Mixing and CP violation in the decay of $B_s \rightarrow J/\psi\ \Phi$ in ATLAS

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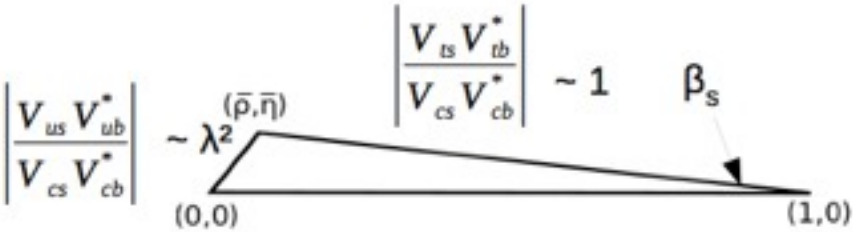
Motivation

- In the Standard Model CP violation is described by a single complex phase in the CKM matrix



$$\beta_s \equiv arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

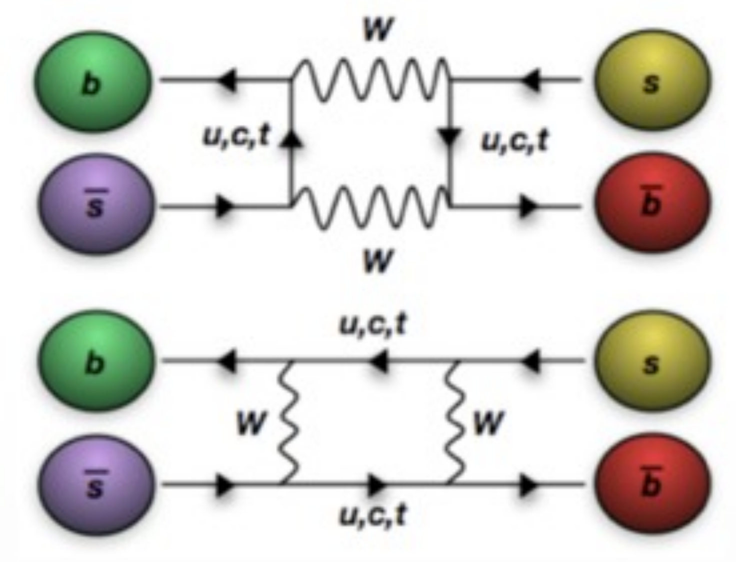
- In the B_s system the Standard Model predicts Φ_s to be small:

$$\phi_s \simeq -2\beta_s = -0.0368 \pm 0.0018 \text{ rad}$$

- Many new physics models predict large values of Φ_s whilst satisfying all existing constraints

The neutral B$_s$ system

- B$_s$ mixing is described at the lowest order by box diagrams
- This leads to two mass eigenstates which have different lifetimes



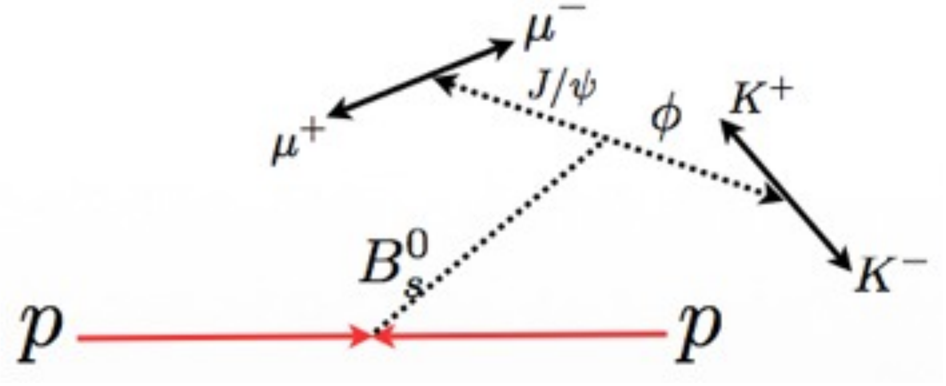
- The standard model predicts these lifetimes will differ by ~O(10%)

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \qquad \Delta\Gamma_s = 0.087 \pm 0.021\ \mathrm{ps}^{-1}$$

- Physics beyond the Standard Model unlikely to affect $\Delta\Gamma_s$ as significantly as Φ_s but can test other theoretical predictions

$B_s \rightarrow J/\psi\ \Phi$ decay

- Theoretically clean extraction of Φ_s is possible
- CP violation is induced through interference between mixing and decay terms



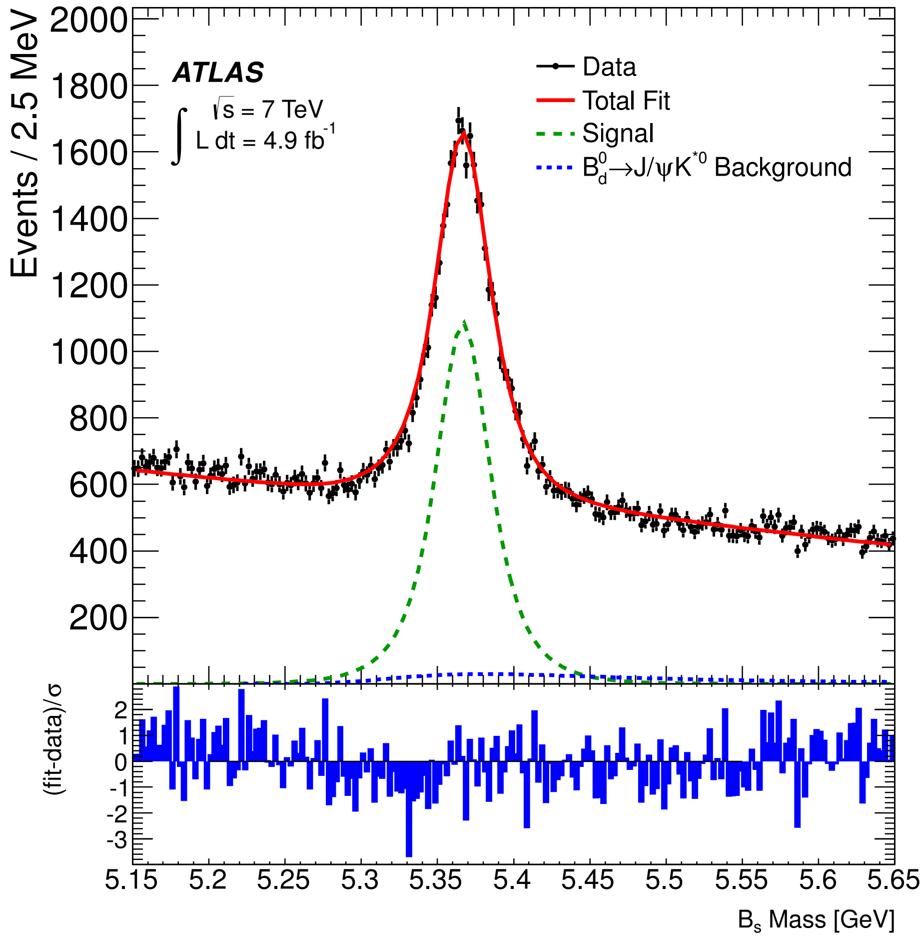
- The final state is an admixture of CP even and CP odd eigenstates that are described by 3 amplitudes A_0, $A_\perp$ and $A_{||}$.
- A fourth amplitude A_s describes non-resonant Bs → $J/\psi\ K^+K^-$ (f_0) decays
- CP states are separated using an angular analysis

Status of analysis

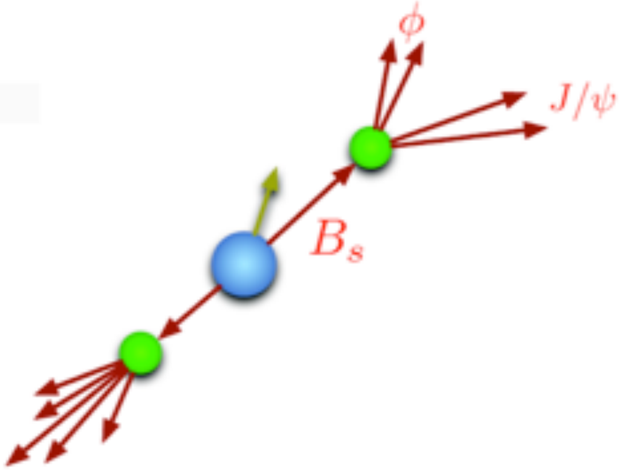
- Untagged analysis on 2011 data (4.7 fb^{-1}) published last year JHEP 12 (2012) 072
- Updated measurement presented using the same dataset but including flavour tagging.
- Analysis procedure:
  - J/ψ Triggers
  - Reconstruction of Bs candidates
  - Selection cuts
  - Tagging - New!
  - Simultaneous fit of mass, lifetime, angular distribution and tagging - Updated

Selection criteria

- Trigger selection based in di-muon and single-muon triggers (pT threshold 4 GeV or higher)
- Offline selection based on:
  - J/ψ and ϕ invariant masses
  - Quality cut on vertex
  - No lifetime cut used
- Average number of primary interactions 5.6
- Wrong association to primary vertex is < 1% and effects are negligible.
- In total 131k Bs candidates within 5.15 < m(Bs) < 5.65 GeV used in the fit.



Flavour tagging



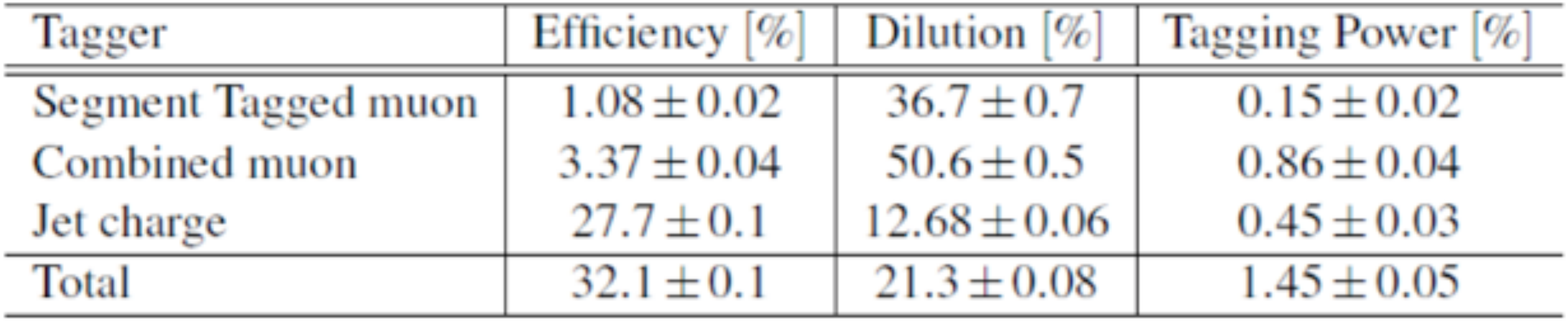
- Opposite side tagging is used: Initial flavour of B_s is inferred from the other B meson produced.
- Initially an additional muon is looked for in the event.
  - Muon must originate near interaction point.
- Separation power can be enhanced by using a weighted sum of the charge of the tracks in a cone around muon:

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

$\boxed{\kappa = 1.1}$

- If no muon can be found a B-jet is looked for next:
  - Weighted sum of tracks is used
  - Needs to be associated to same interaction point
  - Veto signal tracks and jets within $\Delta R < 0.5$ around signal momentum axis

Flavour 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

- Two types of muons:
  - 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.
- Flavour tagging methods are studied and calibrated on $B^+ \rightarrow J/\psi K^+$ and $B^- \rightarrow J/\psi K^-$
- Tagging enters fit as tag probability.

Likelihood fit

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

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

9 physics variables to describe B_s → J/ψΦ and S-wave component: ΔΓ , Φs, Γs, $|A_0(0)|^2$, $|A_{||}(0)|^2$, $\delta_{||}$, $\delta_{\perp}$, $|A_s(0)|^2$ and δs

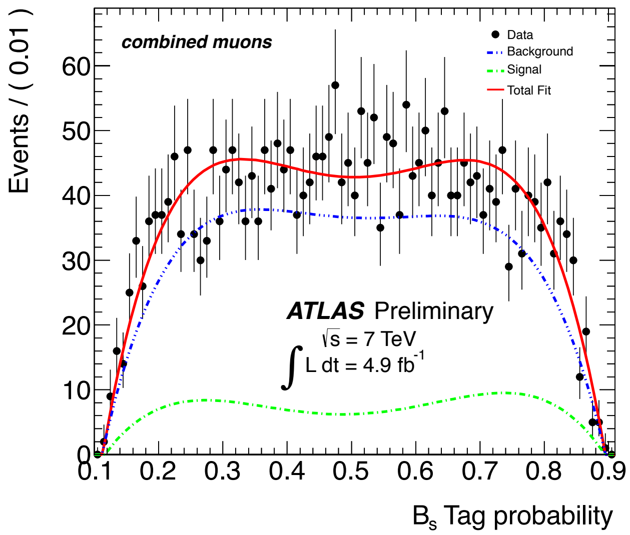
The background due to B^0 → J/ψ K^{*0} and B^0 → J/ψ Kπ (non resonant), described by the parameter f_{B0}, constrained by known branching fractions and acceptance (11% of signal amplitude)

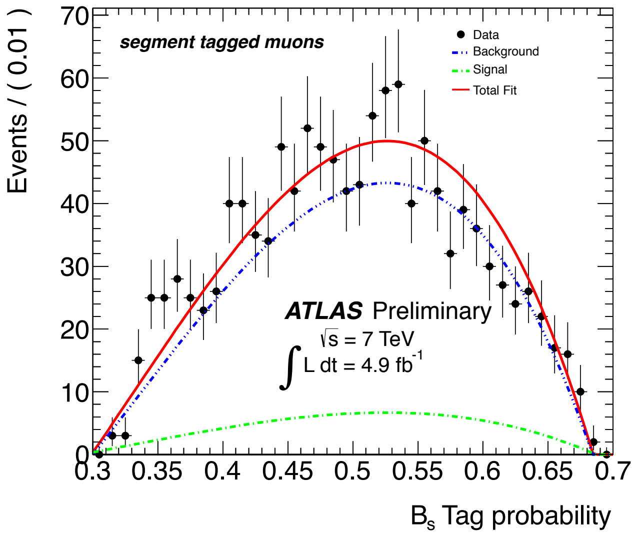
The prompt and non-prompt combinatorial background described with empirical angular distribution. (No K-π discrimination.)

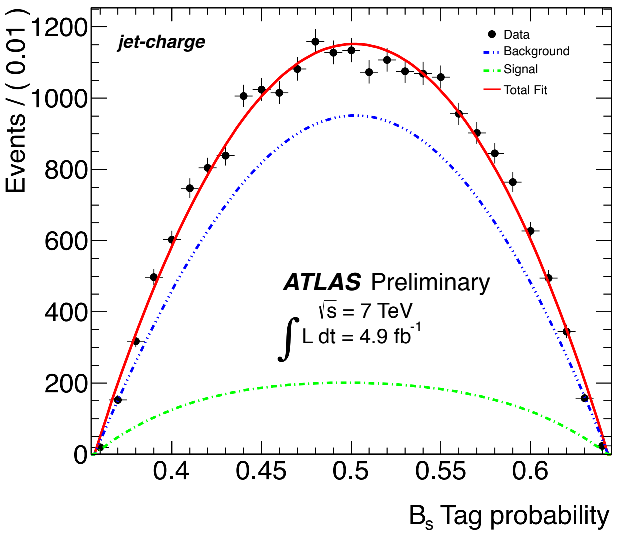
Muon time dependent trigger efficiency

Tagging in the fit

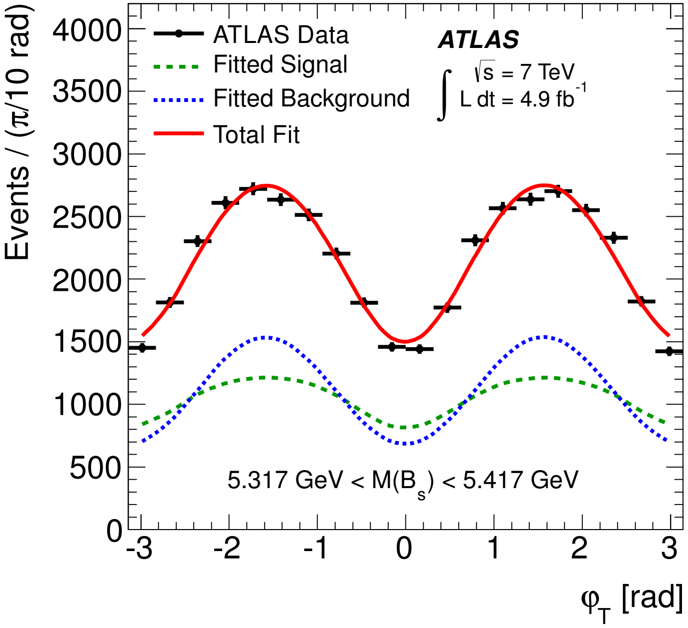
- Tag probability for signal and background is different so must be taken into account in the fit.
- Discrete parts (corresponding to single tracks) are treated separately
- Description of tag-probability PDFs affect the result by less than 10% of statistical uncertainty.

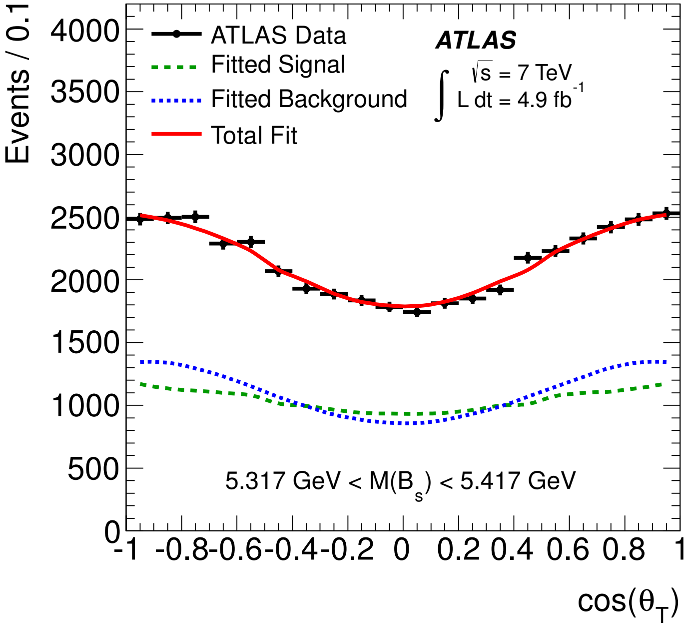


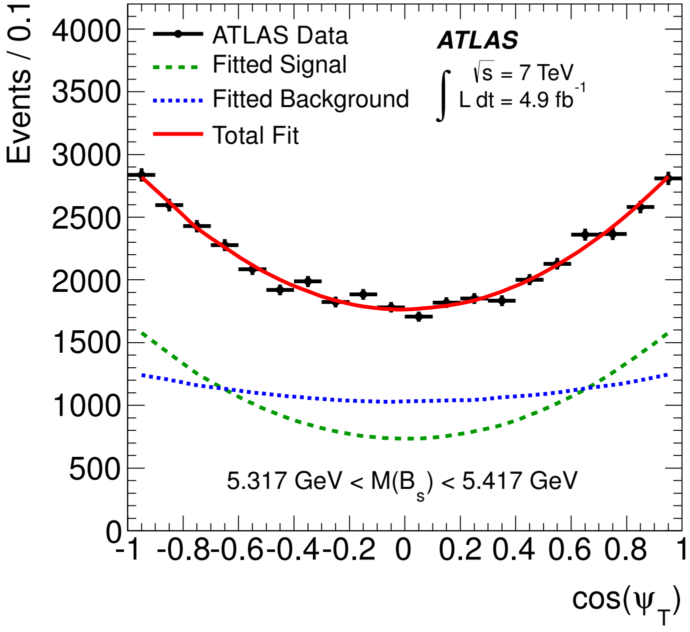


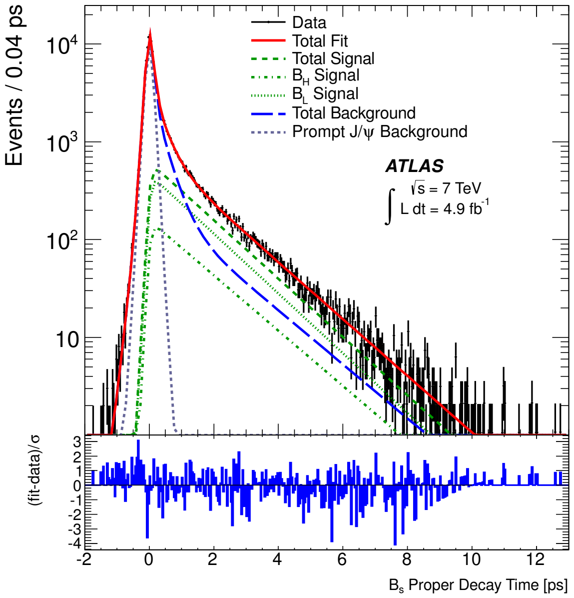


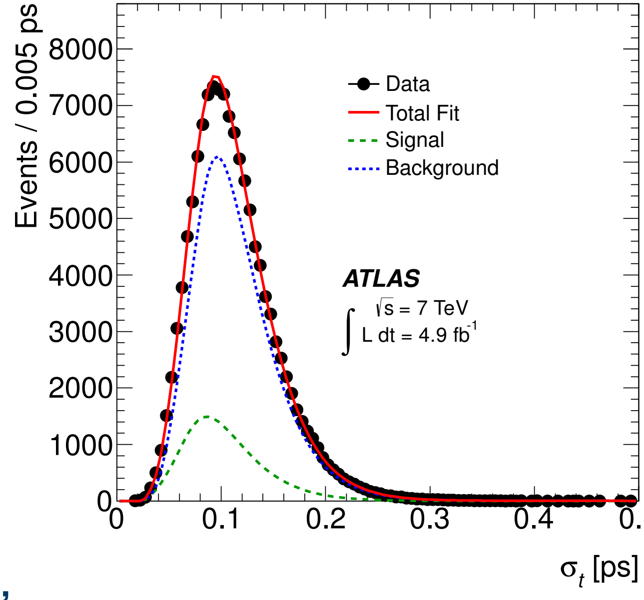
Fit projections











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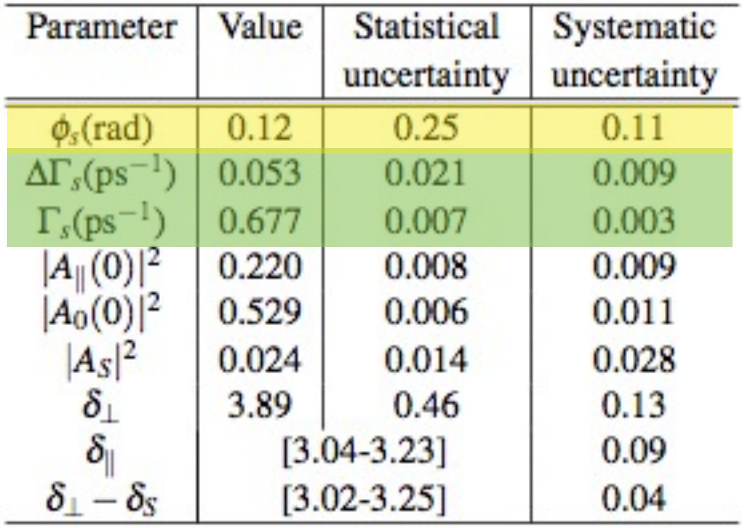
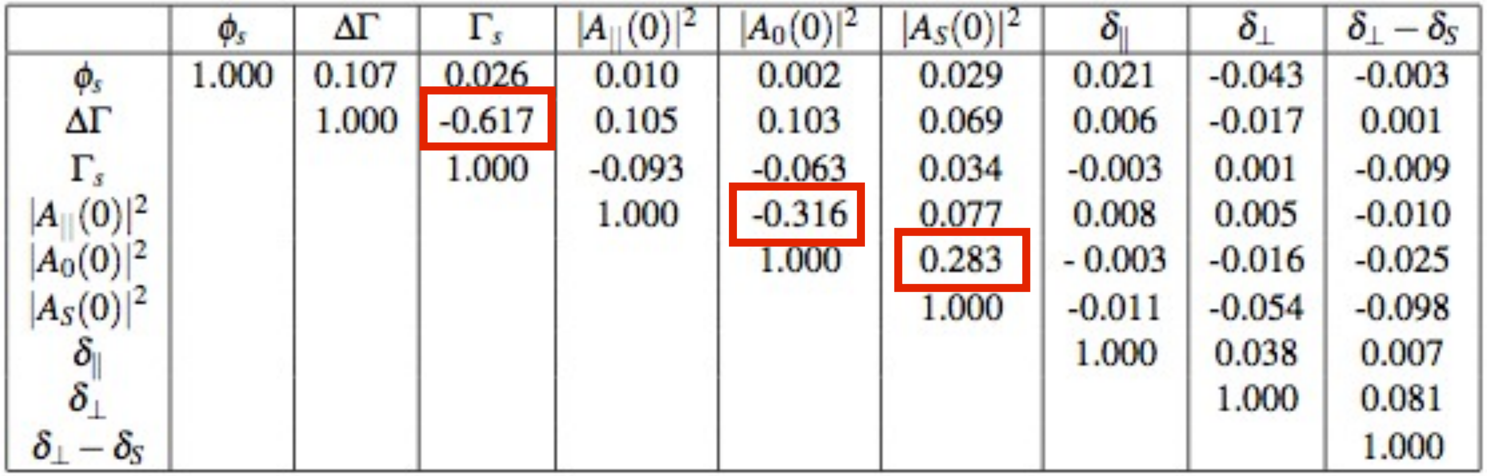
Results



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
Γ_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

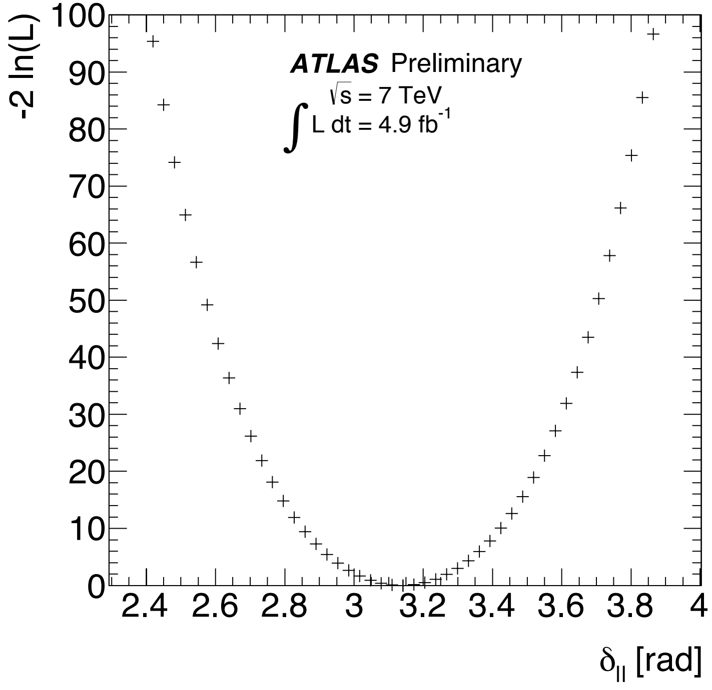
- 22670 ± 150 signal Bs events.
- Consistent with untagged analysis.
- Φs consistent with standard model prediction.
- S-wave amplitude consistent with 0.

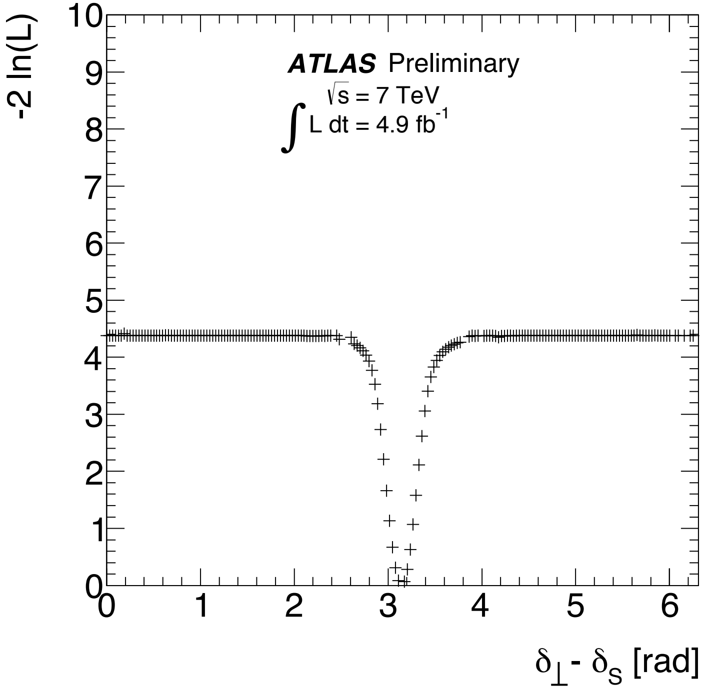


	ϕ_s	$\Delta\Gamma$	Γ_s	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_{\parallel}$	$\delta_\perp$	$\delta_\perp - \delta_S$
ϕ_s	1.000	0.107	0.026	0.010	0.002	0.029	0.021	-0.043	-0.003
$\Delta\Gamma$		1.000	-0.617	0.105	0.103	0.069	0.006	-0.017	0.001
Γ_s			1.000	-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

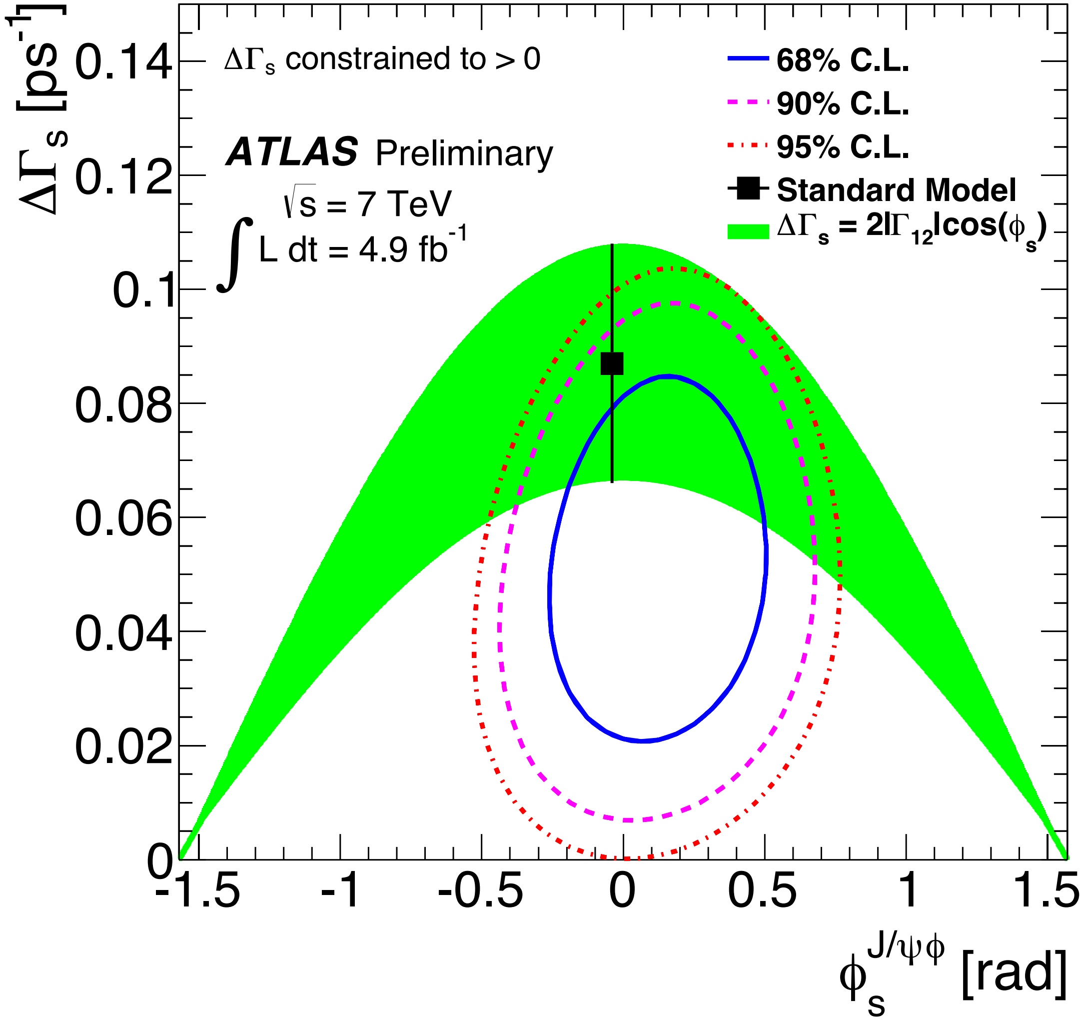
Strong phases

- Strong phases $\delta_{||}$ and $\delta_{\perp}$ - δ_s given as 1σ confidence regions.
- $\delta_{\perp}$ - δ_s has 1D likelihood has unusual behaviour.
- $\delta_{||}$ 1D likelihood is gaussian however systematic studies showed non gaussian pull plot distributions.





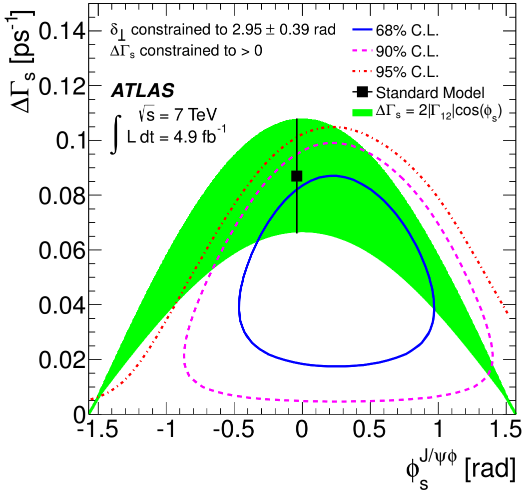
Φ_s - ΔΓ contour plot



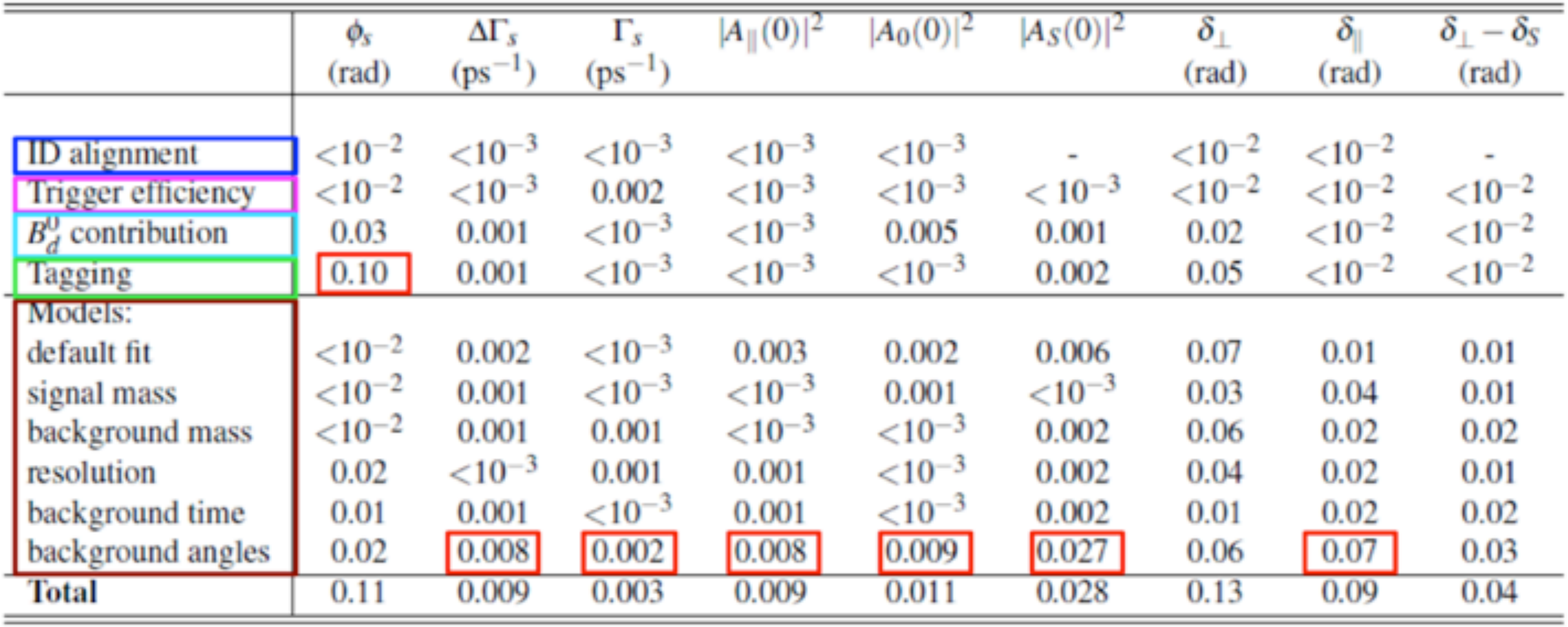
Statistical errors only

- Uncertainty of Φs improves ~40%
- δ⊥ constraint removed
- ΔΓ central value and uncertainty unchanged

Previous untagged measurement



Systematics



	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_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

Summary

- ATLAS updated the Bs → J/ψ Φ analysis of 2011 data with tagging
- Two types of tagging used:
    - Muon cone charge tagging
    - Jet charge tagging
- Improvement in the measured precision of Φs:

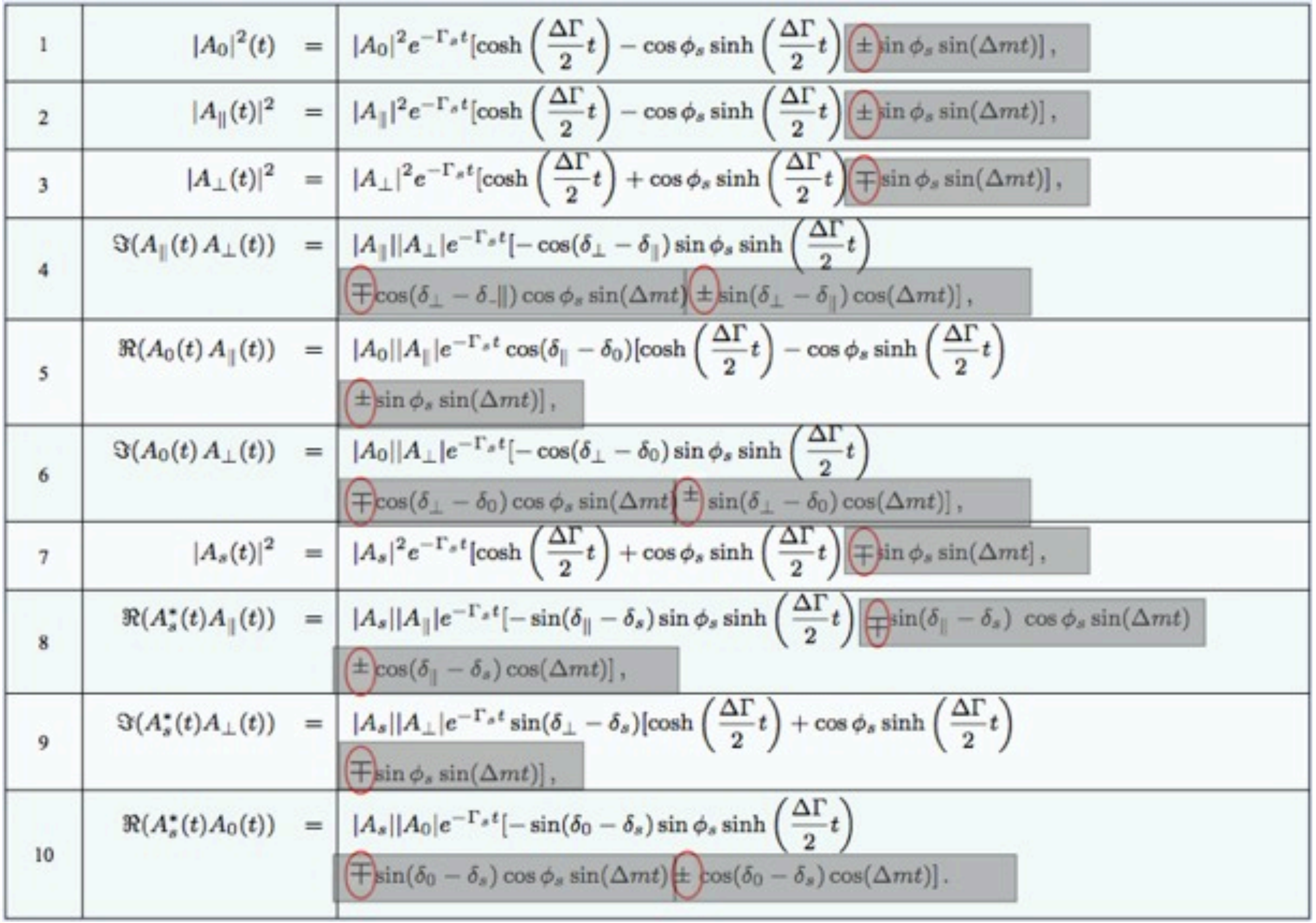
$$\phi_s = 0.12 \pm 0.25\ (\text{stat.}) \pm 0.11\ (\text{syst.})\ \text{rad}$$

$$\Delta\Gamma_s = 0.053 \pm 0.021\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{ps}^{-1}$$

$$\Gamma_s = 0.677 \pm 0.007\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1}$$

Backup

Time dependence



1	$\lvert A_0\rvert^2(t)$	=	$\lvert A_0\rvert^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) \pm \sin\phi_s \sin(\Delta m t)]\,,$
2	$\lvert A_\parallel(t)\rvert^2$	=	$\lvert A_\parallel\rvert^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) \pm \sin\phi_s \sin(\Delta m t)]\,,$
3	$\lvert A_\perp(t)\rvert^2$	=	$\lvert A_\perp\rvert^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) \mp \sin\phi_s \sin(\Delta m t)]\,,$
4	$\Im(A_\parallel(t)\, A_\perp(t))$	=	$\lvert A_\parallel\rvert\lvert A_\perp\rvert e^{-\Gamma_s t}[-\cos(\delta_\perp - \delta_\parallel)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)$ $\mp \cos(\delta_\perp - \delta_{-\parallel})\cos\phi_s \sin(\Delta m t) \pm \sin(\delta_\perp - \delta_\parallel)\cos(\Delta m t)]\,,$
5	$\Re(A_0(t)\, A_\parallel(t))$	=	$\lvert A_0\rvert\lvert A_\parallel\rvert e^{-\Gamma_s t}\cos(\delta_\parallel - \delta_0)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)$ $\pm \sin\phi_s \sin(\Delta m t)]\,,$
6	$\Im(A_0(t)\, A_\perp(t))$	=	$\lvert A_0\rvert\lvert A_\perp\rvert e^{-\Gamma_s t}[-\cos(\delta_\perp - \delta_0)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)$ $\mp \cos(\delta_\perp - \delta_0)\cos\phi_s \sin(\Delta m t) \pm \sin(\delta_\perp - \delta_0)\cos(\Delta m t)]\,,$
7	$\lvert A_s(t)\rvert^2$	=	$\lvert A_s\rvert^2 e^{-\Gamma_s t}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) \mp \sin\phi_s \sin(\Delta m t]\,,$
8	$\Re(A_s^*(t) A_\parallel(t))$	=	$\lvert A_s\rvert\lvert A_\parallel\rvert e^{-\Gamma_s t}[-\sin(\delta_\parallel - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) \mp \sin(\delta_\parallel - \delta_s)\ \cos\phi_s \sin(\Delta m t)$ $\pm \cos(\delta_\parallel - \delta_s)\cos(\Delta m t)]\,,$
9	$\Im(A_s^*(t) A_\perp(t))$	=	$\lvert A_s\rvert\lvert A_\perp\rvert e^{-\Gamma_s t}\sin(\delta_\perp - \delta_s)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)$ $\mp \sin\phi_s \sin(\Delta m t)]\,,$
10	$\Re(A_s^*(t) A_0(t))$	=	$\lvert A_s\rvert\lvert A_0\rvert e^{-\Gamma_s t}[-\sin(\delta_0 - \delta_s)\sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right)$ $\mp \sin(\delta_0 - \delta_s)\cos\phi_s \sin(\Delta m t) \pm \cos(\delta_0 - \delta_s)\cos(\Delta m t)]\,.$