Studies of CP violation with the ATLAS detector in the decay $B_s \to J/\psi\ \phi$

James Walder
On behalf of the ATLAS Collaboration

Flavour tagged time dependent angular analysis of $B_s \to J/\psi(\mu\mu)\ \phi(KK)$ using 2011 4.9 fb^{-1} data.

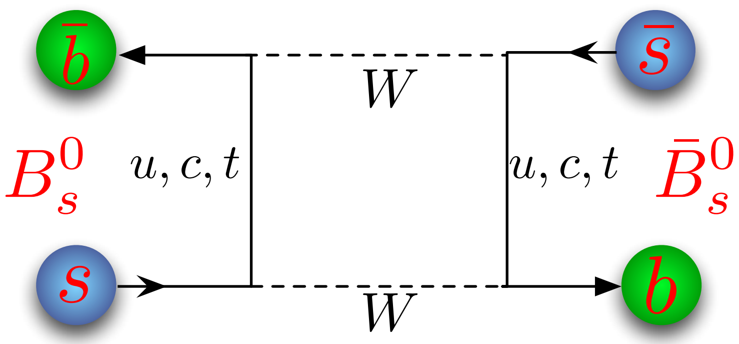
Recently submitted to PRD: arXiv:1407.1796

Update to untagged analysis: JHEP 12 (2012) 072

ATLAS

LANCASTER UNIVERSITY

CP Violation in B_s System



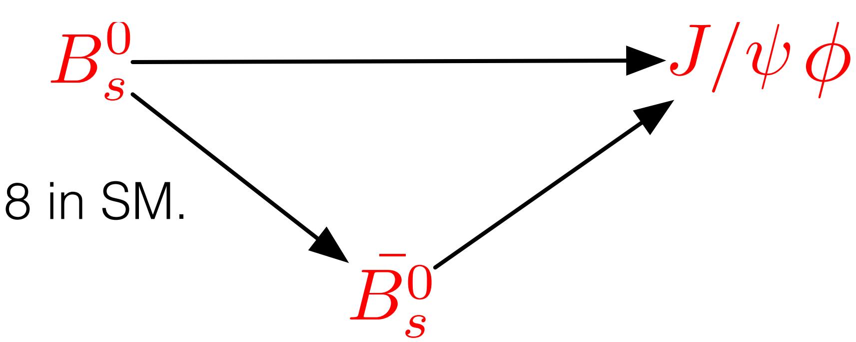
$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{11} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{11} \end{pmatrix}\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix}$$

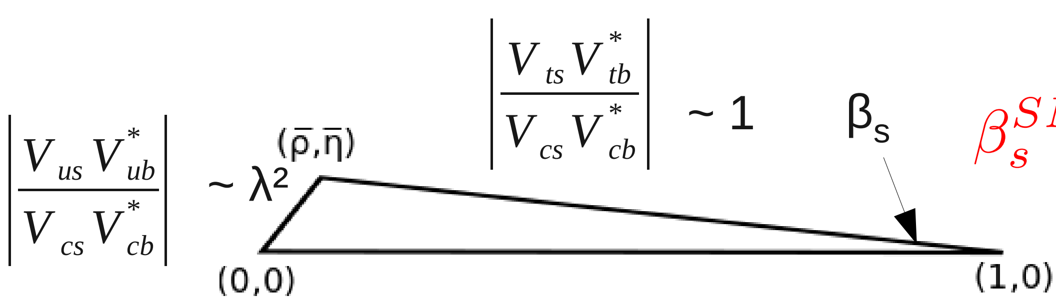
$$|B_{\mathrm{L}}\rangle = p\,|B^0\rangle + q\,|\bar{B}^0\rangle$$
$$|B_{\mathrm{H}}\rangle = p\,|B^0\rangle - q\,|\bar{B}^0\rangle$$

- Mixing between the flavour states give rise to heavy and light mass eigenstates
  - Mass difference now well-measured; $\Delta m_s = m_s^H - m_s^L \approx 2|M_{12}^s|$, $\Delta m_s \approx 17.77 ps^{-1}$
  - Decay width difference (sign established to be Positive): $\Delta\Gamma_s = \Gamma_s^L - \Gamma_s^H$ = 8.7 ± 2.1 %

arXiv:1102.4274 [hep-ph]

- CP violation in $B_s \to J/\psi\, \phi$ occurs through "interference of mixing and direct decay" (same final state)
- Experimentally clean decay channel
- The CP-violating weak phase angle ϕ_s in $B_s \to J/\psi\, \phi$ relates to the CKM matrix elements with $\phi_s \approx -2\beta_s$; ϕ_s = -0.0368 ± 0.0018 in SM.





$$\beta_s^{SM} = \arg\left[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)\right]$$

$$\phi_s = \phi_s^{SM} + \phi_S^{NP} \approx \phi_S^{NP}$$

- If New Physics, contributions most likely to appear through the phase ϕ_s, hence any non-zero observation of this quantity should indicate NP.
- Measurements of the other observable quantities (e.g. ΔΓ) also test theoretical predictions.

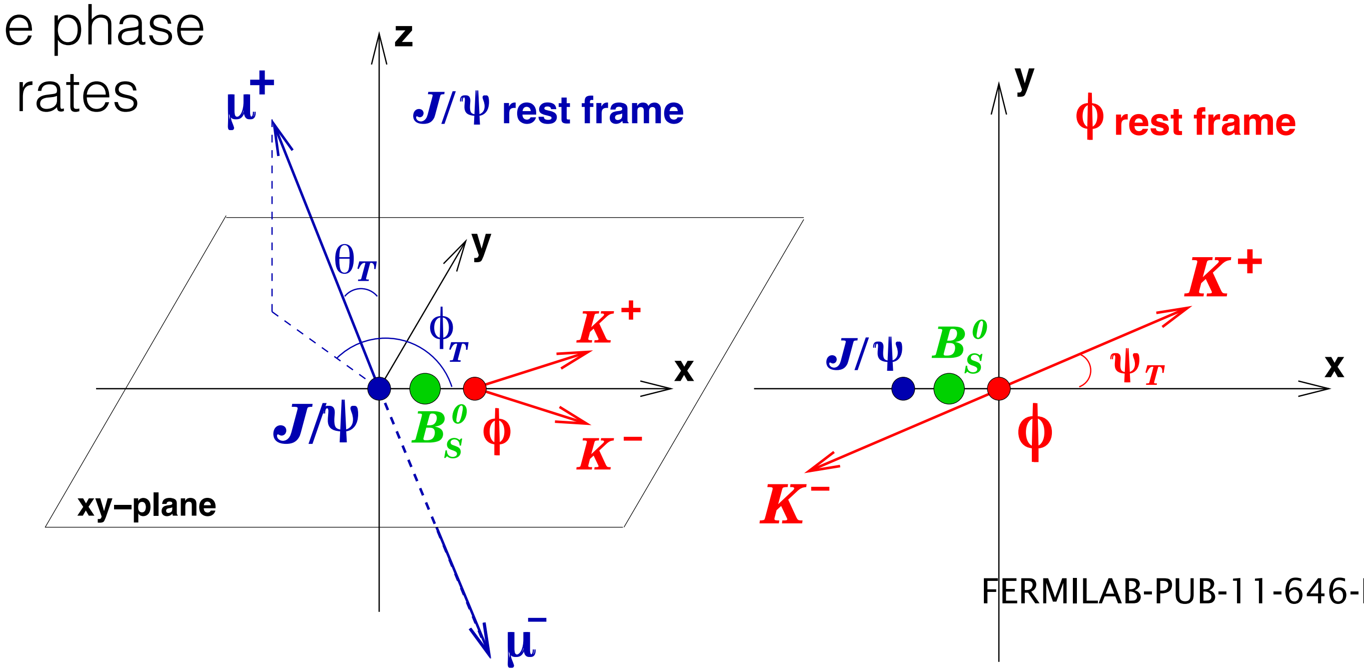
Angular Analysis

- $B_s \rightarrow J/\psi\ \phi$ – pseudo-scalar to vector-vector meson decay
  - CP-even (L=0,2) and CP-odd (L=1) final states
  - Statistically distinguishable through time-dependent angular analysis
  - Results presented here define the 3 angles between final state particles in **Transversity basis**
- From the multi-dimensional fit to the data, the three amplitudes and strong phases are able to be extracted, alongside with the phase ϕ_s and the light (Γ_L) and heavy (Γ_H) decay rates
- Amplitudes:

$$A_0 - \text{ longitudinal CP-even final state}$$
$$A_{||} - \text{ transverse CP-even}$$
$$A_{\perp} - \text{ transverse CP-odd}$$

- Strong Phases:

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



FERMILAB-PUB-11-646-E

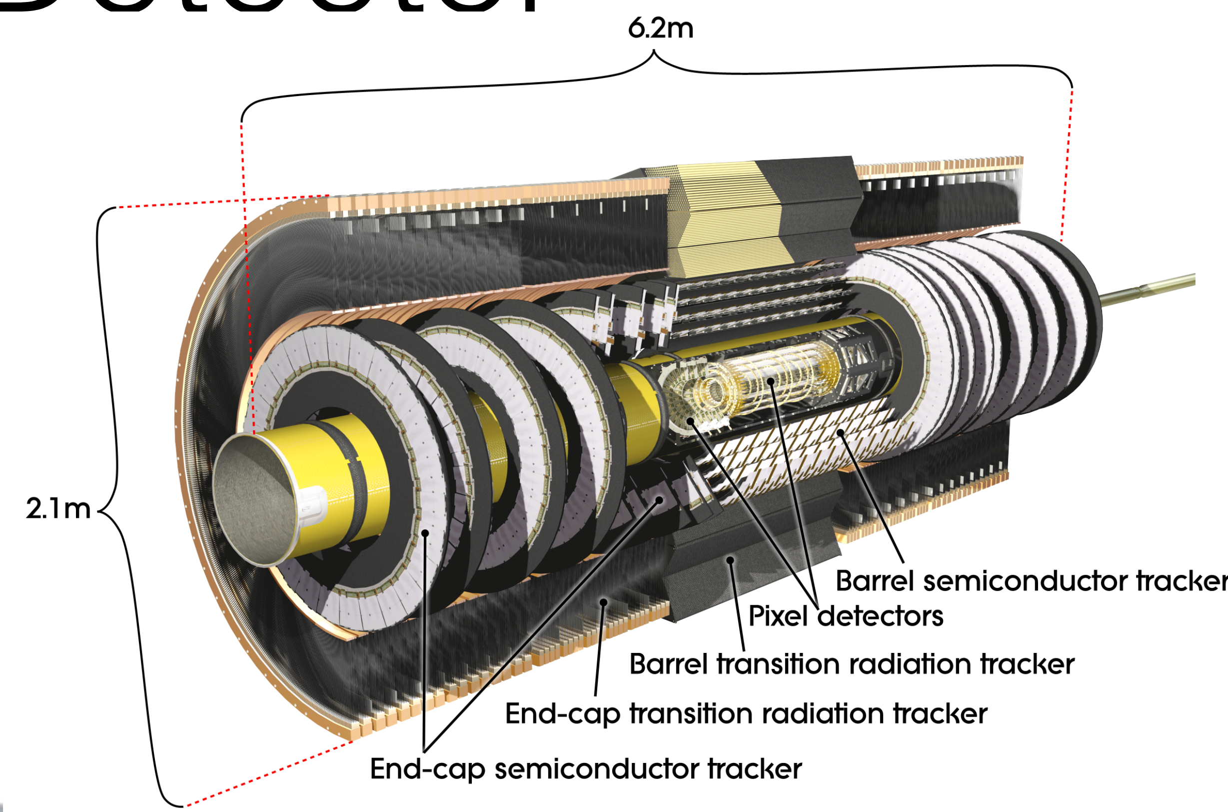
θ is the angle between $p(\mu^+)$ and the x-y plane in the J/ψ meson rest frame

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

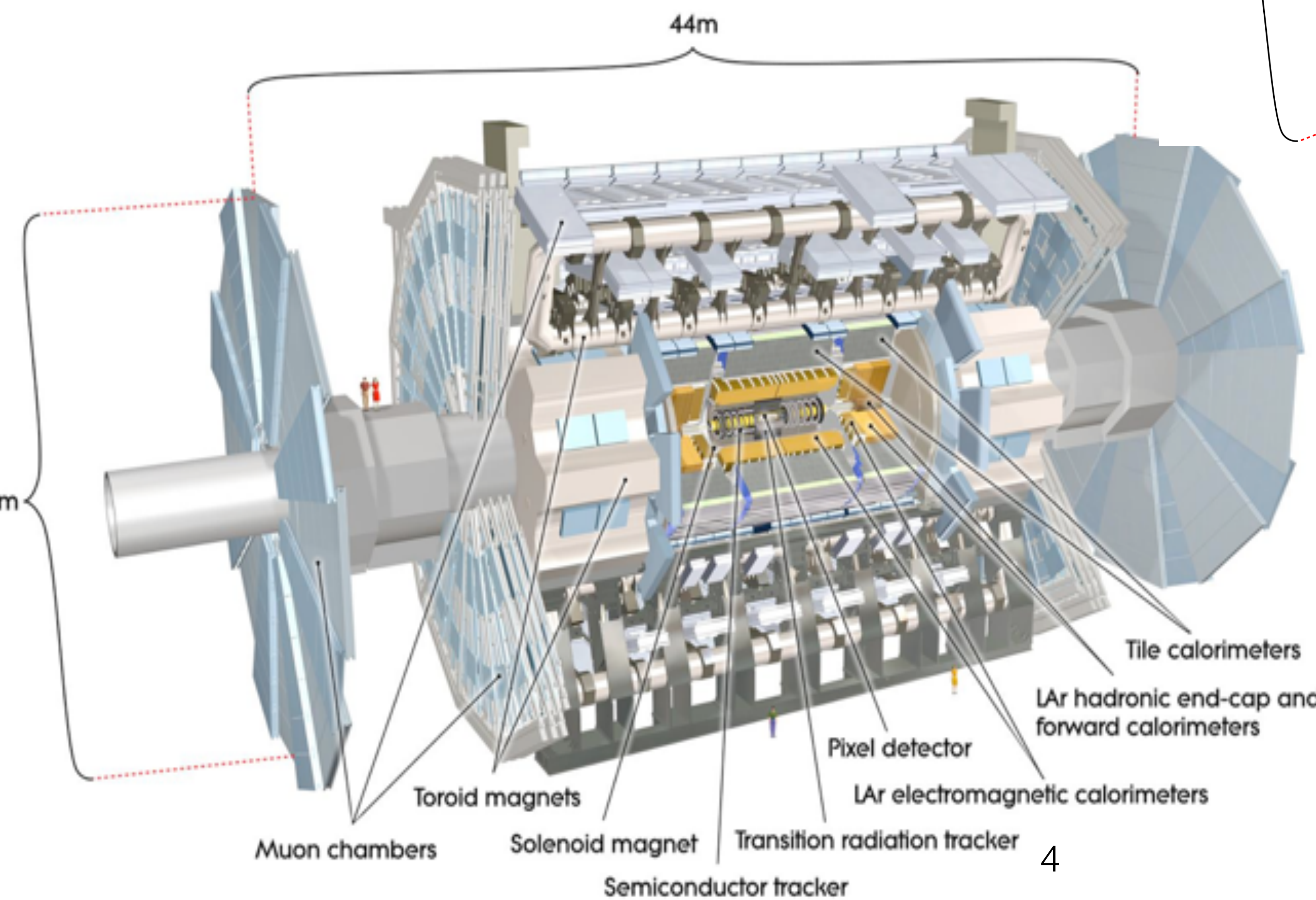
ψ is the angle between $p(K^+)$ and $-p(J/\psi)$ in the Φ meson rest frame

The ATLAS Detector

- Muons are identified using combined information from Muon Spectrometer and Inner Detector tracking.
- Only Inner Detector track parameters are used in fits; provides precision momentum and lifetime measurements



- **Inner Detector**
  - $|\eta|<2.5$,
  - Solenoid B=2T
  - Si Pixels,
  - Si strips,
  - Transition Radiation Tracker (TRT)
  - $\sigma/p_T \sim 3.4\text{x}10\text{-}4\ p_T + 0.015$ for ($|\eta|<1.5$)
  - Used for Tracking and Vertexing:

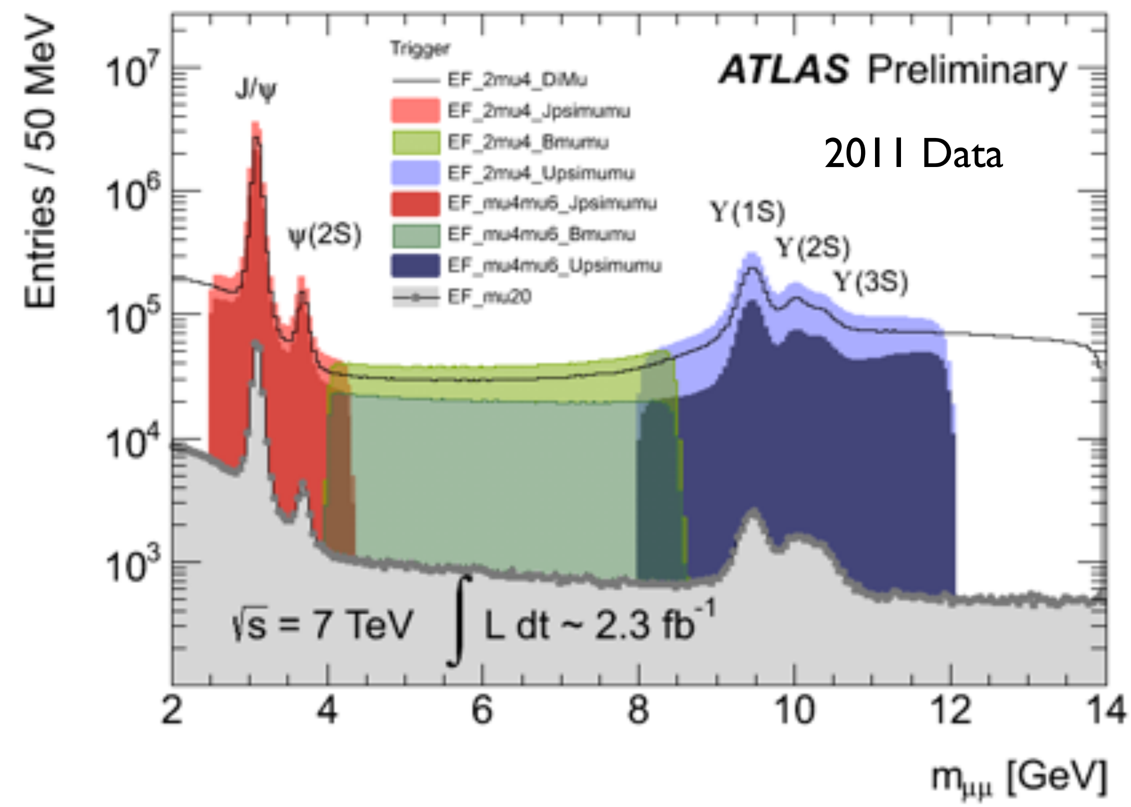


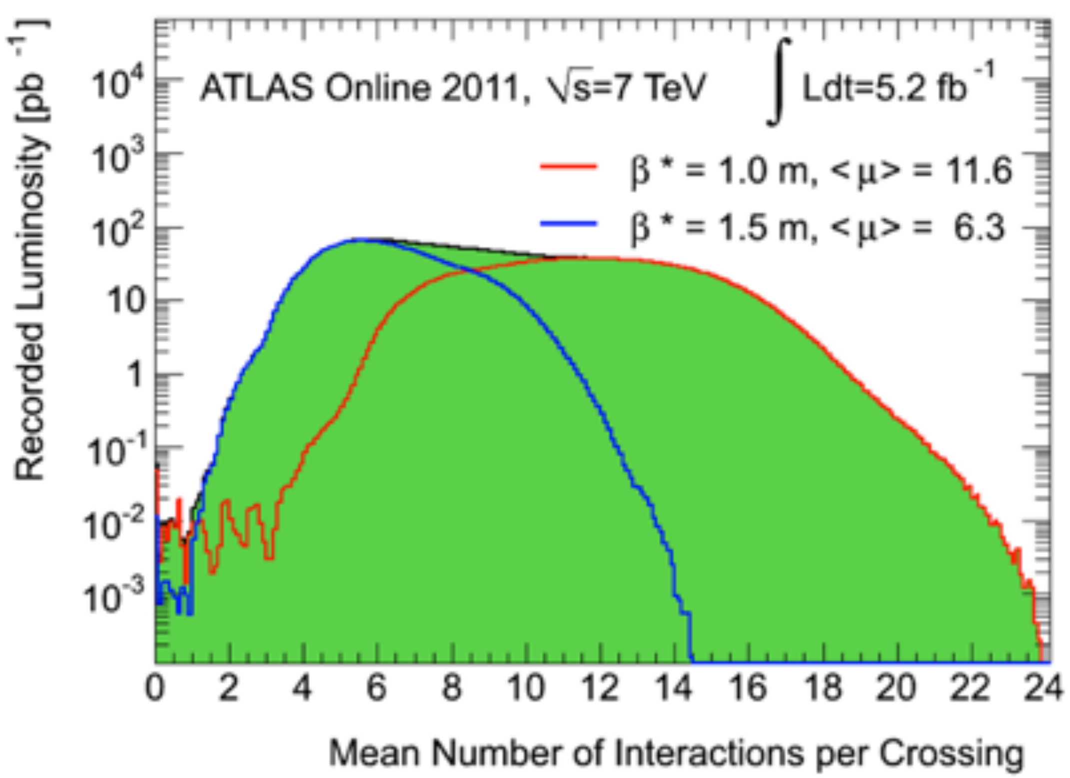
- **Muon Spectrometer**
  - $|\eta|<2.7$
  - Toroid B-Field, average ~0.5T
  - Muon Momentum resolution $\sigma/p <$ 10% up to ~ 1 TeV

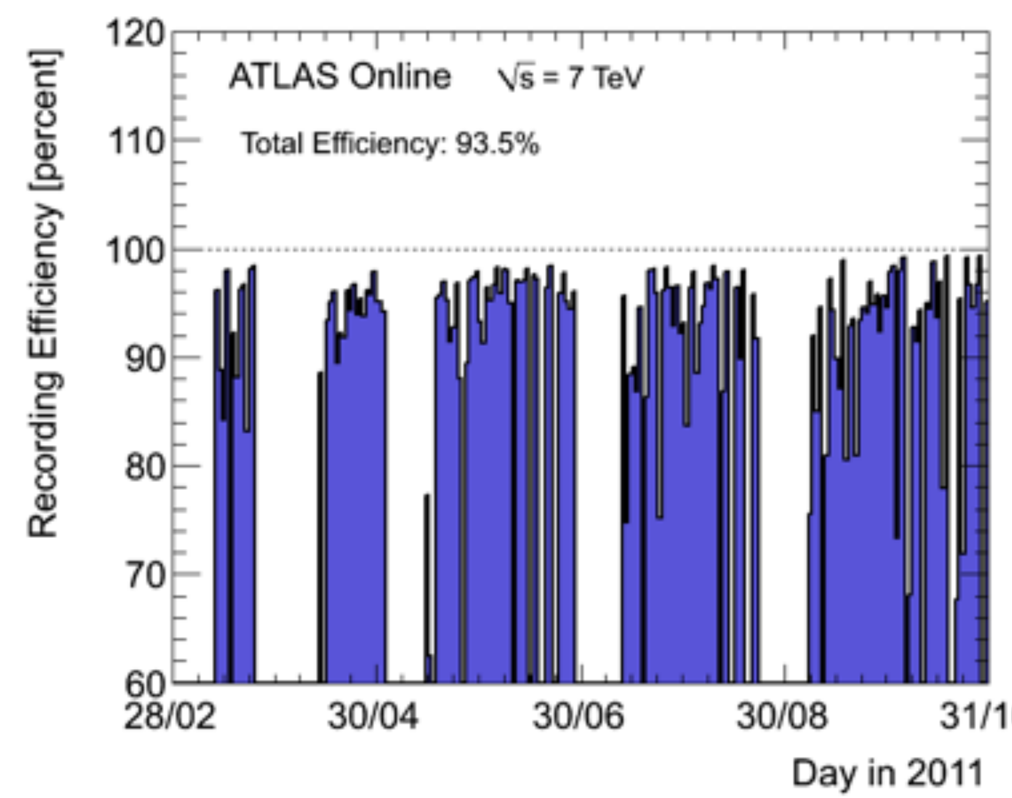
Data Taking

- Data selection begins with optimised suite of single and di-muon triggers:
  - 3-level system (1 Hardware, 2 Software): Rate reduction of 40 MHz to $O(200)$ Hz
  - No decay length requirements applied
- Over 90% data recording efficiency.

- For the final data sample, $\langle\mu\rangle \sim 5.6$ interactions, requiring a choice of Primary Vertex

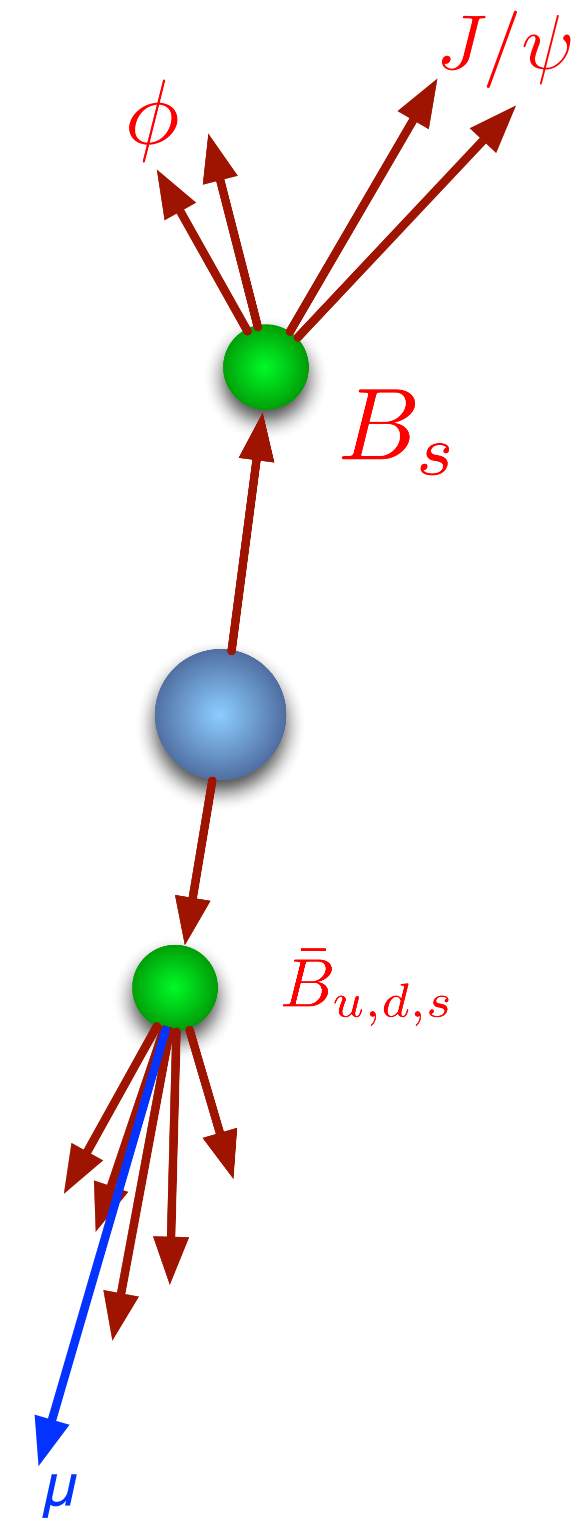






Flavour Tagging

- If initial flavour of B_s meson is known, additional terms appear in the likelihood description of the time-dependent amplitudes:
- Information on initial state therefore leads to
  - Increased sensitivity on ϕ_s, and removal of one of the sign ambiguities in the model.
- Opposite side tagging, use $b - \bar{b}$ pair correlation to infer initial signal flavour from the other B meson.
- Muon Tagging:
  - $b \to \mu$ transitions are clean tagging method, but diluted from $b \to c \to \mu$ decays and neutral B-meson oscillations.
- Jet-charge Tagging:
  - Search for jet corresponding to opposite-side decay.
- Use momentum-weighted track-charge as discriminating variable.

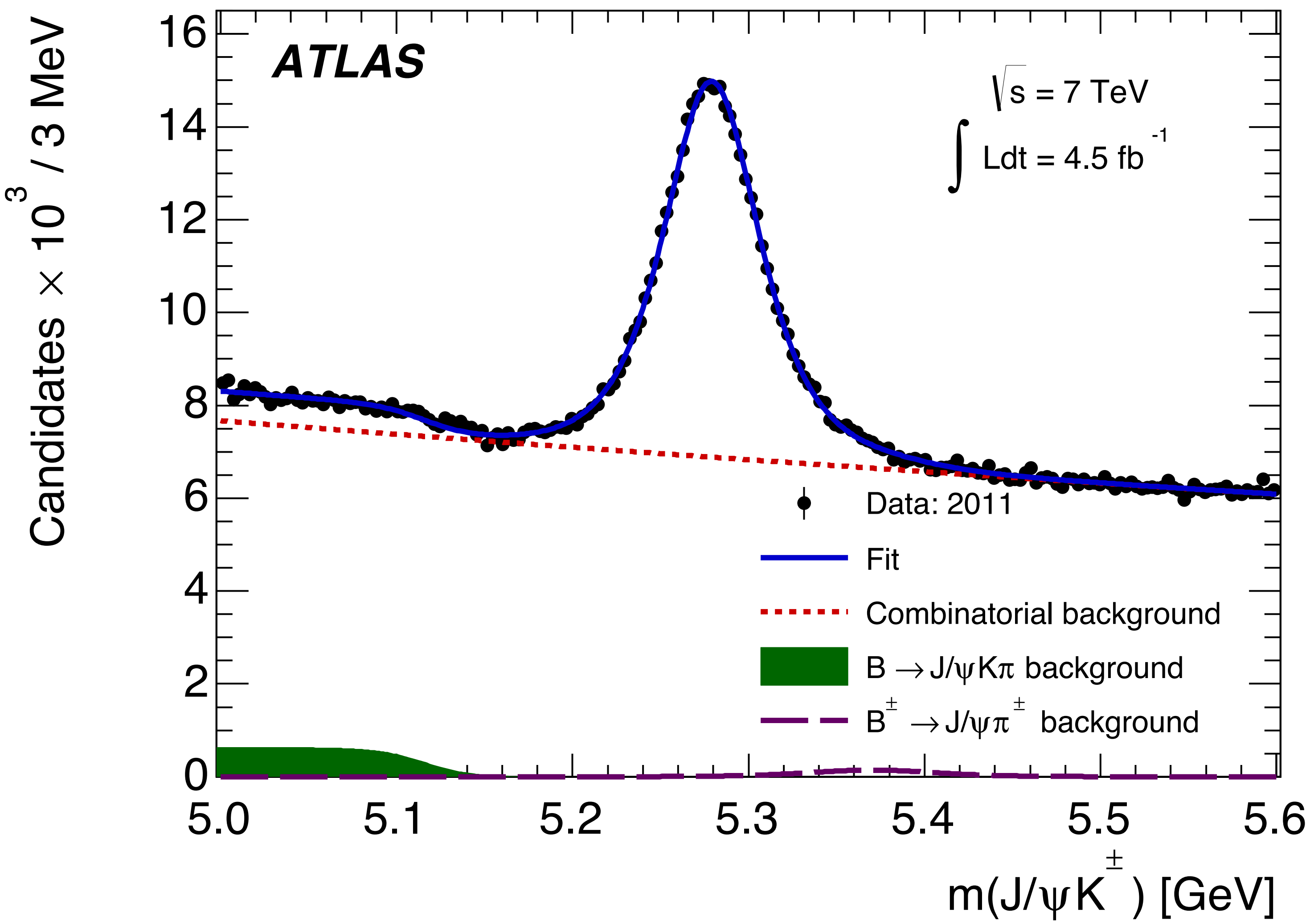


Tagging Calibration Sample

- Calibration of tagging method from self-tagging sample: $B^{\pm} \rightarrow J/\psi K^{\pm}$

•μμ
- •pT(μ)> 4 GeV
- •|η(μ)|<2.5
- • 2.8 < m(μμ) < 3.4 GeV

•J/ψK±
- •pT(K) > 1 GeV
- •|η(K)| < 2.5
- •Lxy > 0.1mm



- Signal sample selected using sideband subtraction from mass distributions to form the calibration data:

•Signal Region:
- • $|m(J/\psi K^{\pm}) - \mu| < 2\sigma$

•Sidebands:
- • $3\sigma < |m(J/\psi) - \mu| < 5\sigma$

Tagging Variables

- **Muon Tagging:**
  - Additional Muon pT(μ)>2.5 GeV, |η| <2.5
  - Originating near the signal primary interaction |Δz| < 5mm

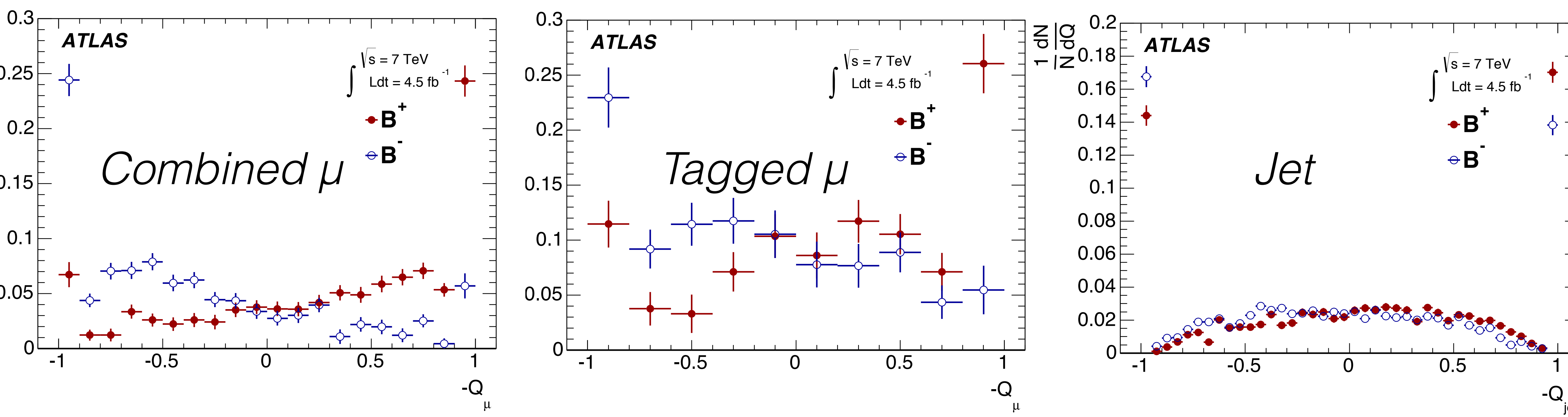
  - Use muon and tracks within cone ΔR<0.5 around muon to construct momentum-weighted muon-cone charge

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

- **Jet charge Tagging:**
  - In absence of muon use b-tagged jet (Anti-Kt, 0.6 cone size)
  - Use tracks from ΔR<1.0 around jet, originating near signal primary interaction.
  - Construct jet-charge from momentum-weighted charge of the selected tracks

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

Tagging prob. $P(B|Q) = \dfrac{P(Q|B^+)}{P(Q|B^+) + P(Q|B^-)}$

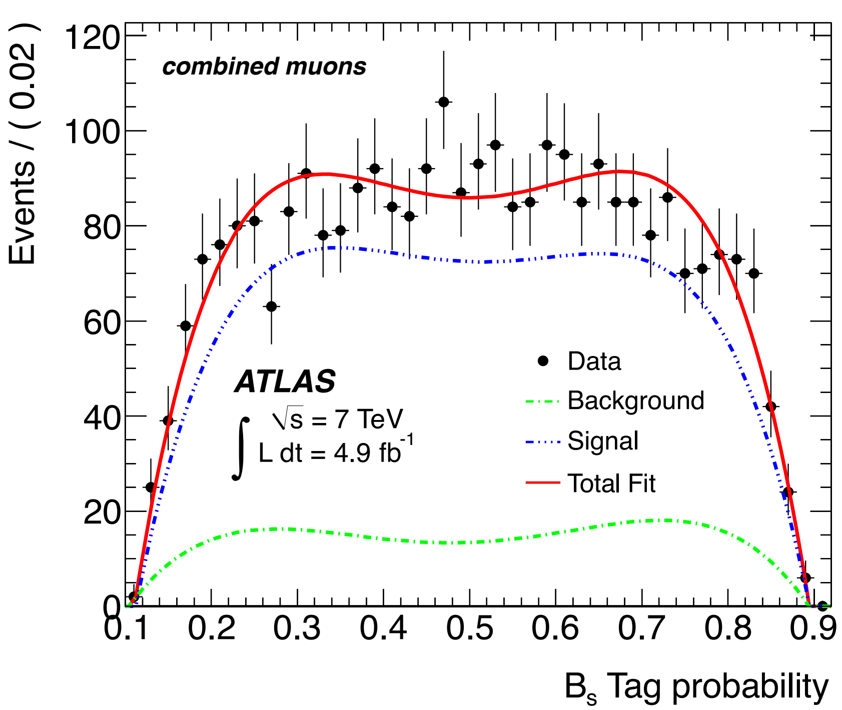


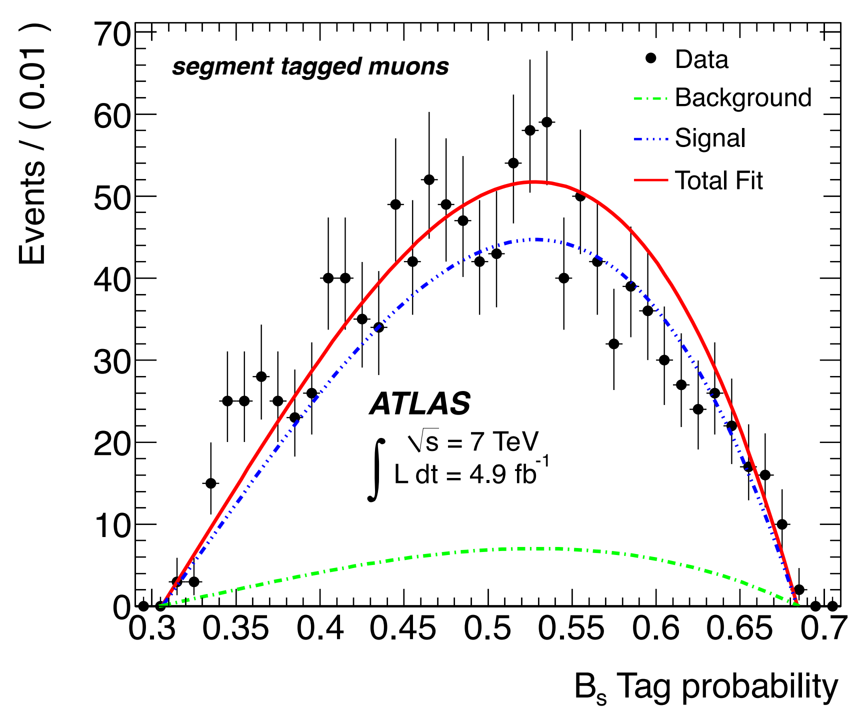
Tagging Performance

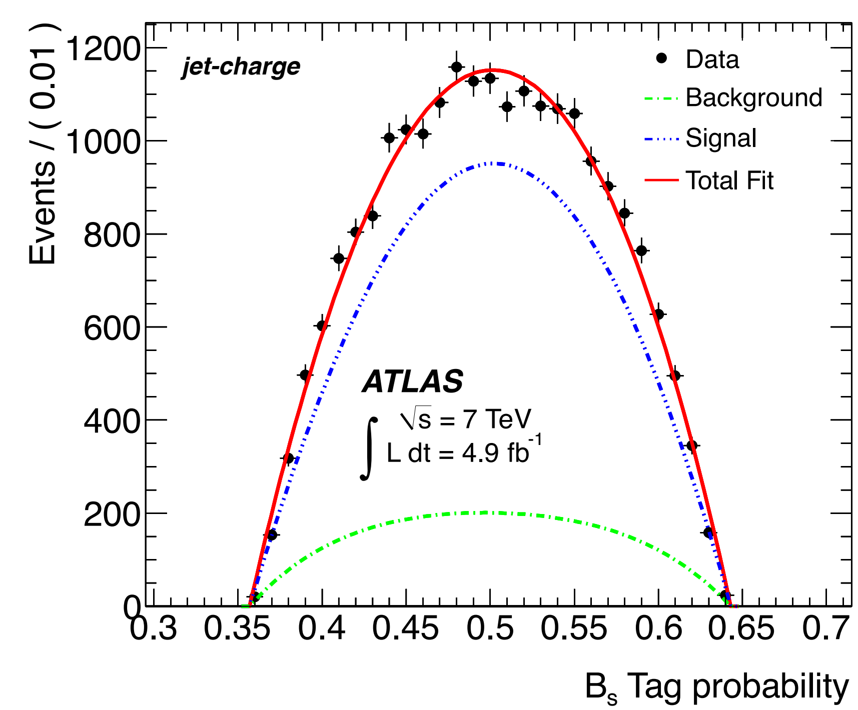
- Tagging performance estimated to be:
  - Tagging performance estimated to be:
    - (1.45 ± 0.05 (stat.))% from $B^{\pm} \to J/\psi K^{\pm}$

Tagger	Efficiency [%]		Dilution [%]		Tagging Power [%]	
Combined μ	$\epsilon = \frac{1}{N}\sum_{\text{n bins}}^{i} n_i$	3.37 ± 0.04	$D_{\text{eff}} = \sqrt{\frac{TP}{\epsilon}}$	50.6 ± 0.5	$\text{TP} = \frac{1}{N}\sum_{\text{n bins}}^{i} n_i(2P_i - 1)^2$	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

- In likelihood fit to B_s data, the per-candidate probability and probability distributions (Punzi terms) are considered.
- Punzi terms are parameterised from fit to sideband-subtracted (signal), and sideband (background) B_s data; P=0.5 in absence of tagging information.







Consequence of Tagging in Decay Rate

- Complex combination of time-dependent and angular terms define the differential decay rate: $\frac{d^4\Gamma}{dt\ d\Omega} = \sum_{k=1}^{10} \mathcal{O}^{(k)}(t) g^{(k)}(\theta_T, \psi_T, \phi_T),$
- Without tagging, many terms cancel in the differential decay rate

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

Consequence of Tagging in Decay Rate

- Without tagging, many terms cancel in the differential decay rate
  - With Tagging, ϕ_s (and $\delta_\perp$) gain sensitivity.

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

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

Fit Model

- Unbinned maximum likelihood technique, with per-event errors
- Observables:
  - m(J/ψKK), $t = \frac{L_{xy} M^B}{p_T^B}$ σ(m),σ(t)
  - Three transversity angles: Ω
  - Tagging probability P(B|Q)

- 25 free parameters in the fit
  - Δm fixed.
  - 9 signal parameters extracted:

$$\phi_s[\mathrm{rad}]$$
$$\Delta\Gamma_s[\mathrm{ps}^{-1}]$$
$$\Gamma_s[\mathrm{ps}^{-1}]$$
$$|A_\parallel(0)|^2$$
$$|A_0(0)|^2$$
$$|A_S(0)|^2$$
$$\delta_\perp$$
$$\delta_\parallel$$
$$\delta_\perp - \delta_S$$

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

Muon time dependent trigger efficiency

Signal PDF (including S-wave contribution)

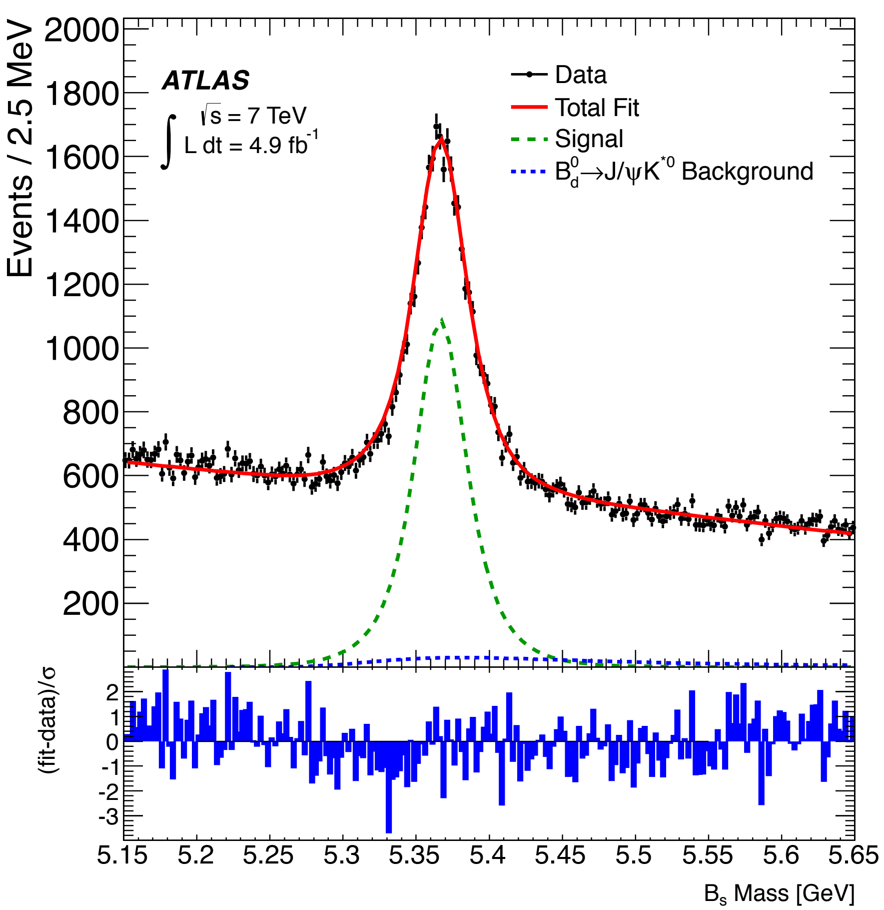
$$\mathcal{F}_s(m_i, t_i, \Omega_i, P(B|Q)) = P_s(m_i, \sigma_{m_i}) \cdot P_s(\sigma_{m_i}) \cdot P_s(\Omega_i, t_i, P(B|Q), \sigma_{t_i}) \cdot P_s(\sigma_{t_i}) \cdot P_s(P(B|Q)) \cdot A(\Omega_i, p_{\mathrm{T}i}) \cdot P_s(p_{\mathrm{T}i})$$

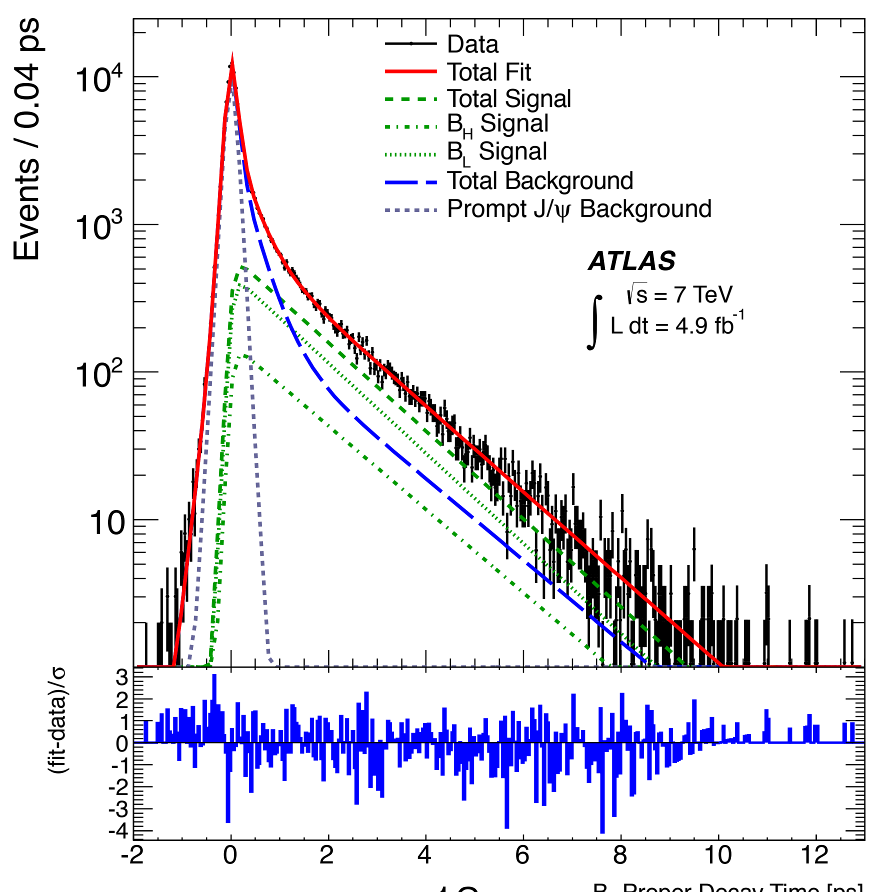
Background from $B^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi K\pi$ (non-resonant), constrained to known fractions and acceptance

Prompt and non-Prompt combinatorial background - with empirical angular distribution

Event Selection

- Data from 2011 at $\sqrt{s}$ = 7 TeV – 4.9 fb^{-1}.
- 132k Bs candidates after selections; mass range [5.15,5.65] GeV.
- Choice of Primary Vertex using unsigned 3d-impact parameter. Negligible effects from selection of incorrect primary vertex due to pileup (<μ> ~5.6).
- No requirement is made on proper-time cut,
  - Full prompt contribution considered in fit
- 22,670 ± 150 signal events are estimated from the final fit.



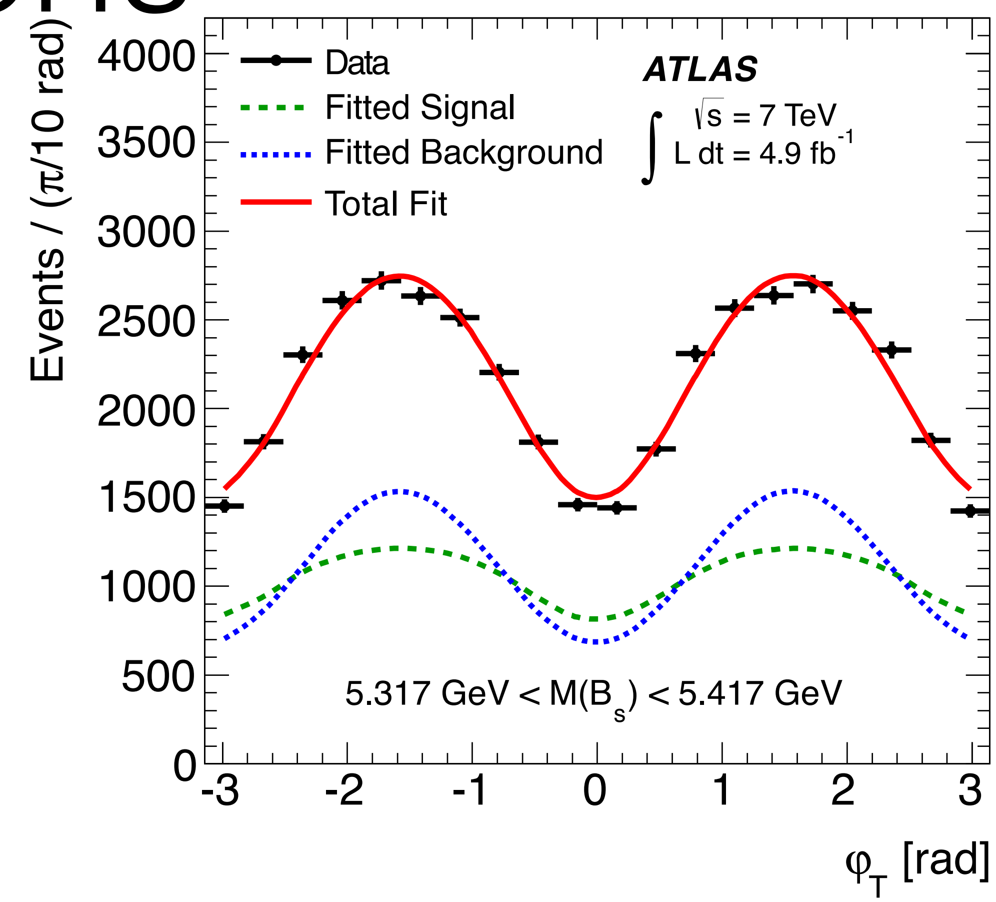


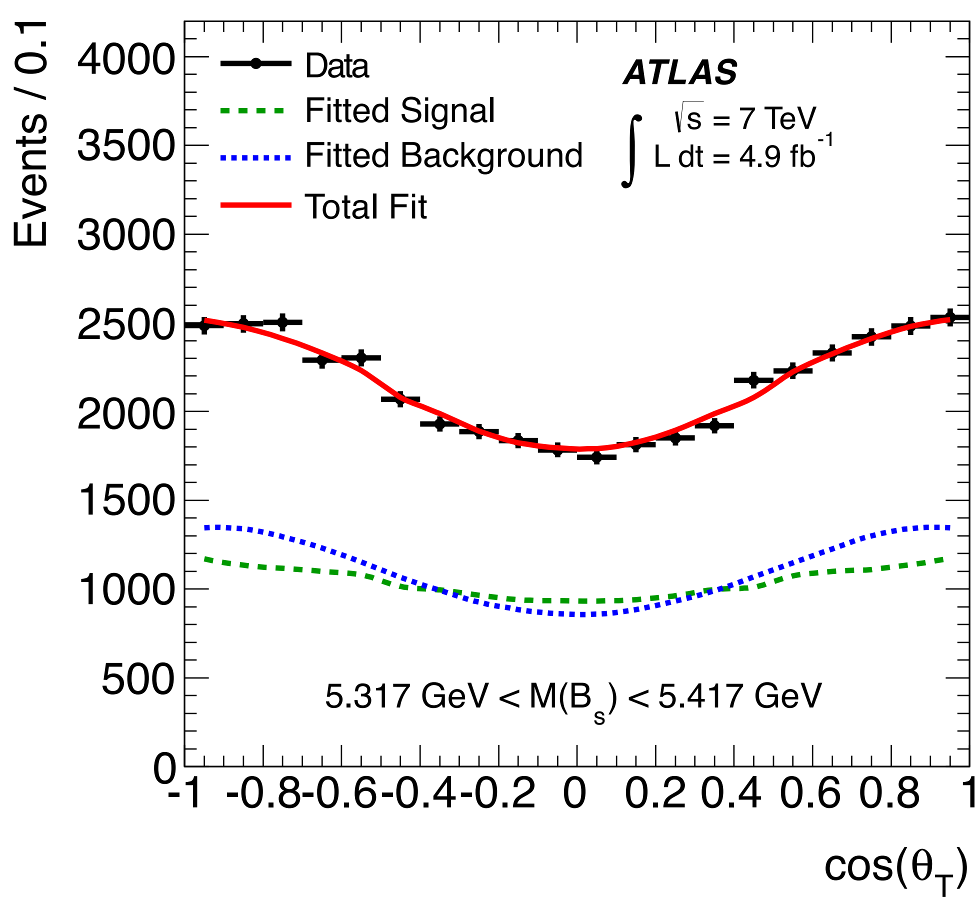
- **Trigger:**
  - Single and di-muon trigger suite
  - Requiring at least one muon
  - Varying p_T thresholds, minimum of $p_T(\mu)$ > 4 GeV
- **J/ψ:**
  - $p_T(\mu)$ > 4 GeV
  - $|\eta(\mu)|$ < 2.5
  - $|\eta(\mu)|$ dependent mass cuts (retains 99.8% of signal)
  - χ^2/ndf < 10
- **φ:**
  - Oppositely-charged track pair
  - $p_T(K)$ > 0.5 GeV
  - $|\eta(K)|$ < 2.5
  - $p_T(\varphi)$ > 1.0 GeV
  - $|m(\varphi) - m^{PDG}(\varphi)|$ < 11 MeV
- **B_s:**
  - μμKK Vertex fit
  - J/ψ mass constraint
  - Vertex χ^2/ndf < 3
  - 5.15 < m(J/ψKK) <5.65 GeV

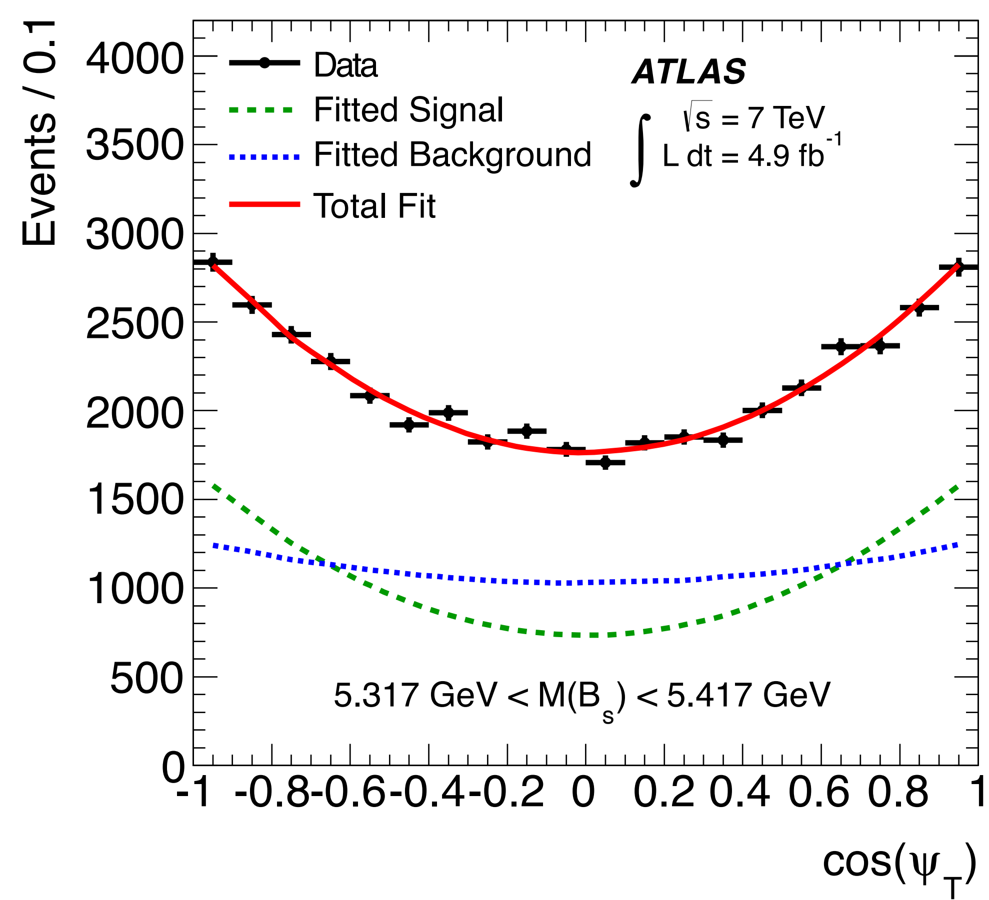
Angular Projections

- Projections of the fit results for the transversity angles.

- θ_T, the angle between $\vec{p}(\mu^+)$ and the normal to the x–y plane, in the J/ψ meson rest frame
- ϕ_T, the angle between the x-axis and $\vec{p}_{xy}(\mu^+)$, the projection of the μ^+ momentum in the x–y plane, in the J/ψ meson rest frame
- ψ_T, the angle between $\vec{p}(K^+)$ and $-\vec{p}(J/\psi)$ in the ϕ meson rest frame







Systematics

- Sources of systematics to measured 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]
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

Effect of residual misalignment studied in signal MC

Systematics

- Sources of systematics to measured 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]
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

Uncertainty of trigger efficiency corrections

Systematics

- Sources of systematics to measured parameters:

	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	$\vert A_\parallel(0)\vert^2$	$\vert A_0(0)\vert^2$	$\vert A_S(0)\vert^2$	$\delta_\perp$ [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

Variations of input fractions

Systematics

- Sources of systematics to measured parameters:

	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^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

Variations of Calibration parameterisations. Uncertainty due to finite B+/- sample included in the statistical error of the fit results.

Systematics

- Sources of systematics to measured parameters:

	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^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

Uncertainty estimated from MC tests of acceptance fitting technique

Systematics

- Sources of systematics to measured 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]
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

Uncertainties of fit model
derived in pseudo-experiments
with variations of parameterisations

Results

- From the fit the parameters ϕ_s, Γ_s $\Delta\Gamma_s$, amplitudes and strong phases are extracted.

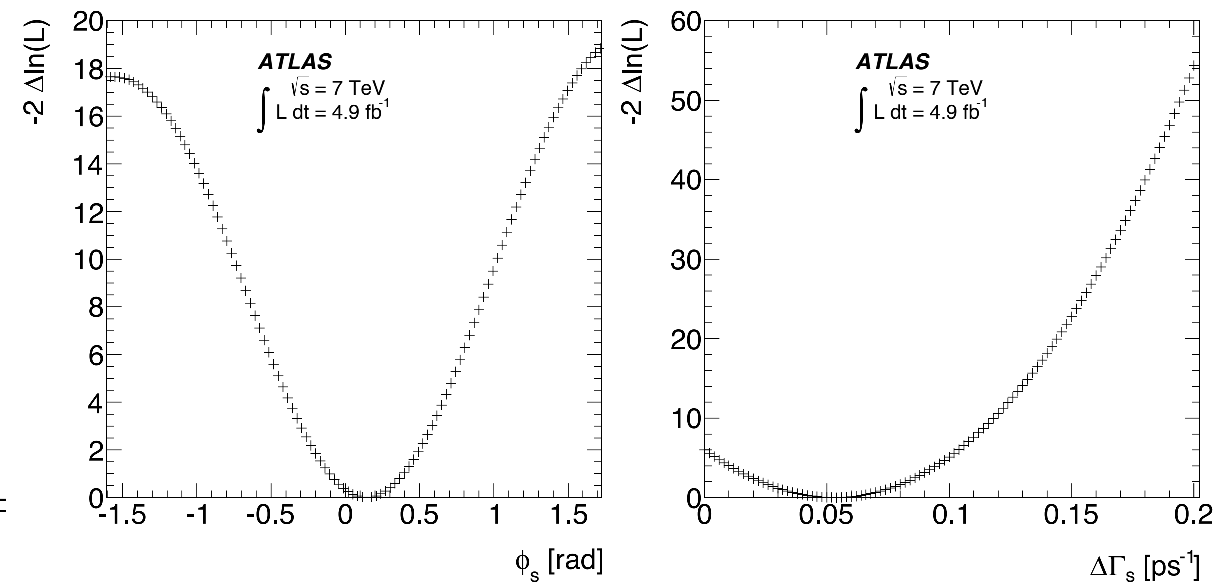
Parameter	Value	Statistical uncertainty	Systematic uncertainty
$\phi_s[\text{rad}]$	0.12	0.25	0.05
$\Delta\Gamma_s[\text{ps}^{-1}]$	0.053	0.021	0.010
$\Gamma_s[\text{ps}^{-1}]$	0.677	0.007	0.004
$\lvert A_{\parallel}(0)\rvert^2$	0.220	0.008	0.009
$\lvert A_0(0)\rvert^2$	0.529	0.006	0.012
$\lvert A_S(0)\rvert^2$	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

- Ambiguity in sign of $\Delta\Gamma_s$

$$\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_{\parallel}\} \rightarrow \{\pi - \phi_s, -\Delta\Gamma_s, \pi - \delta_\perp, 2\pi - \delta_{\parallel}\}$$

PRL 108 (2012) 241801

- Constrain $\Delta\Gamma_s > 0$

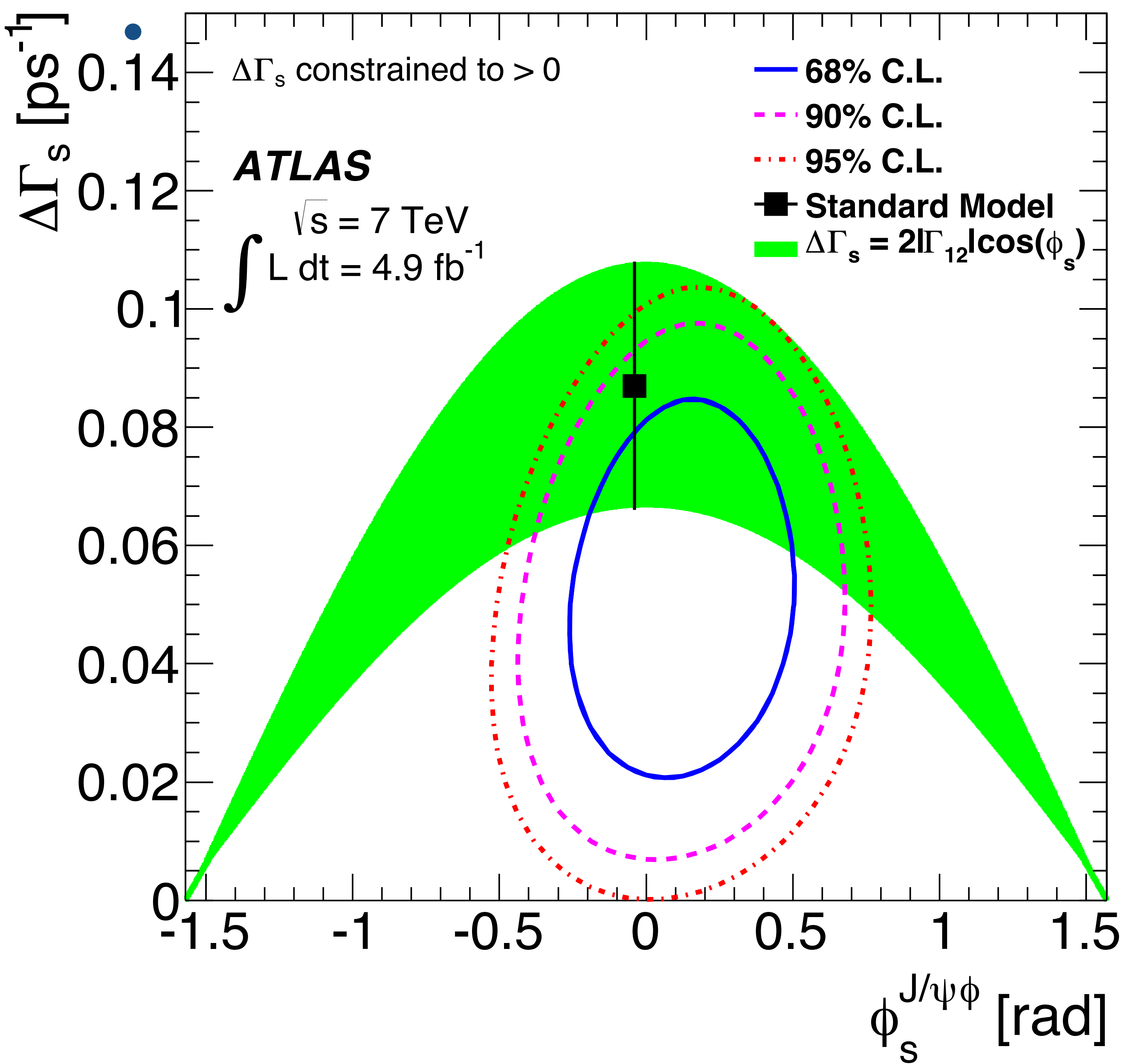


- The contribution of $B_s^0 \rightarrow J/\psi K^+K^-$ and $B_s^0 \rightarrow J/\psi f_0$ is consistent with zero, within the uncertainties

- Measurements are compatible with theory and other experiments.

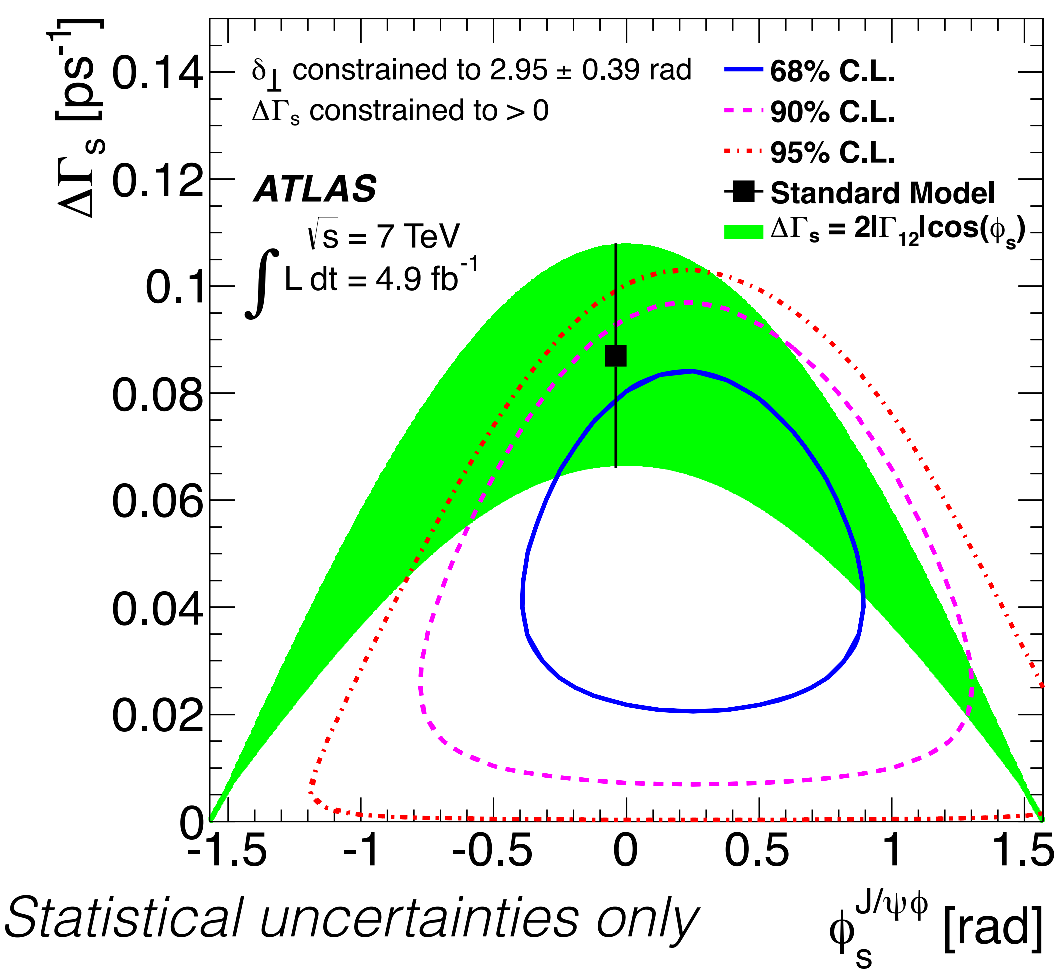
Impact of Flavour Tagging

- Comparison to previous published (untagged) analysis:
  - Same dataset; improvement on ϕ_s precision by ~40%
  - $\Delta\Gamma_s$ central value and uncertainty unchanged
  - Gained sensitivity to $\delta_\perp$(constrained to external measurement in the untagged analysis)



Untagged

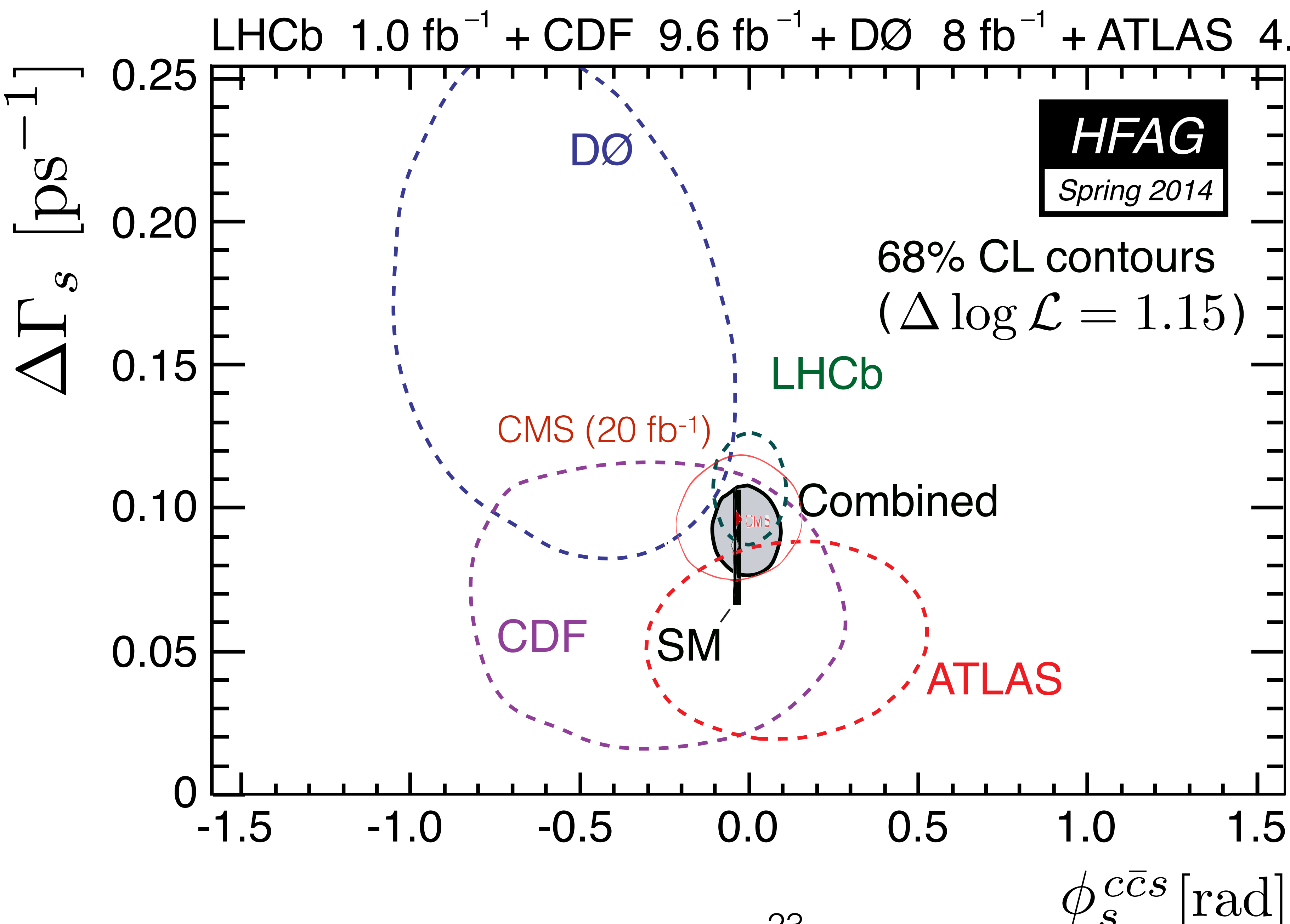
JHEP 12 (2012) 072



Statistical uncertainties only

Combination

- Good agreement between experiments:
  - HFAG combination shows excellent agreement with SM predictions



Combination not including CMS result: CMS-PAS-BPH-11-006 which is superimposed

$$\phi_s = -0.03 \pm 0.11\ (\text{stat.}) \pm 0.03\ (\text{syst.})\ \text{rad}\ ,$$
$$\Delta\Gamma_s = 0.096 \pm 0.014\ (\text{stat.}) \pm 0.007\ (\text{syst.})\ \text{ps}^{-1}\ .$$

Conclusions

- Time-dependent Flavour-tagged angular measurement performed in the decay $B_s^0 \to J/\psi\phi$, using data from 2011
  - The weak phase ϕ_s, and $\Delta\Gamma_s$ are found to be:

    $$\phi_s = 0.12 \pm 0.25\ (\text{stat.}) \pm 0.05\ (\text{syst.})\ \text{rad}$$

  - $$\Delta\Gamma_s = 0.053 \pm 0.021\ (\text{stat.}) \pm 0.010\ (\text{syst.})\ \text{ps}^{-1}$$
  - Within the uncertainties, no S-wave contribution is reported.
- The results are in good agreement with SM expectations and other experimental results
- This result improves on previously (untagged) published result
  - JHEP 12 (2012) 072 using the same dataset,
  - and is submitted to PRD: CERN-PH-EP-2014-043, arXiv:1407.1796
- With 2012 data from run-I of LHC to be included, with significant increase in statistics, precision will be improved.
- Run-II data-taking (and beyond) will be exciting time to produce precision measurements.

BACKUP

Tag Probabilities

- Fractions of tagged events with single-track tagging methods

Tag method	Signal		Background	
	f_{+1}	f_{-1}	f_{+1}	f_{-1}
Combined μ	0.106 ± 0.019	0.187 ± 0.022	0.098 ± 0.006	0.108 ± 0.006
Segment tag μ	0.152 ± 0.043	0.153 ± 0.043	0.098 ± 0.009	0.095 ± 0.008
Jet charge	0.167 ± 0.010	0.164 ± 0.010	0.176 ± 0.003	0.180 ± 0.003

- Fraction of tagged events

Tag method	Signal	Background
Combined μ	0.0372 ± 0.0023	0.0272 ± 0.0005
Segment tag μ	0.0111 ± 0.0014	0.0121 ± 0.0003
Jet charge	0.277 ± 0.007	0.254 ± 0.002
Untagged	0.675 ± 0.011	0.707 ± 0.003

Fit Parameter Correlations

- Correlations between the physics parameters extracted from the fit.

	ϕ_s	$\Delta\Gamma$	Γ_s	$\lvert A_{\lvert\lvert}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_{\lvert\lvert}$	$\delta_{\perp}$	$\delta_{\perp} - \delta_S$
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
$\lvert A_{\lvert\lvert}(0)\rvert^2$				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
$\delta_{\lvert\lvert}$							1.000	0.038	0.007
$\delta_{\perp}$								1.000	0.081
$\delta_{\perp} - \delta_S$									1.000

Likelihood Scans