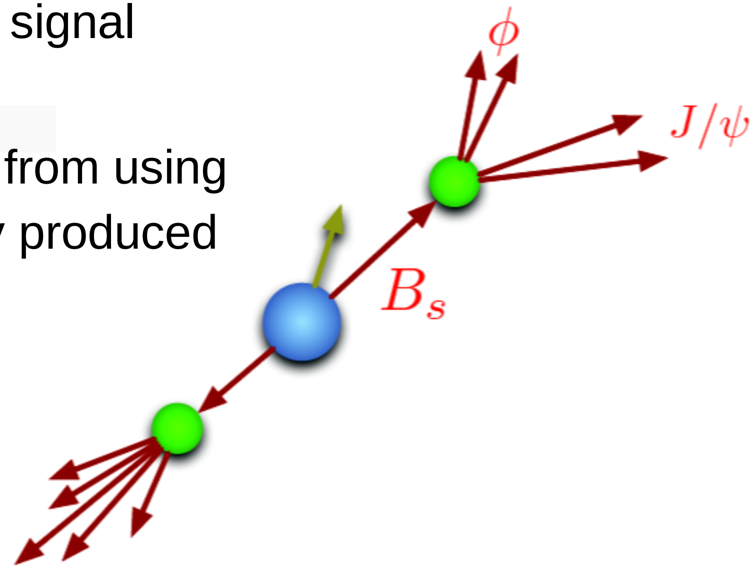
Uncertainty source	$\Delta\Gamma_s$ [ps^{-1}]	$c\tau$ [cm]	$\|A_0\|^2$	$\|A_\perp\|^2$	$\delta_{\|\|}$ [rad]
Signal PDF modeling					
Signal mass model	0.00072	0.00012	0.0022	0.0006	0.039
Proper time resolution	0.00170	0.00006	0.0007	0.0000	0.007
ϕ_s approximation	0.00000	0.00001	0.0000	0.0000	0.002
S-wave assumption	0.00109	0.00001	0.0130	0.0066	0.056
Background PDF modeling					
Background mass model	0.00019	0.00000	0.0000	0.0001	0.003
Background lifetime model	0.00040	0.00000	0.0001	0.0002	0.003
Peaking B^0 background	0.00025	0.00006	0.0002	0.0022	0.050
Background angular model	0.00175	0.00003	0.0001	0.0064	0.161
Limited simulation statistics					
Angular efficiency parameters	0.00019	0.00002	0.0057	0.0055	0.037
Temporal efficiency parameters	0.00000	0.00005	0.0000	0.0000	0.000
Temporal efficiency parametrization	0.00181	0.00014	0.0005	0.0007	0.001
Angular efficiency parametrization	0.00063	0.00003	0.0021	0.0086	0.007
Likelihood function bias	0.00000	0.00004	0.0004	0.0000	0.014
Total uncertainty	0.00341	0.00022	0.0146	0.0140	0.187

ATLAS Analysis with Flavor Tagging

- Update of untagged $B_s \to J/\psi\ \Phi$ analysis published last year JHEP 12 (2012) 072
- 4.9 fb^{-1} collected with the ATLAS detector in 2011 at $\sqrt{s}$ = 7 TeV
- No cut on B_s proper lifetime
- S-wave component included
  - non-resonant decay $B_s \to J/\psi\ K^+K^-$ & decay $B_s \to J/\psi\ f_0(K^+K^-)$ have same final state
  - S-wave state is CP odd and is described by an additional amplitude A_S and related strong phase δ_s
  - Normalization $|A_{//}|^2 + |A_\perp|^2 + |A_0|^2 + |A_s|^2 = 1$
- B_d reflections: final state pion is mis-reconstructed as a kaon
  - $B^0_d \to J/\psi\ K^*$ (6.5 ± 2.4) % & non-resonant $B^0_d \to J/\psi\ K^+ \pi^-$ (4.5 ± 1.7) %
  - fractions, mass and angular shapes are determined from MC and fixed in the fit
- Initial state flavor tagging: muon & jet charge tag

Flavor Tagging

- Analysis benefits from knowledge of initial flavor of signal decay
- Opposite side tagging: initial flavor of B_s is inferred from using information from the other B-meson that is typically produced from the $b\bar{b}$ pair
- Flavor tagging methods are studied and calibrated on $B^+ \rightarrow J/\psi K^+$ and $B^- \rightarrow J/\psi K^-$
- Tagging enters the fit as tag probability for B_s / $\bar{B}_s$



Muon Cone Charge Tagger

- additional muon (p_T > 2.5 GeV, |η| < 2.5) from semi-leptonic B-decay originating near the primary interaction (Δz < 5 mm)
- Muon cone charge variable of Inner Detector tracks (p_T > 0.5 GeV, |η| < 2.5) within a cone of ΔR < 0.5 around muon momentum axis is used to derive tag probability

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

- κ = 1.1 (tuned to optimize tagging power)

Jet Charge Tagger

- b-tagged anti-k_T jet with tracks associated to the same primary interaction as signal decay
- Veto signal decay tracks and jets within ΔR < 0.5 around signal momentum axis
- tag probability is derived from jet charge of tracks in the jet with ΔR < 1.0 around the jet momentum axis

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

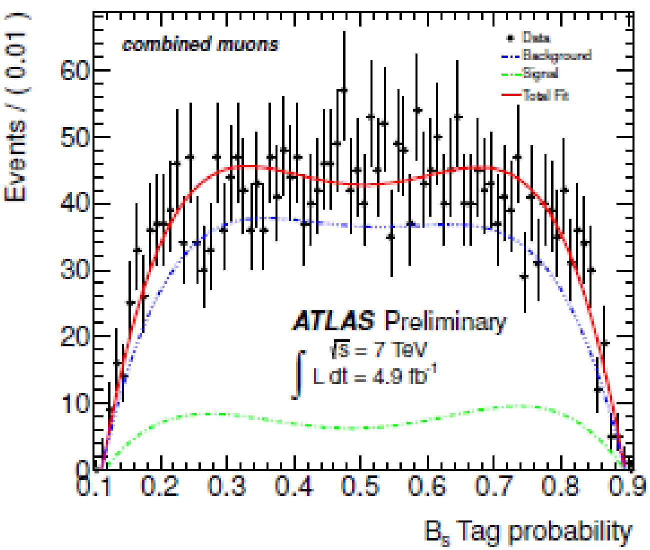
- κ = 1.1 (tuned to optimize tagging power)

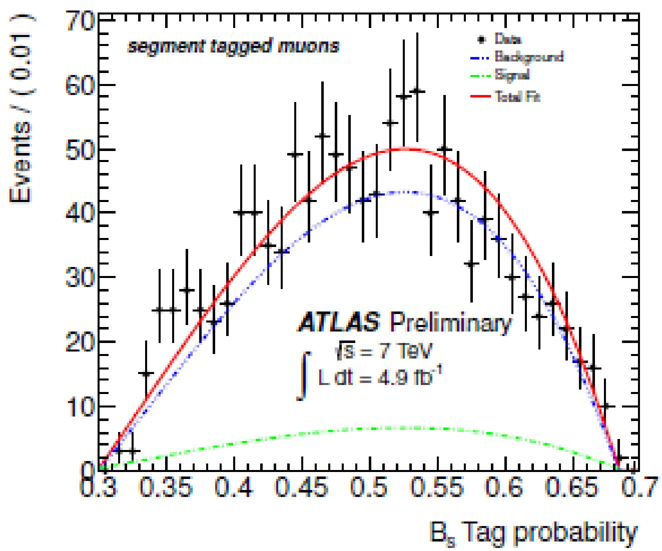
Flavor Tagging

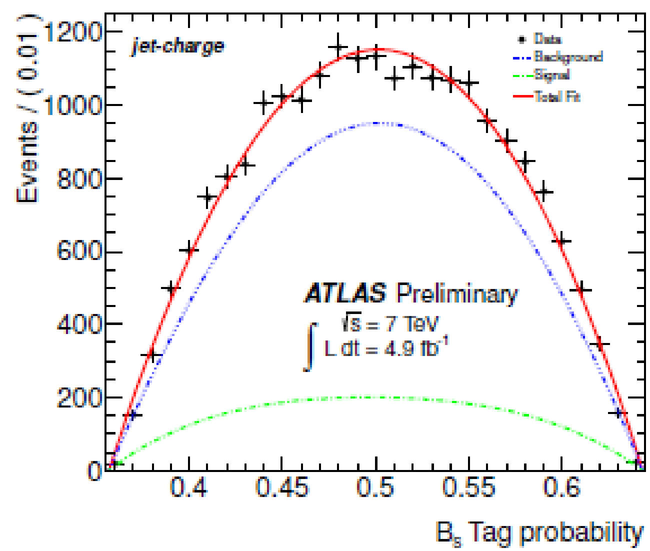
Tagger	Efficiency [%]	Dilution [%]	Tagging Power [%]
Segment Tagged muon	1.08 ± 0.02	36.7 ± 0.7	0.15 ± 0.02
Combined muon	3.37 ± 0.04	50.6 ± 0.5	0.86 ± 0.04
Jet charge	27.7 ± 0.1	12.68 ± 0.06	0.45 ± 0.03
Total	32.1 ± 0.1	21.3 ± 0.08	1.45 ± 0.05

- Combined muon: combination of Inner Detector track and Muon spectrometer track
- Segment Tagged muon: full Inner Detector track matched to track segment in the muon spectrometer

Tag probabilities







Unbinned Maximum Likelihood Fit

signal — B_d reflections

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

background

- N number of selected candidates
- f_S signal fraction
- f_B0 fraction of specific B_d BG

- Signal model
  - time and angles: differential decay rates convoluted with Gaussian resolution with per event proper decay time errors
  - Mass modeled by Gaussian with event by event mass resolution
  - angular efficiency
- Background model
  - Mass described by linear function
  - proper time: sum of a Gaussian, two positive exponentials and a negative exponential
  - Angles: described by empirical determined functions

$$f(\cos\theta_T) = \frac{a_0 - a_1\cos^2(\theta_T) + a_2\cos^4(\theta_T)}{2a_0 - 2a_1/3 + 2a_2/5}$$

$$f(\varphi_T) = \frac{1 + b_1\cos(2\varphi_T + b_0)}{2\pi}$$

$$f(\cos\psi_T) = \frac{c_0 + c_1\cos^2(\psi_T)}{2c_0 + 2c_1/3}$$

25 free parameters

Fit parameters describing signal decay

- ϕ_s , $\Delta\Gamma_s$, Γ_s
- Δm fixed in the fit
- $|A_0(0)|^2$, $|A_{||}(0)|^2$, $\delta_{||}$, $\delta_{\perp}$ (δ_0 set to 0)
- S-wave A_S, δ_S

Measured variables

- B_s mass m & uncertainty σ_m
- 3 angles Ω (θ, φ, ψ)
- B_s lifetime t & uncertainty σ_t

Results

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s(rad)	0.12	0.25	0.11
$\Delta\Gamma_s(ps^{-1})$	0.053	0.021	0.009
$\Gamma_s(ps^{-1})$	0.677	0.007	0.003
$\lvert A_{\parallel}(0)\rvert^2$	0.220	0.008	0.009
$\lvert A_0(0)\rvert^2$	0.529	0.006	0.011
$\lvert A_S\rvert^2$	0.024	0.014	0.028
$\delta_{\perp}$	3.89	0.46	0.13
$\delta_{\parallel}$	[3.04-3.23]		0.09
$\delta_{\perp} - \delta_S$	[3.02-3.25]		0.04

- 22670 ± 150 signal B_s events
- consistent with untagged analysis
- Φ_s consistent with Standard Model
- S-wave amplitude is consistent with 0
- $\delta_{\parallel}$ and $\delta_{\perp} - \delta_S$ are given as 1σ confidence level

Result of untagged measurement
$\Phi_s = 0.21 \pm 0.41$ (stat.) ± 0.10 (syst.) rad

Correlation Table

	ϕ_s	$\Delta\Gamma$	Γ_s	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_{\parallel}$	$\delta_{\perp}$	$\delta_{\perp} - \delta_S$
ϕ_s	1.000	0.107	0.026	0.010	0.002	0.029	0.021	-0.043	-0.003
$\Delta\Gamma$		1.000	-0.617	0.105	0.103	0.069	0.006	-0.017	0.001
Γ_s			1.000	-0.093	-0.063	0.034	-0.003	0.001	-0.009
$\lvert A_{\parallel}(0)\rvert^2$				1.000	-0.316	0.077	0.008	0.005	-0.010
$\lvert A_0(0)\rvert^2$					1.000	0.283	- 0.003	-0.016	-0.025
$\lvert A_S(0)\rvert^2$						1.000	-0.011	-0.054	-0.098
$\delta_{\parallel}$							1.000	0.038	0.007
$\delta_{\perp}$								1.000	0.081
$\delta_{\perp} - \delta_S$									1.000

Systematic Uncertainties

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

Uncertainties of fit model derived in pseudo-experiment studies

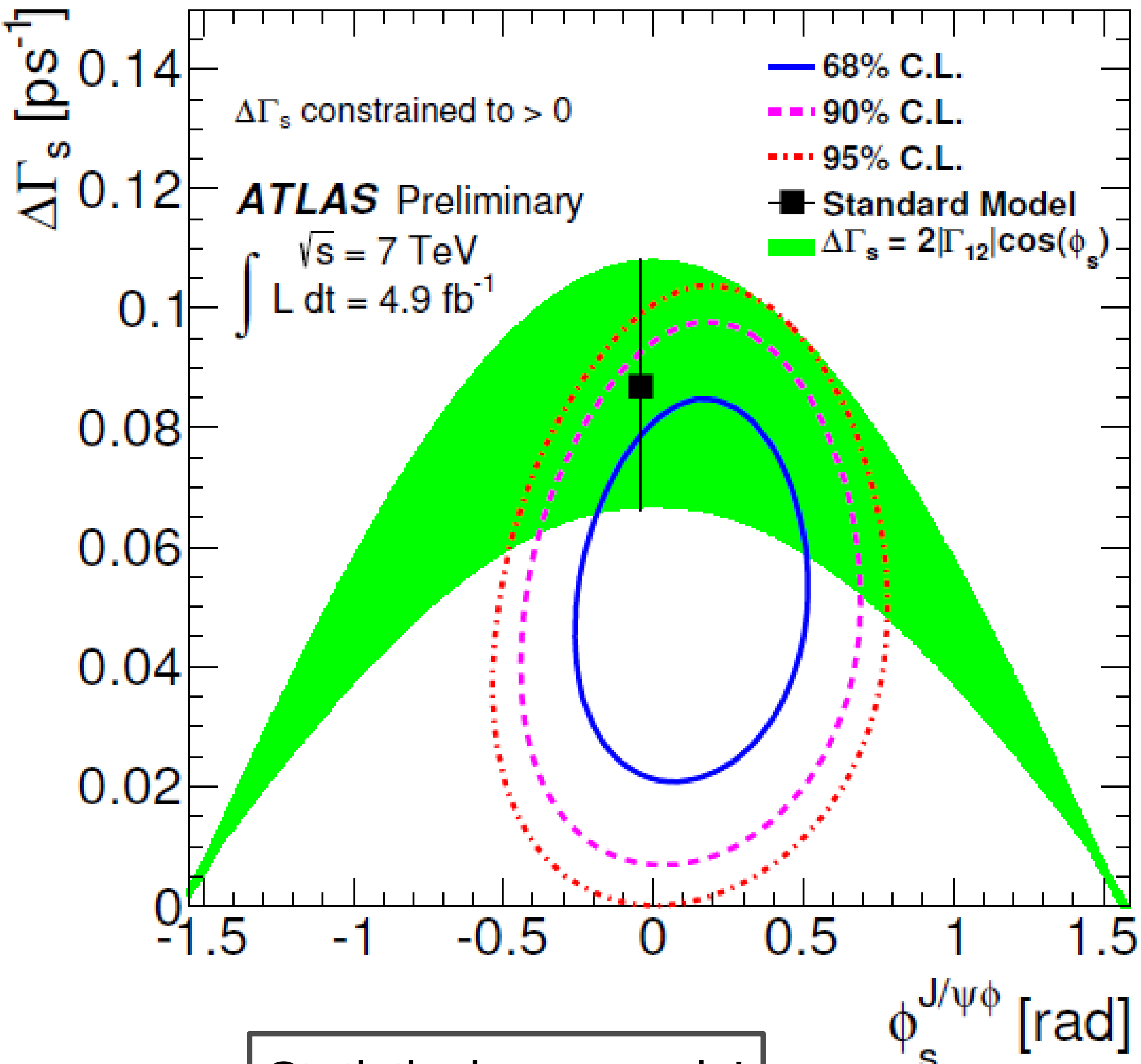
Effect of residual misalignment studied in signal MC

Uncertainty in trigger selection efficiency

Uncertainty in the calibration of the tag probability

Uncertainty in the relative fraction of B_d background

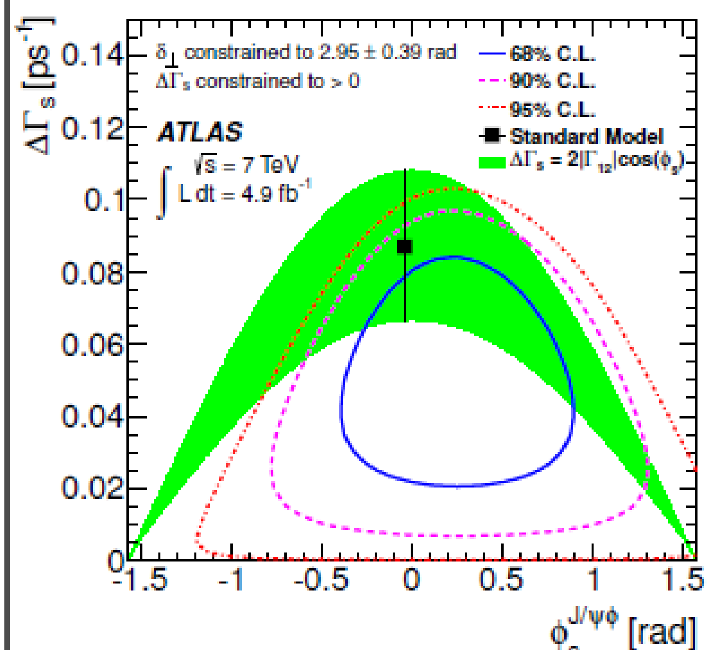
Likelihood Contour in ϕ_s - $\Delta\Gamma$ plane



Statistical errors only!

- Uncertainty of Φ_s improved by ~40 % compared to untagged analysis
- $\Delta\Gamma_s$ central value and uncertainty unchanged

Untagged Measurement



Summary

- CMS has measured average lifetime and decay width difference in an untagged angular analysis of $B_s \rightarrow J/\psi\ \Phi$ of 2011 data assuming $\Phi_s = 0$

$$\Delta\Gamma_s = 0.048 \pm 0.024\ (\text{stat.}) \pm 0.003\ (\text{syst.})$$
$$\tau_{B_s} = 0.04580 \pm 0.00059\ (\text{stat.}) \pm 0.00022\ (\text{syst.})$$

Derived from τ_{B_s} : $\Gamma_s = 0.655 \pm 0.008\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1}$

- ATLAS updated the $B_s \rightarrow J/\psi\ \Phi$ analysis of 2011 data using muon and jet charge tagging improving the precision of the Φ_s measurement

$$\phi_s = 0.12 \pm 0.25\ (\text{stat.}) \pm 0.11\ (\text{syst.})\ \text{rad}$$
$$\Delta\Gamma_s = 0.053 \pm 0.021\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{ps}^{-1}$$
$$\Gamma_s = 0.677 \pm 0.007\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1}$$

Backup

Differential Decay Rate in CMS Analysis

$$\frac{d^4\Gamma(B_s(t))}{d\Theta\, dt} = f(\Theta, t; \alpha) = \sum_{i=1}^{6} O_i(\alpha, t).g_i(\Theta)$$

time-dependent part

$$\begin{aligned}
O_1 &= |A_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) - \cos\phi_s \sinh(\Delta\Gamma_s t/2)] \\
O_2 &= |A_{||}(t)|^2 = |A_{||}(0)|^2 e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) - \cos\phi_s \sinh(\Delta\Gamma_s t/2)] \\
O_3 &= |A_{\perp}(t)|^2 = |A_{\perp}(0)|^2 e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) + \cos\phi_s \sinh(\Delta\Gamma_s t/2)] \\
O_4 &= Im(A_{||}^*(t)A_{\perp}(t)) = |A_{||}(0)||A_{\perp}(0)|e^{-\Gamma_s t}[-\cos(\delta_{\perp} - \delta_{||})\sin\phi_s \sinh(\Delta\Gamma_s t/2)] \\
O_5 &= Re(A_0^*(t)A_{||}(t)) = |A_0(0)||A_{||}(0)|\cos\delta_{||} e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) - \cos\phi_s \sinh(\Delta\Gamma_s t/2)] \\
O_6 &= Im(A_0^*(t)A_{\perp}(t)) = |A_0(0)||A_{\perp}(0)|e^{-\Gamma_s t}[-\cos\delta_{\perp} \sin\phi_s \sinh(\Delta\Gamma_s t/2)]\ ,
\end{aligned}$$

angular part

$$\begin{aligned}
g_1 &= 2\cos^2(\psi_T)(1 - \sin^2(\theta_T)\cos^2(\varphi_T)), \\
g_2 &= \sin^2(\psi_T)(1 - \sin^2(\theta_T)\sin^2(\varphi_T)), \\
g_3 &= \sin^2(\psi_T)\sin^2(\theta_T), \\
g_4 &= -\sin^2(\psi_T)\sin^2(2\theta_T)\sin(\varphi_T), \\
g_5 &= \frac{1}{\sqrt{2}}\sin(2\psi_T)\sin^2(\theta_T)\sin(2\varphi_T), \\
g_6 &= \frac{1}{\sqrt{2}}\sin(2\psi_T)\sin(2\theta_T)\sin(\varphi_T)\ .
\end{aligned}$$

- With the assumption fo no CPV (Φ_s =0) terms $O_4 \cdot g_4$ and $O_6 \cdot g_6$ are zero.
- S-wave component is assumed to be negligible
- Untagged: equal probability for B_s / $\overline{B}_s$

Differential Decay Rate in ATLAS Analysis

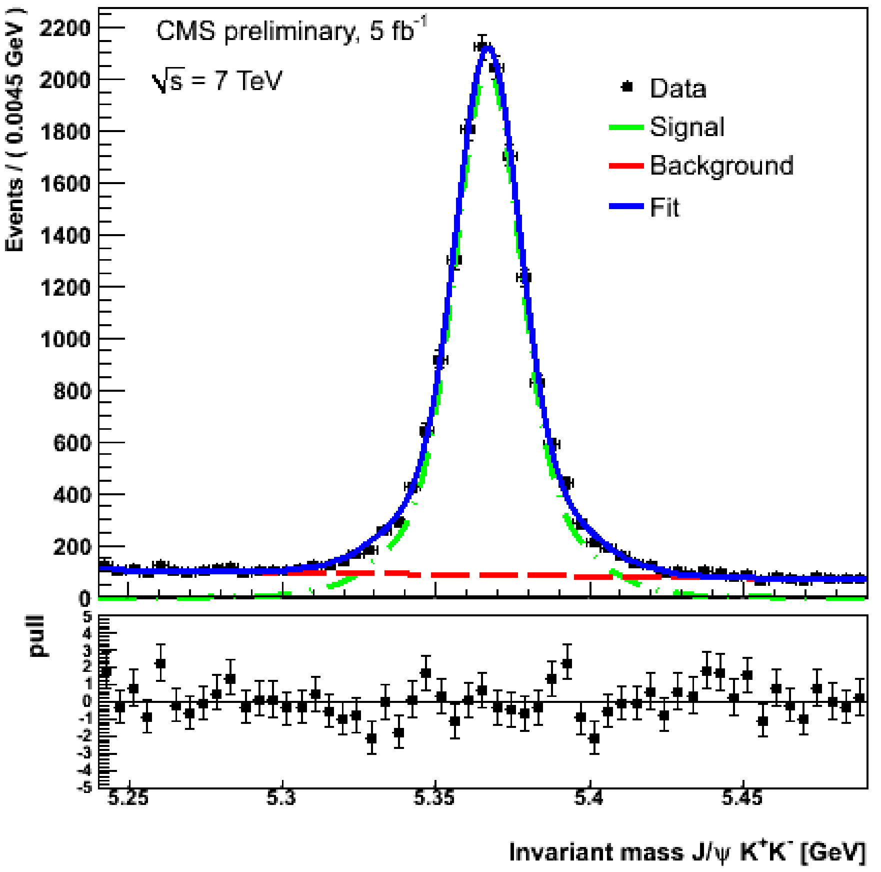
$$\frac{d^4\Gamma}{dt\,d\Omega} = \sum_{k=1}^{10} \mathcal{O}^{(k)}(t)\, g^{(k)}(\theta_T, \psi_T, \varphi_T)$$

time-dependent part | angular part

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

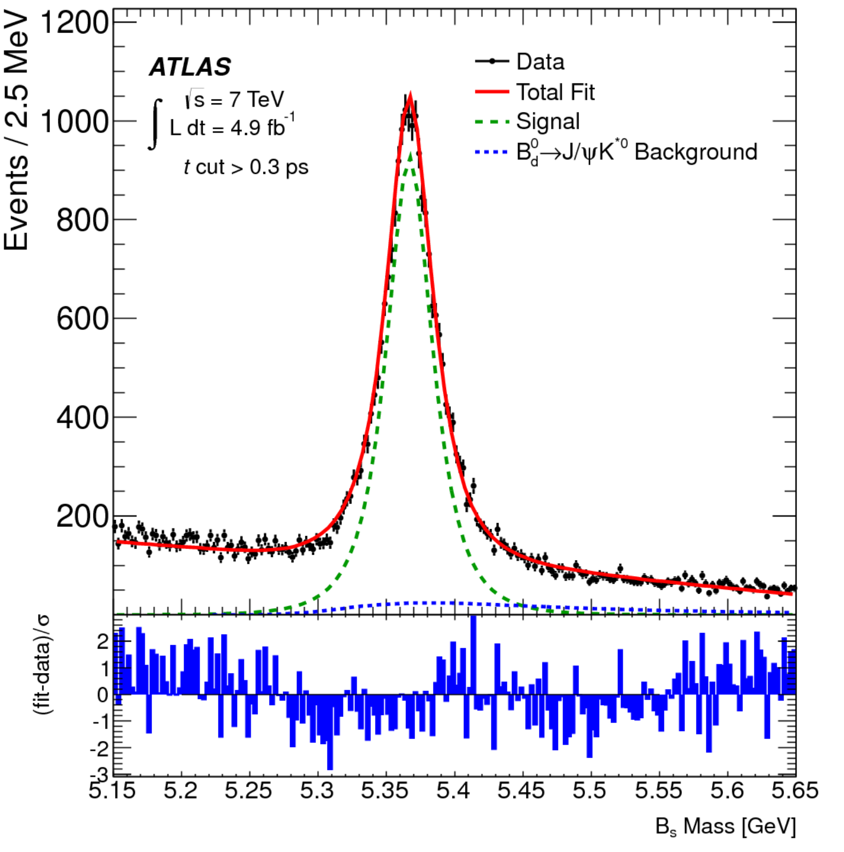
Mass Projection Comparison With Cut

CMS



$ct(B_s) > 0.02$ cm

ATLAS

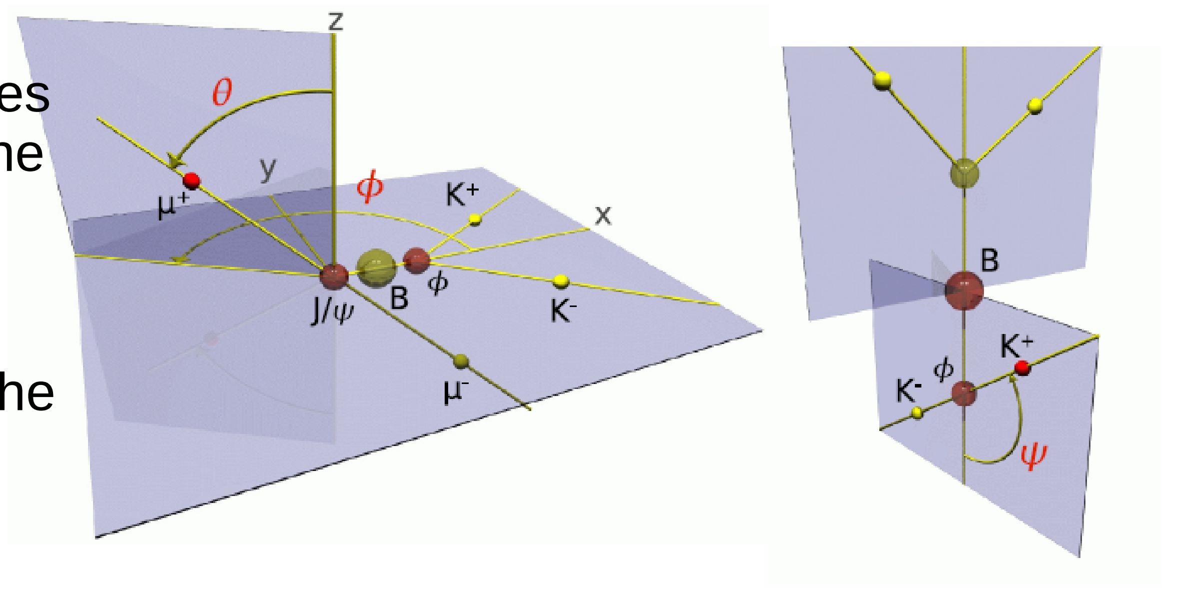


$\tau > 0.3$ ps

Measurement of CPV in the $B_s \rightarrow J/\psi\ \phi$ Decay

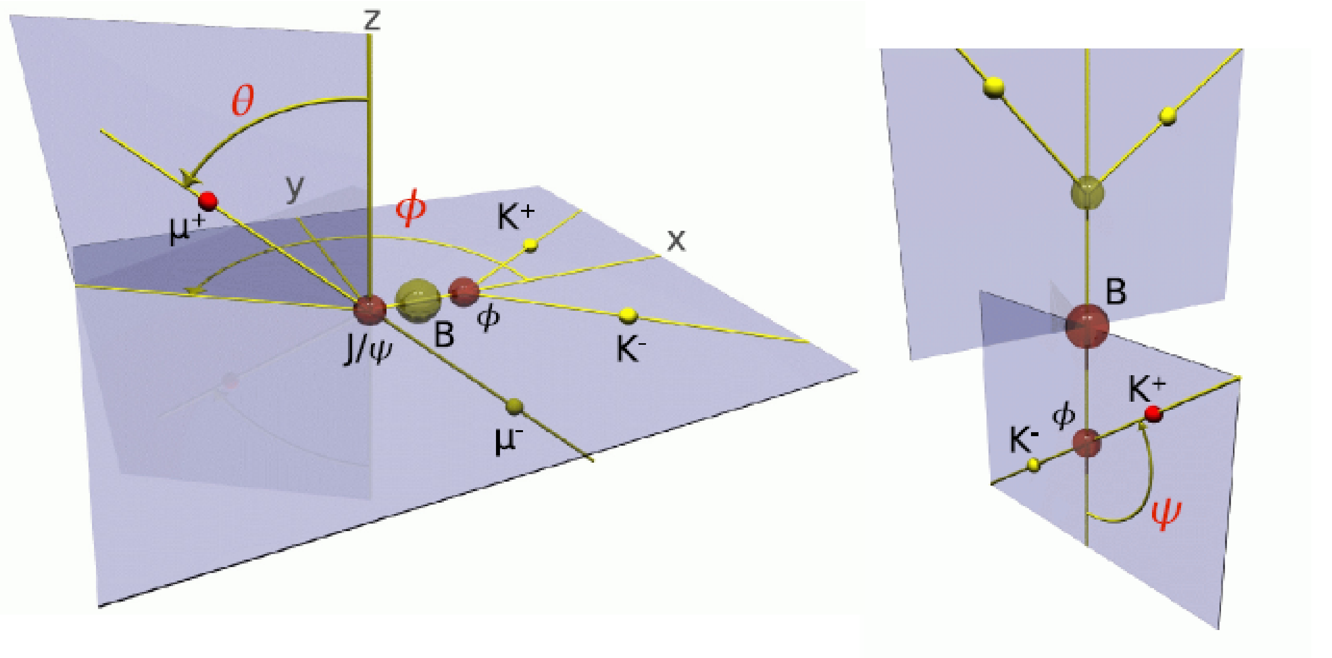
- B_s (pseudoscalar with spin 0) decays into 2 vector mesons with spin 1
- Conservation of total angular momentum leads to three different values of relative orbital angular momentum between J/ψ and ϕ
  - L = 0 & L = 2: even CP eigenstates (~75 %)
  - L = 1: odd CP eigenstate (~25 %)
- Final state $J/\psi\ \phi$ is a mixture of CP even and CP odd eigenstates

- An angular analysis is used to determine 3 transversity amplitudes and 3 strong phases that define the three states
- CP state is determined from the angular distribution of the final state particles $\mu^+ \mu^- K^+ K^-$ in the transversity basis



Coordinate system in the transversity basis

The x−axis is determined by the direction of the Φ meson in the J/ψ rest frame. The K^+K^--plane defines the xy-plane, where $p_y(K+) > 0$.



- θ is the angle between $p(\mu^+)$ and the xy plane in the J/ψ meson rest frame
- Φ is the angle between the x− axis and $p_{xy}(\mu^+)$, the projection of the μ+ momentum in the xy plane, in the J/ψ meson rest frame
- ψ is the angle between $p(K^+)$ and −p(J/ψ) in the Φ meson rest frame

Event Selection / Reconstruction

ID tracks: ≥ 1 hits in Pixel and ≥ 4 hits in SCT detector

Muon tracks: both combined (ID+muon track) and tagged (ID only), no explicit pT cut applied; muon track parameters taken from ID alone (ID precision dominates at low p_T)

$J/\psi \rightarrow \mu\mu$ candidates selection:

- vertex fit $\chi^2/NDF < 10$
- 3 invariant mass windows for both muons in barrel (BB), both in endcap (EE), or combination (EB):
  - BB: $2989 < m(J/\psi) < 3199$ MeV
  - EB: $2944 < m(J/\psi) < 3242$ MeV
  - EE: $2827 < m(J/\psi) < 3357$ MeV
  - windows retaining 99.8% of the signal

$\phi \rightarrow KK$ candidates selection:

- mass: $1009 < m(\phi) < 1031$ MeV
- $K^{\pm}$ transverse mom. > 1 GeV

B_s candidates selection:

- vertex fit of all the 4 tracks, with muons pair constrained to J/ψ PDG mass
- all 4 tracks vertex fit $\chi^2/NDF < 3.0$
- B-candidate proper lifetime error $\delta\tau_i < 0.3$ ps
- no attempt for K/π identification
- if more B-candidates are found in an event, only the one with the lowest vertex fit χ^2/NDF is kept

Trigger Bias

- the muon trigger biases the transverse impact parameter of muons toward smaller values
- trigger selection efficiency was measured in data and MC simulation using a tag-and-probe method
- re-weighting of the events with a factor depending on the measured B_s lifetime before the correction
- ε = 0.013 ± 0.004 ps

$$w = e^{-|t|/(\tau_{\rm sing}+\epsilon)} / e^{-|t|/\tau_{\rm sing}}$$

- ε is determined using MC events by comparing the B_s lifetime of an unbiased sample with the lifetime obtained after including the dependence of the trigger efficiency on the muon transverse impact parameter as measured from the data
- uncertainty reflects the precision of the tag-and-probe method and is used to assign a systematic

Acceptance

- four dimensional binned acceptance method
- event-by-event efficiency according to the transversity angles (θ_T , ψ_T , ϕ_T) and the p_T of the B_s
- Takes into account
  - detector sculpting
  - trigger efficiency
  - reconstruction
  - selection cuts
- acceptance maps are calculated from $B_s \rightarrow J/\psi\ \phi$ MC events
- is treated as an angular sculpting PDF
- Multiplied to signal time- and angular-dependent PDF
- Taken into account in the normalization
- Effect of variation of the bins is negligible (systematic check)

Tag Probability

- P(B|Q): Probability to identify the flavor of the signal B meson as B_S
- $P(\overline{B}|Q) = 1 - P(B|Q)$: probability for $\overline{B}_S$
- Q is discriminating variable
- The samples of B^+ and B^- are used to extract and calibrate the probability distribution

$$P(B|Q) = \frac{P(Q|B^+)}{P(Q|B^+) + P(Q|B^-)}$$

- For comparison of the different tagging methods the following quantities are defined:
  - Efficiency $\epsilon = N_{\mathrm{tagged}}/N_{\mathrm{Bcandidates}}$
  - Tagging Power $\epsilon D^2 = \sum_i \epsilon_i D_i^2$
  - Effective Dilution $D_i = 2P(B|Q) - 1$

$$D = \sqrt{\frac{\epsilon D^2}{\epsilon}} = \sqrt{\frac{\sum_i \epsilon_i D_i^2}{\sum_i \epsilon_i}}$$