Determination of $\Delta\Gamma_S$ and φ_s from the decay B_S to $J/\psi\ \phi$ in ATLAS

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on behalf of the ATLAS Collaboration

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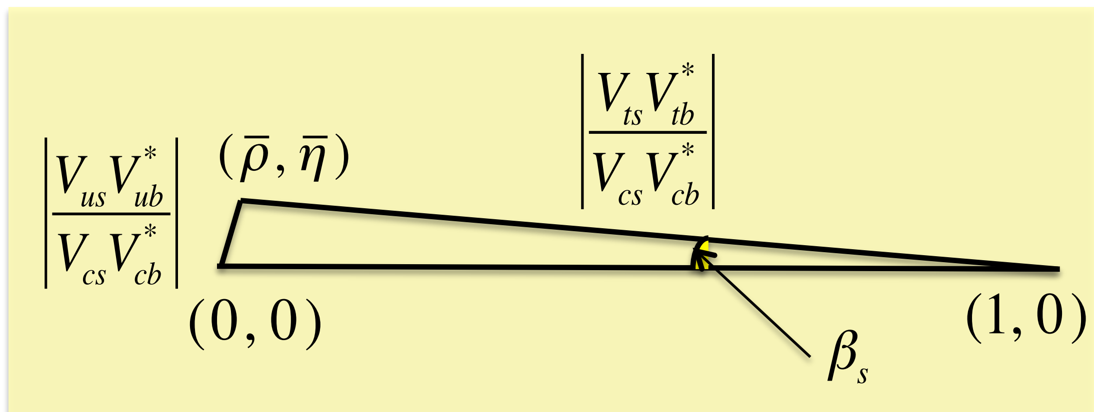
B_s phenomenology

Due to flavor changing couplings to common states, the time evolution of the meson B_S and $\bar{B}_S$ is described by the superposition of B_H and B_L states, with masses $m_S \pm \Delta m_S/2$ and lifetimes $\Gamma_S \mp \Delta\Gamma_S/2$.

These states deviate from defined values $CP = \pm 1$, as described in the SM by the mixing phase φ_s :

$$\varphi_s = -2\beta_s ,$$

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

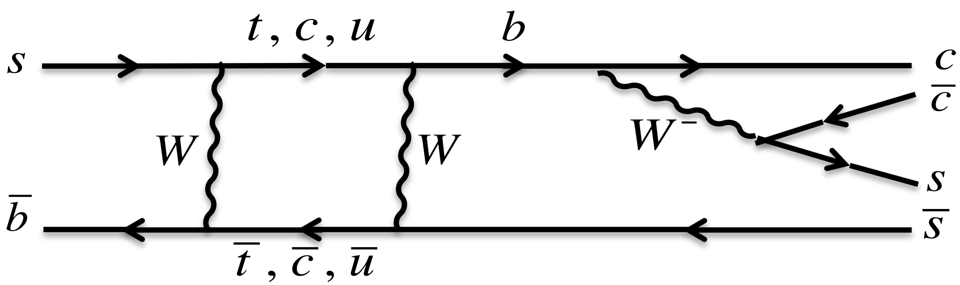


SM prediction (fit): $\varphi_s = -0.0368 \pm 0.0018$ rad

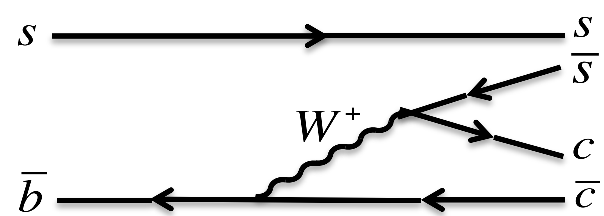
$\Delta\Gamma_S = 0.082 \pm 0.021$ ps^{-1}

New Physics might add an additional contribution to φ_s , and might change the ratio $\Delta\Gamma_S/\Delta m_S$.

In general, the decay to a final state that is coupled to B_S and/or $\overline{B}_S$ exhibits fast oscillations driven by Δm_S. Interference between amplitudes for both states generates *CP* violation, and conveys information on φ_s .



Decay amplitude with mixing (φ_s)



Amplitude with direct decay

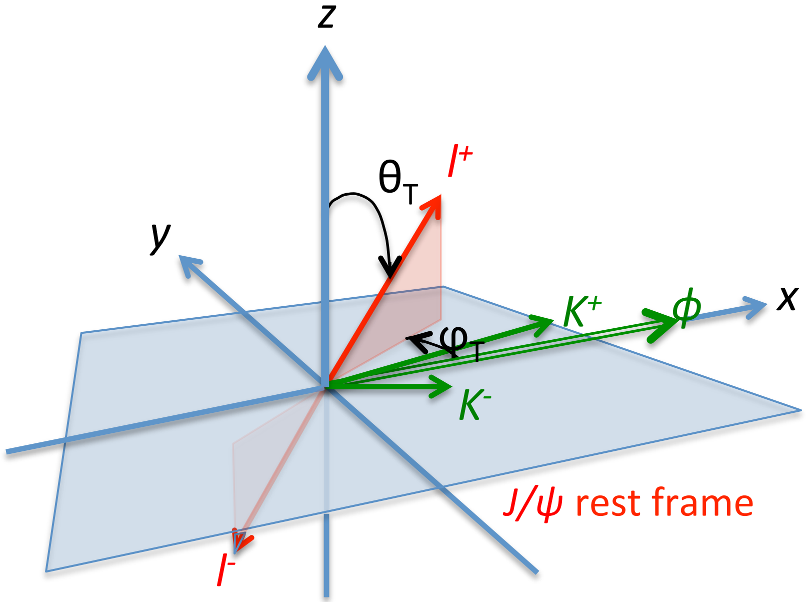
If B / $\overline{B}$ flavor at production is not determined (not *tagged*), the fast oscillations cannot be observed,

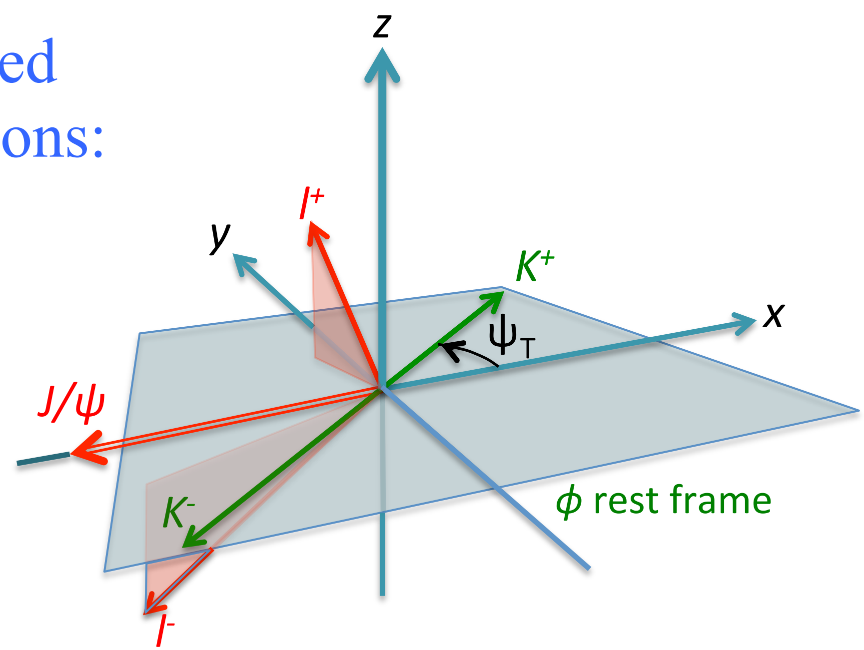
but interference terms remain if the final state is described by a superposition of amplitudes of different *CP* .

Angular correlations and CP

In the decay B_S $(\overline{B}_S) \rightarrow J/\psi\ \phi \rightarrow l^+ l^-\ K^+ K^-$
different components in the angular-distributions amplitudes correspond to $CP = +1$ or -1.

The "*transversity angles*" are used to describe the angular distributions:





In the J/ψ (or ϕ) rest frames, the direction of ϕ (opposite to J/ψ) defines the x axis, and the xy-plane is defined by the K^+K^- decay plane, with K^+ oriented towards positive y; θ_T and φ_T are the polar angles of l^+, ψ_T is the angle between K^+ and x-axis

Angles and time dependent distributions

Different decay amplitudes correspond to angular amplitudes of defined *CP*. The overall time- and angle-dependent probability is:

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

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

CP= +1
CP= +1
CP= −1

Interference terms

Terms related to non-resonant and f^0 amplitude for K^+K^- (S-wave)

Notice the presence of strong phases δ_X

The measurement of ATLAS

- Analysis using data collected in 2011 (4.7 fb-1).
- Trigger selection based in di-muon and single-muon triggers (p_T threshold 4 GeV or higher)

- Offline selection based on J/ψ and ϕ invariant masses, χ_2/NDF < 3 in fit to decay vertex, $|\eta|<2.5$ for all tracks, $p_T > 0.5$ GeV for kaon candidates.
- Decay time computed in the plane normal to collision axis.
- Average number of primary interactions 5.6, wrong association to primary vertex is < 1% and effects are negligible.

- Acceptance computed on large samples of signal and background channels (e.g.: $B^0 \rightarrow J/\psi\, K^{0*}$, $bb \rightarrow J/\psi\, X$, $pp \rightarrow J/\psi\, X$).
- Efficiency via data-driven procedures.

Maximum likelihood fit

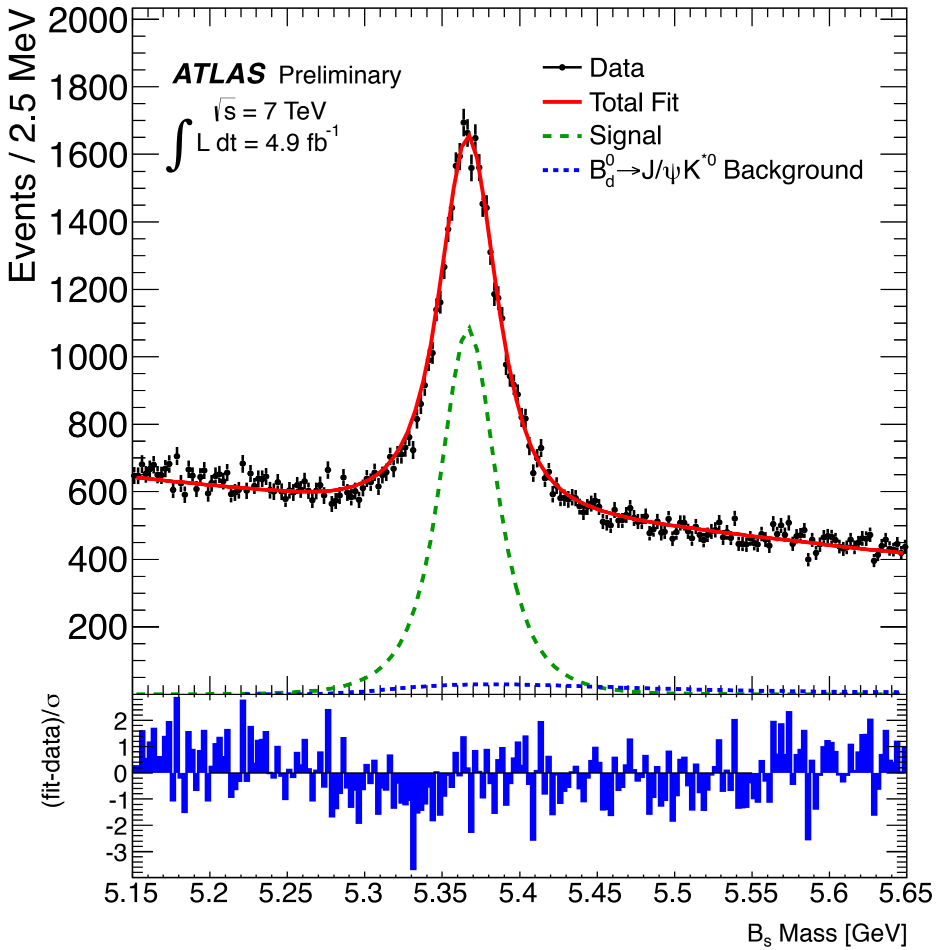
$$\ln\ \mathcal{L} = \sum_{i=1}^{N} \{ w_i \cdot \ln(f_s \cdot \mathcal{F}_s(m_i, t_i, \Omega_i) + f_s \cdot f_{B^0} \cdot \mathcal{F}_{B^0}(m_i, t_i, \Omega_i)$$

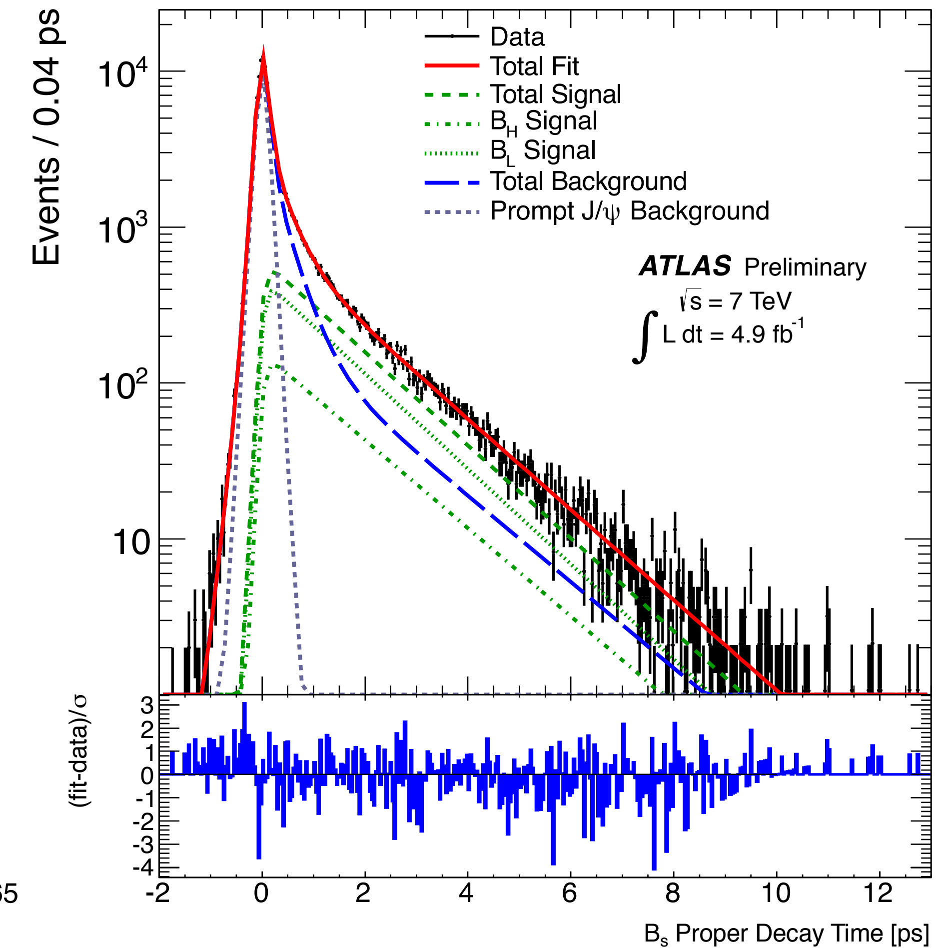
$$+ (1 - f_s \cdot (1 + f_{B^0})) \mathcal{F}_{bkg}(m_i, t_i, \Omega_i)) \} + \ln P(\delta_\perp)$$

Terms describing:

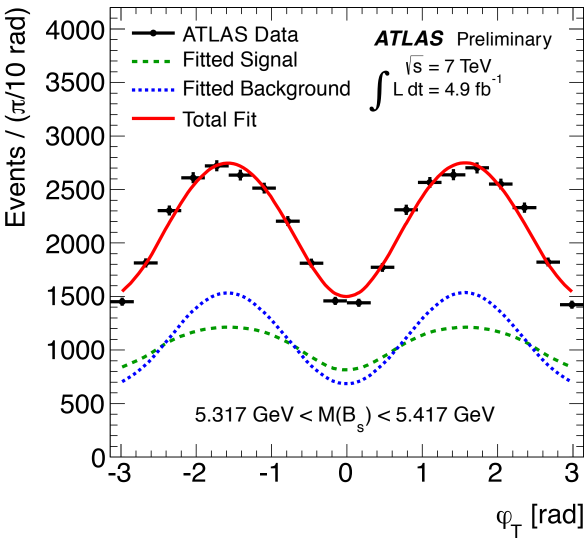
- the signal (the 10 terms discussed above), with relative amplitude described by the parameter f_s.
- The background due to $B^0 \rightarrow J/\psi\ K^{*0}$ and $B^0 \rightarrow J/\psi\ K\pi$ (non resonant), described by the parameter f_{B^0}, constrained by known branching fractions and acceptance (11% of signal amplitude)
- The prompt and non-prompt combinatorial background described with empirical angular distribution. (No K-π discrimination.)
- w_i describes a small trigger inefficiency (~1%).
- $P(\delta_\perp)$ is discussed below.

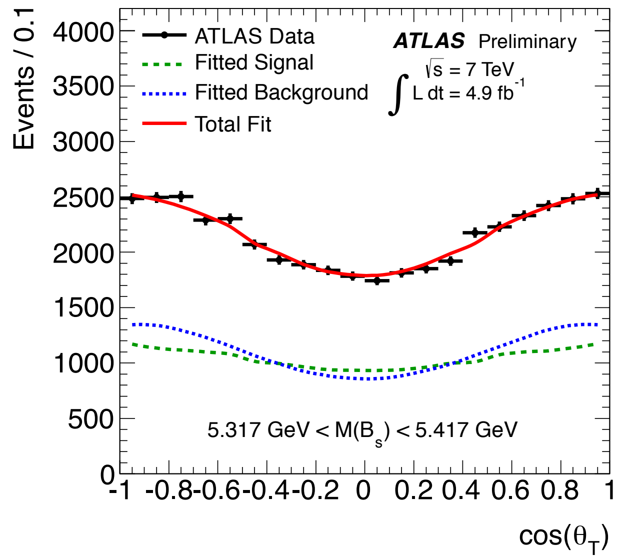
Result of the fit:
projection on B_S mass and proper decay time

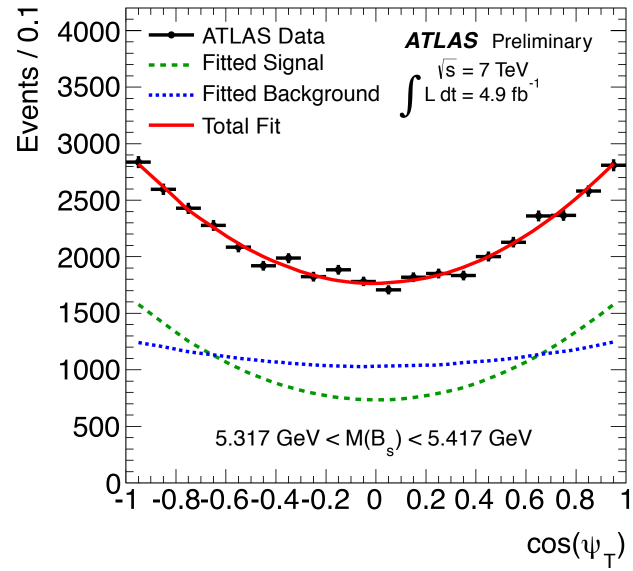


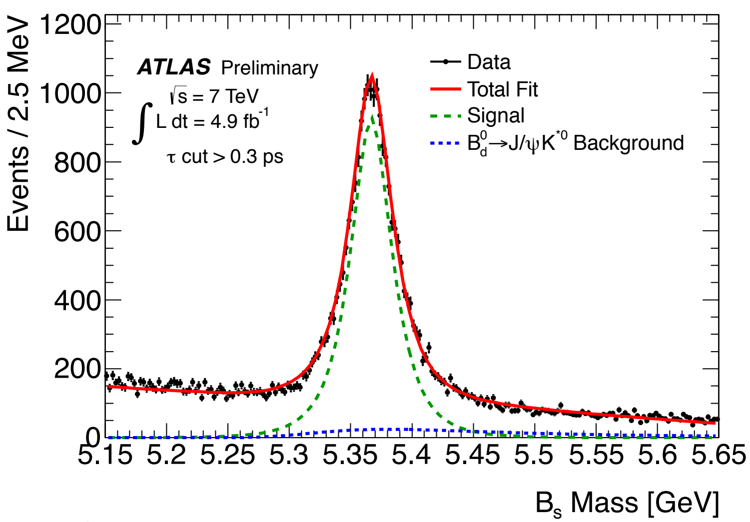


Result of the fit: projection on transversity angles









Mass projection for proper decay-time larger than 0.3 ps

Systematic uncertainties

Systematic	ϕ_s(rad)	$\Delta\Gamma_s$(ps^{-1})	Γ_s(ps^{-1})	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$
Inner Detector alignment	0.04	< 0.001	0.001	< 0.001	< 0.001	< 0.01
Trigger efficiency	< 0.01	< 0.001	0.002	< 0.001	< 0.001	< 0.01
Signal mass model	0.02	0.002	< 0.001	< 0.001	< 0.001	< 0.01
Background mass model	0.03	0.001	< 0.001	0.001	< 0.001	< 0.01
Resolution model	0.05	< 0.001	0.001	< 0.001	< 0.001	< 0.01
Background lifetime model	0.02	0.002	< 0.001	< 0.001	< 0.001	< 0.01
Background angles model	0.05	0.007	0.003	0.007	0.008	0.02
B^0 contribution	0.05	< 0.001	< 0.001	< 0.001	0.005	< 0.01
Totals	0.10	0.008	0.004	0.007	0.009	0.02

These are calculated with different techniques, including:

- changes in detector simulation (alignment),
- data based studies (efficiency),
- pseudo-experiments Montecarlo (mass models, background angles)
- and variations in analysis methods and assumptions.

Symmetries in likelihood, parameters determination

The term describing $B_S \rightarrow J/\psi\ \phi$ is invariant under the transformations:

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

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

with the latter characteristic of *untagged* analyses.

As shown below, the fit to the data favors values of φ_s close to 0 (π), for which an untagged analysis is scarcely sensitive to the phase $\delta_\perp$.

We therefore proceed as follows:

- we constrain the value of $\delta_\perp$ to 2.95 ± 0.39 rad as recently measured (LHCb) [or its complement to π].[Ref.s in slide n. 16]
- the four minima of the likelihood do not overlap, only one of them is compatible with previous measurements, and we show below the result for that minimum.

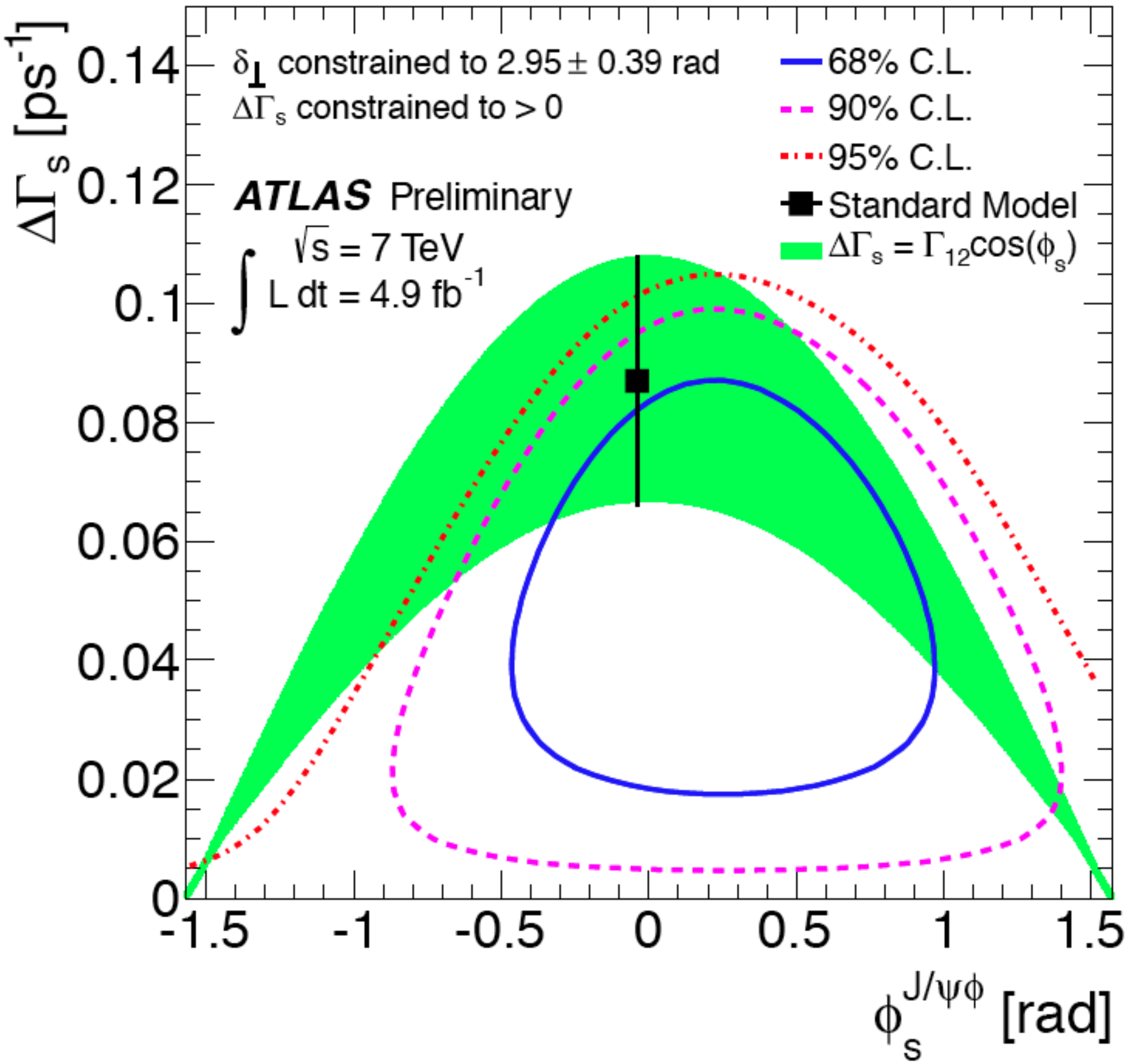
Result of likelihood fit

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s(rad)	0.22	0.41	0.10
$\Delta\Gamma_s(\mathrm{ps}^{-1})$	0.053	0.021	0.008
$\Gamma_s(\mathrm{ps}^{-1})$	0.677	0.007	0.004
$\|A_0(0)\|^2$	0.528	0.006	0.009
$\|A_\parallel(0)\|^2$	0.220	0.008	0.007
$\|A_S(0)\|^2$	0.02	0.02	0.02

Correlation coefficients

	ϕ_s	$\Delta\Gamma_s$	Γ_s	$\|A_0(0)\|^2$	$\|A_\parallel(0)\|^2$	$\|A_S(0)\|^2$
ϕ_s	1.00	−0.13	0.38	−0.03	−0.04	0.02
$\Delta\Gamma_s$		1.00	−0.60	0.12	0.11	0.10
Γ_s			1.00	−0.06	−0.10	0.04
$\|A_0(0)\|^2$				1.00	−0.30	0.35
$\|A_\parallel(0)\|^2$					1.00	0.09
$\|A_S(0)\|^2$						1.00

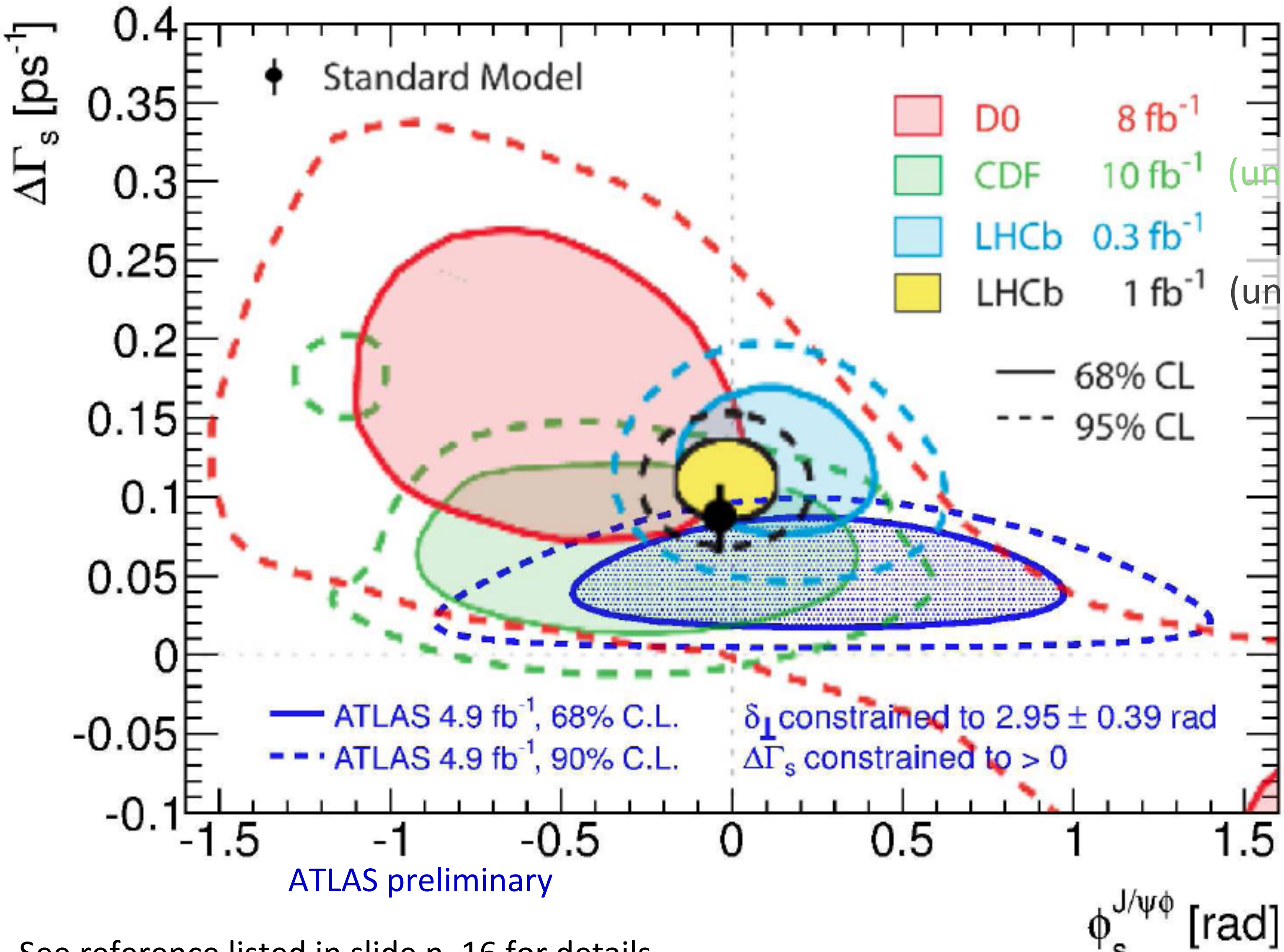
Likelihood profiles in the $\phi_s \times \Delta\Gamma_s$ plane



(Statistical errors only)

Agreement with the SM prediction

Comparison with other experiments



See reference listed in slide n. 16 for details concerning contour plots from other experiments.

Conclusions

From 4.9 fb-1 collected by ATLAS in 2011, decay time and angular distributions have been studied in a sample of 22000 $B_S \rightarrow J/\psi\ \phi$ events. Without flavor tagging, and assuming $\delta_\perp$ = 2.95 ± 0.39 rad, the preliminary result is:

$$\phi_s = 0.22 \pm 0.41 \text{ (stat.)} \pm 0.10 \text{ (syst.) rad}$$

$$\Delta\Gamma_s = 0.053 \pm 0.021 \text{ (stat.)} \pm 0.008 \text{ (syst.) ps}^{-1}$$

$$\Gamma_s = 0.677 \pm 0.007 \text{ (stat.)} \pm 0.004 \text{ (syst.) ps}^{-1}$$

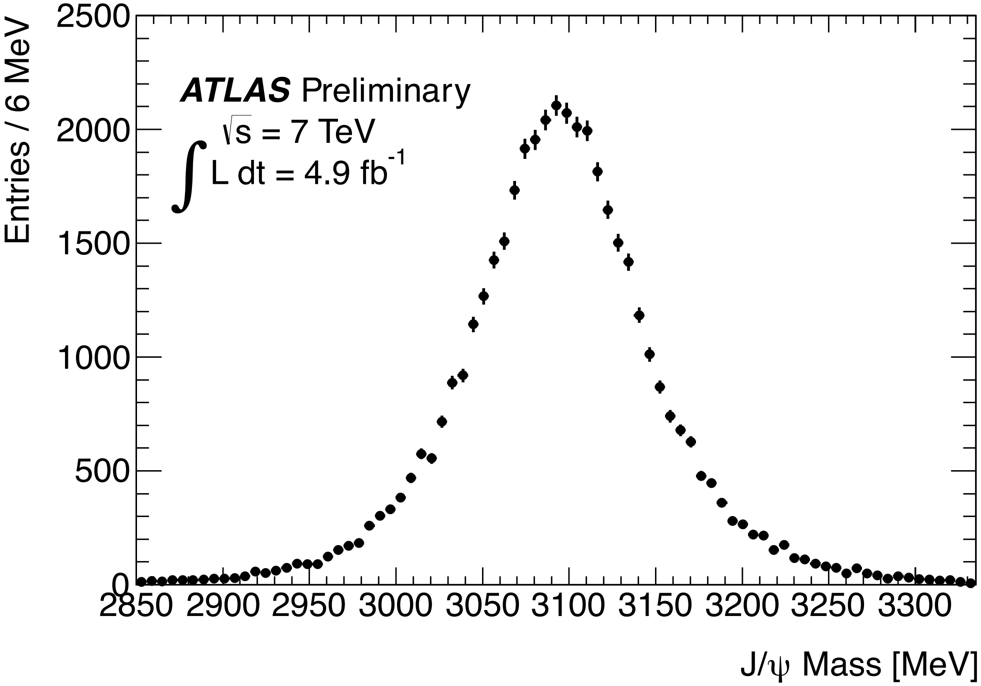
$$|A_0(0)|^2 = 0.528 \pm 0.006 \text{ (stat.)} \pm 0.009 \text{ (syst.)}$$

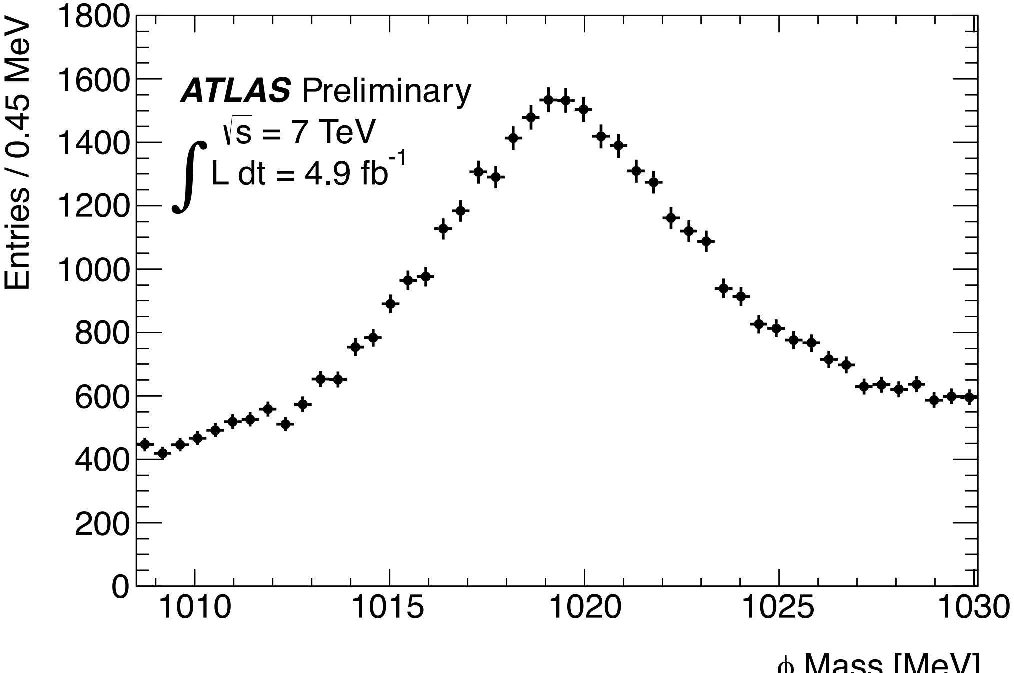
$$|A_{||}(0)|^2 = 0.220 \pm 0.008 \text{ (stat.)} \pm 0.007 \text{ (syst.)}$$

References

- SM expected value for ϕ_s , $\Delta\Gamma_S$: Utfit Collaboration, PRL 97 (2006) 151803; A. Lenz and U. Nierste, JHEP 06 (2007) 072; arXiv: 1102.4274
- Decay time and angular correlation formalism: A. Dighe, I. Dunietz and R. Fleischer, EPJ-C 6 (1999) 647
- $\delta_\perp$: LHCb Collaboration: PLR 108, 101803 (2012)
- Strong phases and sign of $\Delta\Gamma_S$: LHCb Collaboration, PRL 108, 241801
- (2012)
- Previous measurements in $\varphi_s \times \Delta\Gamma_{S:}$
  - CDF Collaboration: CDF-Public-Note-10778
  - D0 Collaboration: PRD85, 032006 (2012)
  - LHCb Collaboration: LHCb-CONF-2012-002 and ibid.
  - Plot in slide n. 14 modified from: P. Clarke, Moriond EW 2012.

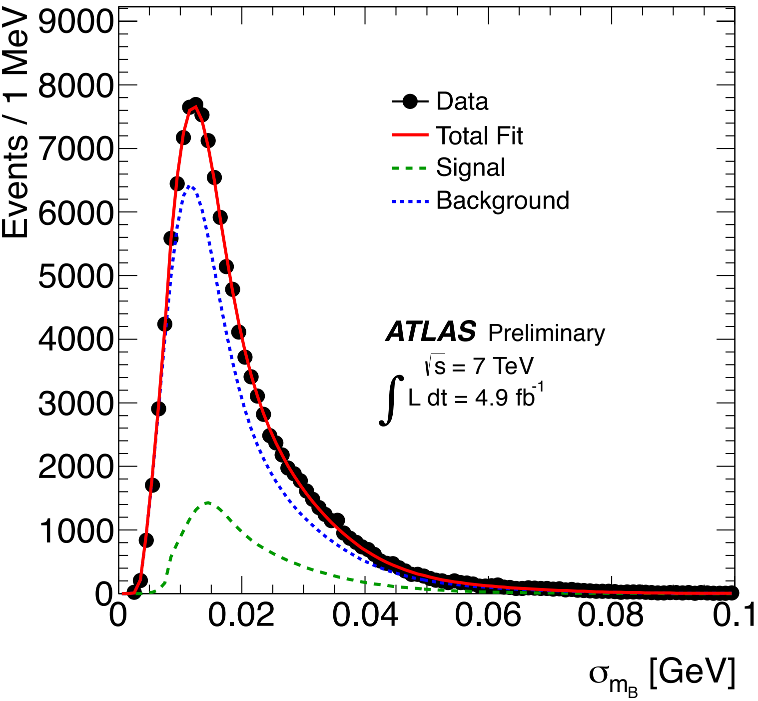
ADDITIONAL SLIDES

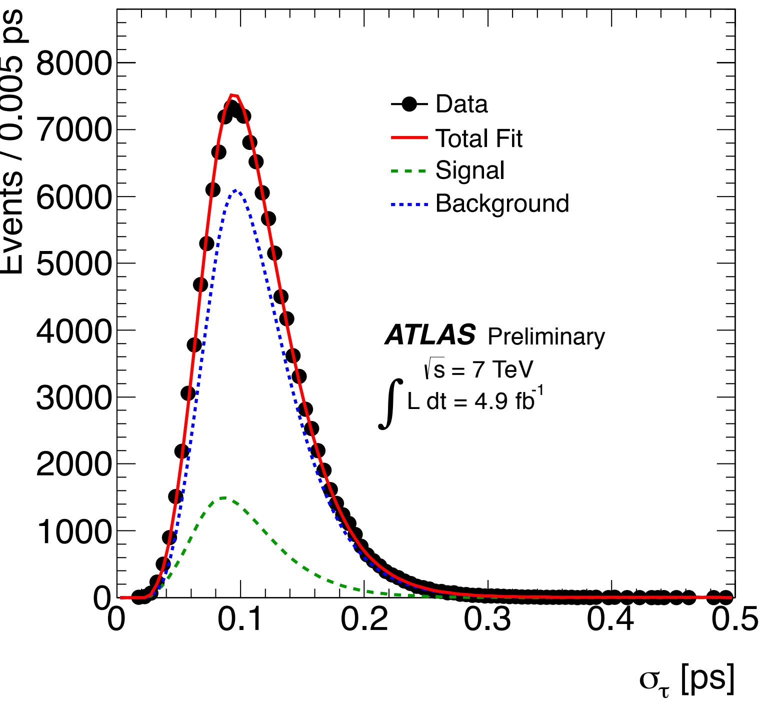




Mass distribution J/ψ $(\mu^+\mu^-)$ and ϕ (K^+K^-) for B_S candidates with 5317 < m < 5417 MeV.

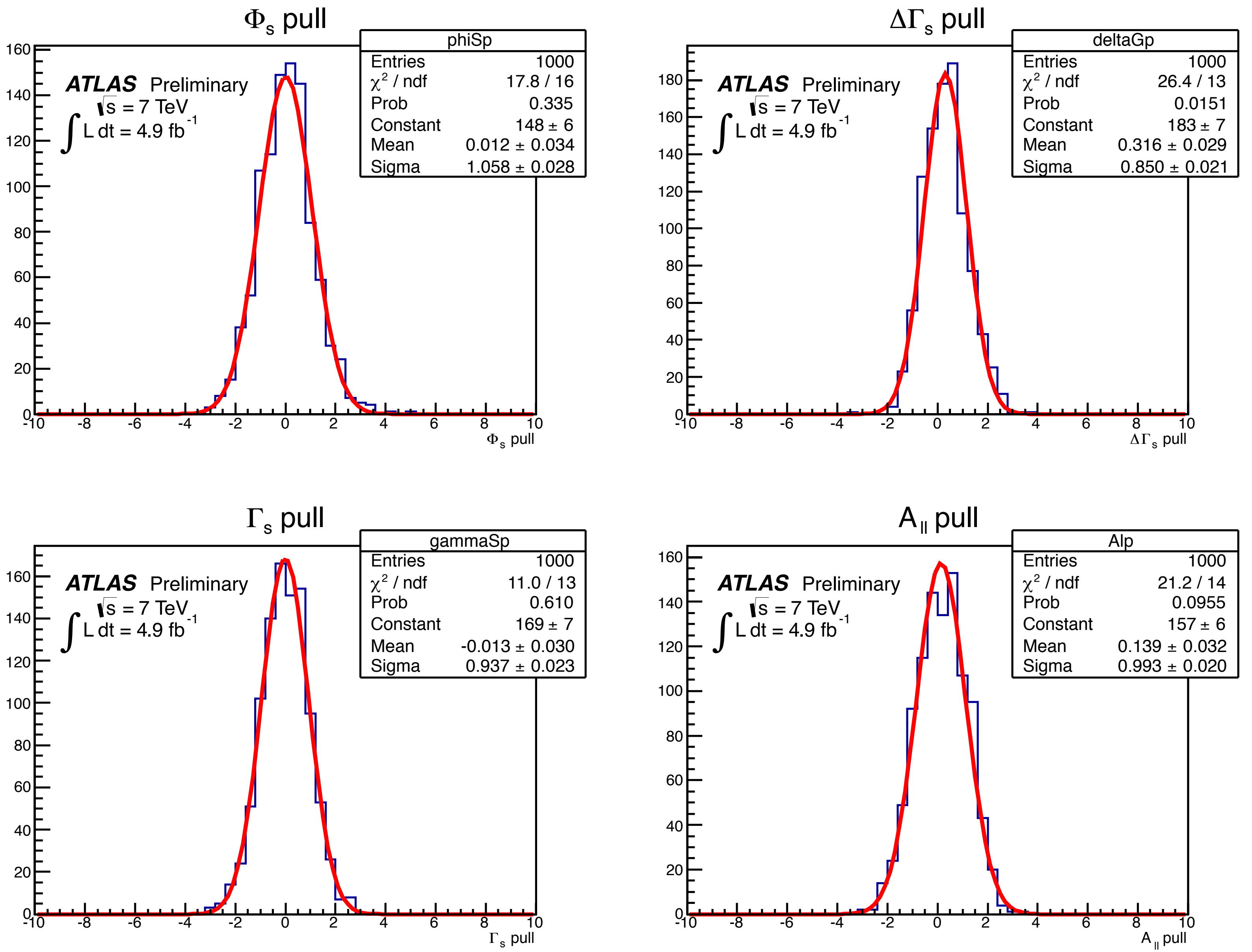
Selection cuts:
J/ψ mass within ±135-240 MeV (η dependent),
ϕ mass within ±11 MeV.



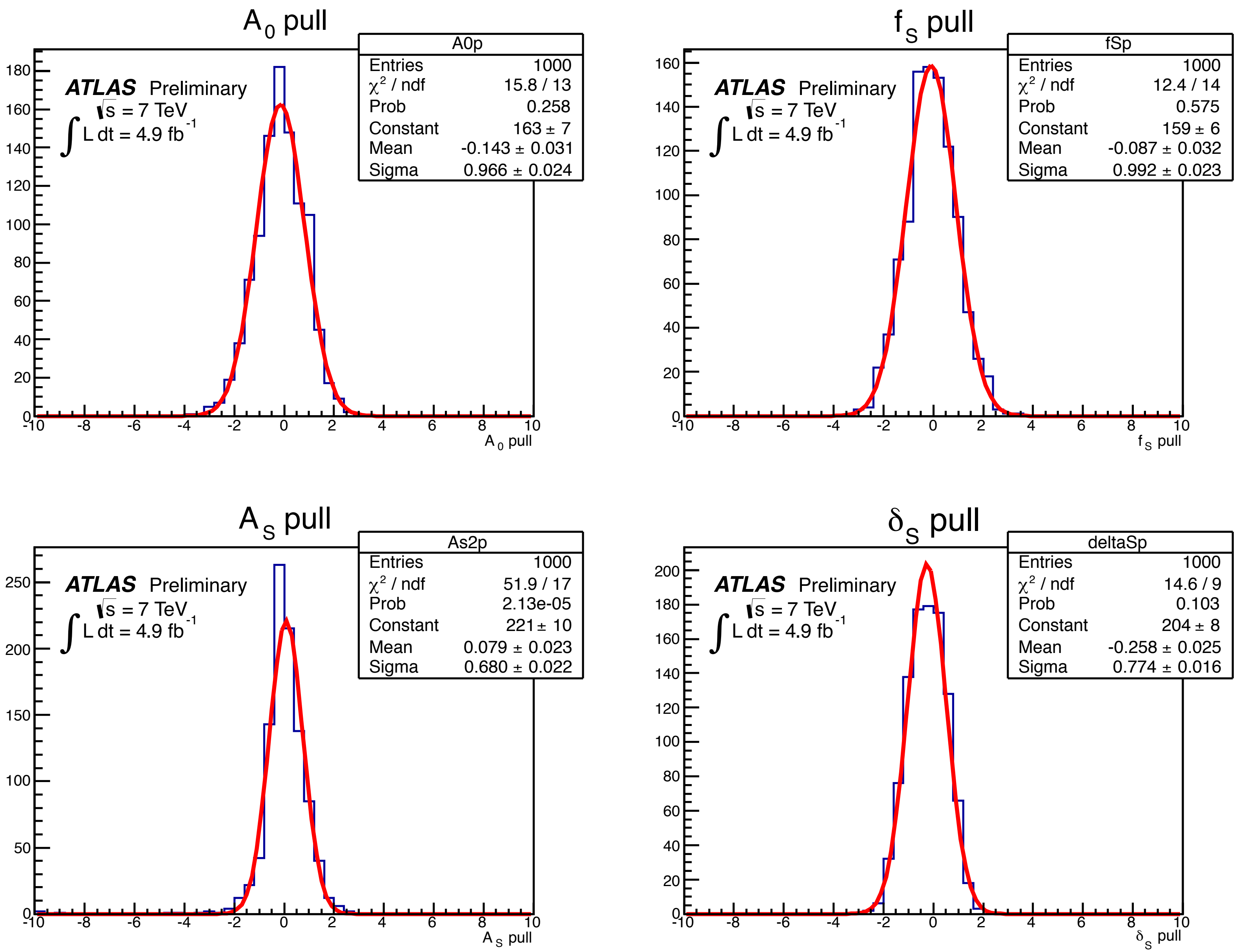


Mass and proper decay-time per-candidate uncertainties

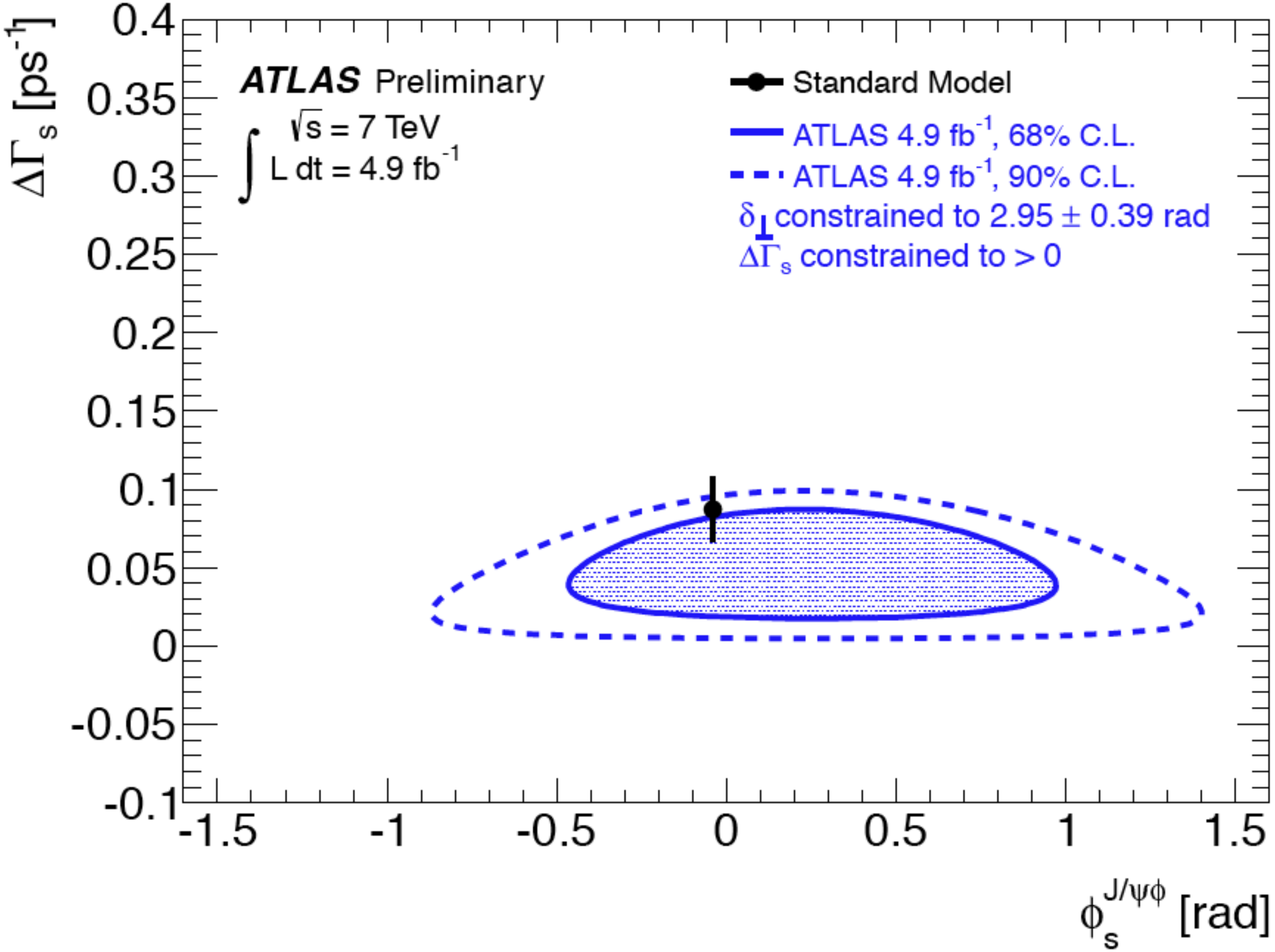
Mass and decay-time measurements enter the likelihood with event-by-event uncertainties. The distributions are extracted from data.



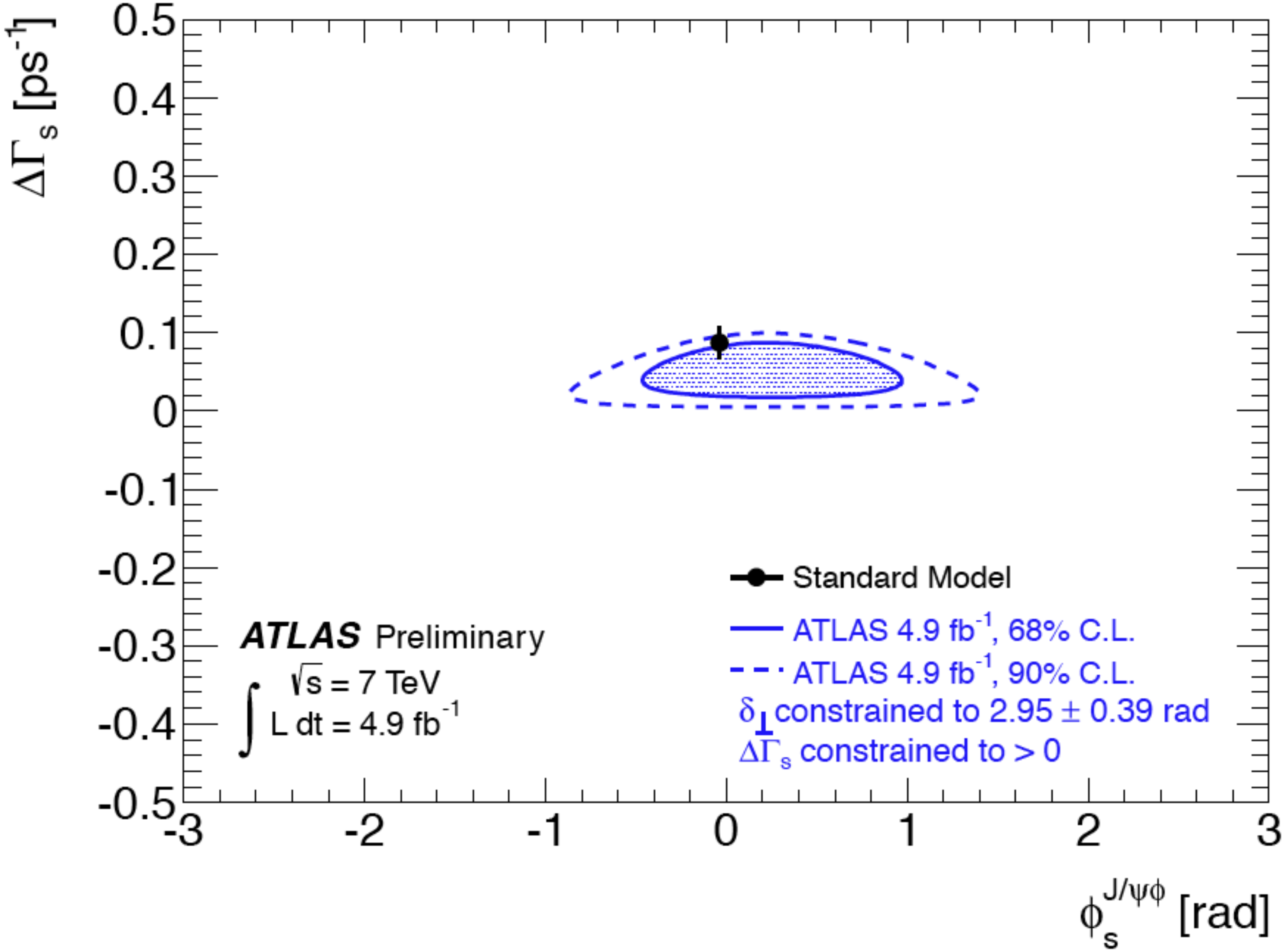
Pull distributions from pseudo-experiments simulation - 1



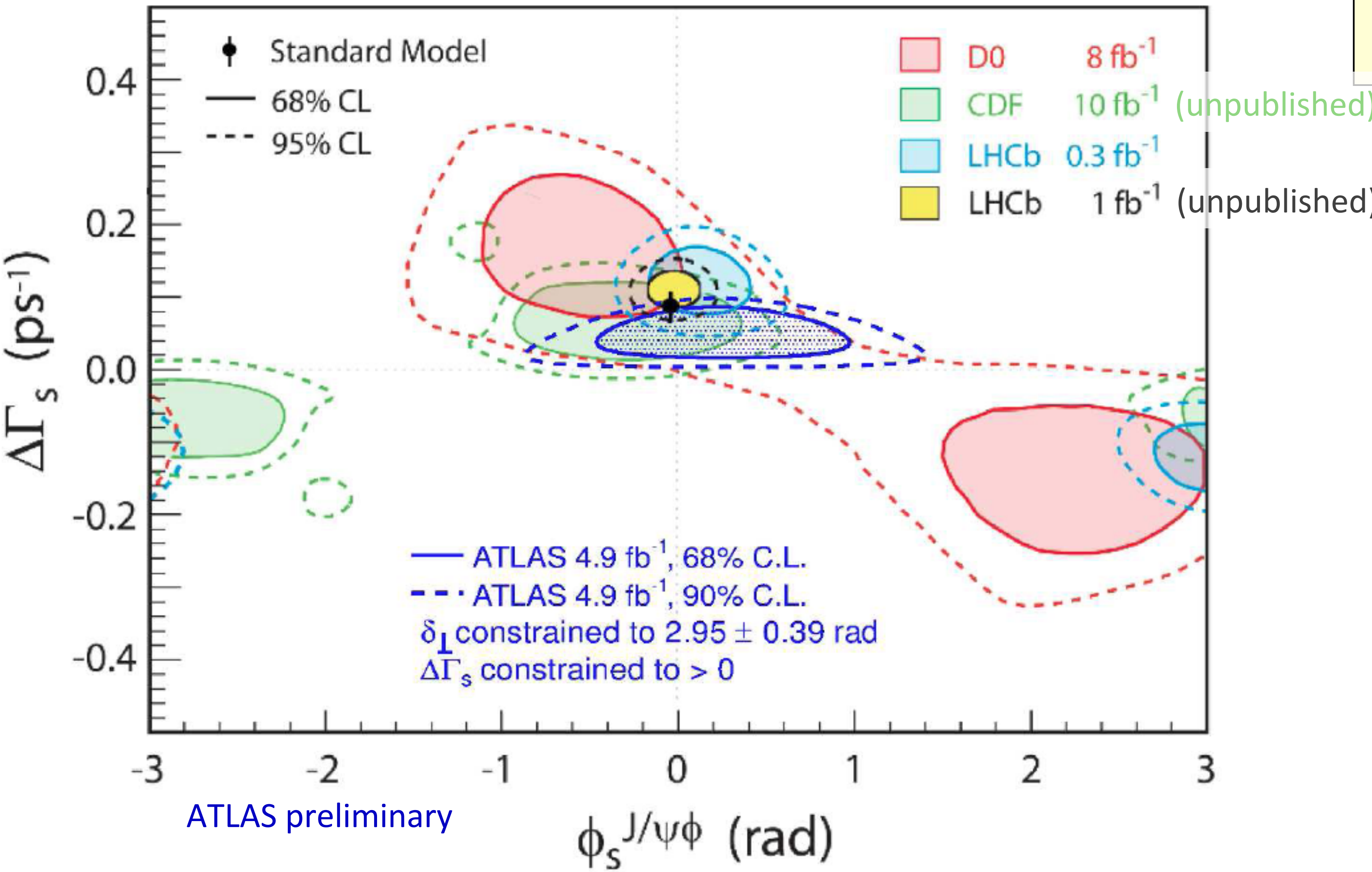
Pull distributions from pseudo-experiments simulation - 2



ATLAS Preliminary
√s = 7 TeV
∫ L dt = 4.9 fb^-1
Standard Model
ATLAS 4.9 fb^-1, 68% C.L.
ATLAS 4.9 fb^-1, 90% C.L.
δ⊥ constrained to 2.95 ± 0.39 rad
ΔΓs constrained to > 0
ΔΓs [ps^-1]
φs^J/ψφ [rad]



$\Delta\Gamma_s$ [ps^{-1}]
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-3
-2
-1
0
1
2
3
$\phi_s^{J/\psi\phi}$ [rad]
Standard Model
ATLAS 4.9 fb^{-1}, 68% C.L.
ATLAS 4.9 fb^{-1}, 90% C.L.
$\delta_\perp$ constrained to 2.95 ± 0.39 rad
$\Delta\Gamma_s$ constrained to > 0
ATLAS Preliminary
$\sqrt{s}$ = 7 TeV
$\int$ L dt = 4.9 fb^{-1}



See reference listed on slide n. 16 for details concerning contour plots from other experiments.

Likelihood fit to strong phases

δ_{perp}	Constrained to 2.95 ± 0.39 rad
δ_{par}	Best fit: π, 1 σ range: 3.04—3.24 rad
$\delta_{perp} - \delta_S$	0.03 ± 0.13 rad

ATLAS - 4.9 fb^{-1} - Preliminary

Comparisons of recent measurements

	Γ_S [ps-1]	$\Delta\Gamma_S$ [ps-1]	$\|A_0\|^2$	$\|A_{par}\|^2$	φ_s [rad]	$\|A_S\|^2$	δ_{perp} [rad]	δ_{par} [rad]	δ_S [rad]	**Signal sample**
D0 (8 fb-1, stat(+)syst $\Delta\Gamma s>0$ case)	0.693 -0.020 +0.015	0.179 -0.060 +0.059	0.565 ±0.017	0.249 -.022 +.021	-0.56 -0.32 +0.36	0.173 ±0.036 *effective*	*Near π [Assum. cos (δ_{perp}) <0]*	3.15 ±0.19	cos(δ_{perp}-δ_S) = -.20 -.27+.26	~5300
CDF (10fb^{-1}, unpublished)	0.654 ±0.008 ±0.004	0.068 ±0.026 ±0.007	0.512 ±0.012 ±0.017	0.229 ±0.010 ±0.014	=SM Fit:-0.24±0.36	*Appar. small*	2.79 ±0.53 ±0.15	*Near π*	*Small effect*	11000
LHCb (1fb^{-1}, unpublished)	0.6580 ±0.0054 ±0.0066	0.116 ±0.018 ±0.006	0.523 ±0.007 ±0.024	*0.231 ±0.021* [*]	-0.001 ±0.101 ±0.027	0.022 ±0.012 ±0.007	2.90 ±0.36 ±0.07	*Near π ±0.33 ±0.13*	2.90 ±0.36 ±0.08	21000
ATLAS (4.9fb^{-1}, preliminary)	0.677 ±0.007 ±0.004	0.053 ±0.021 ±0.008	0.528 ±0.006 ±0.009	0.220 ±0.008 ±0.007	0.22 ±0.41 ±0.10	0.02 ±0.02 ±0.02	*Assum. 2.95 ±.39*	*near π*	*Near δ_{perp}*	23000

[*] from $|A_0|^2$ and $|A_{par}|^2$, summing stat. and syst. errors in quadrature and using quoted (negative) correlation coefficient.

See references listed on slide n. 16 for details concerning other experiments.