New physics searches with heavy flavour observables at ATLAS

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on behalf of the ATLAS B-physics group

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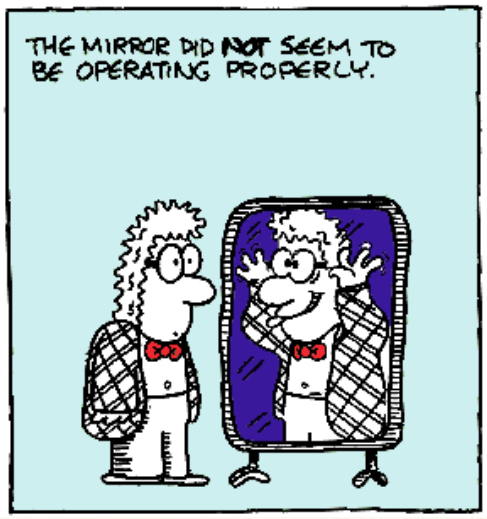
UNIVERSITY of WASHINGTON

Outline

- Overview of the ATLAS detector
- Flavour-tagged time-dependent angular analysis in $B_s \to J/\psi\,\phi$
  - Measurement of $\Delta\Gamma_s$ and ϕ_s
    - Angular analysis
    - Flavour tagging
    - Results with 2012 data
    - Combination of 2011 and 2012 data

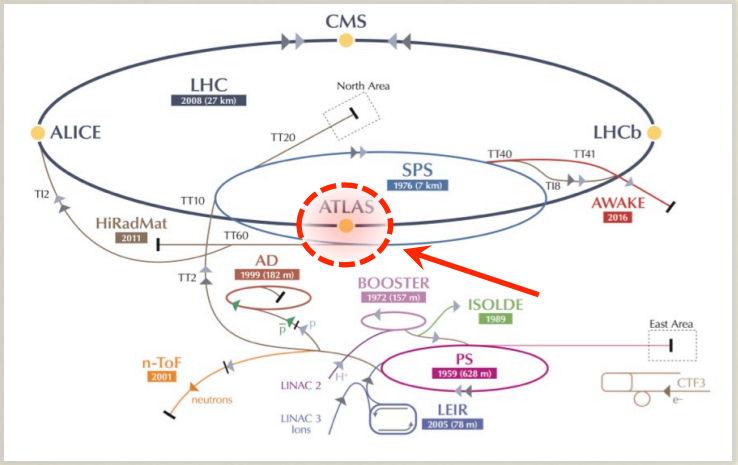


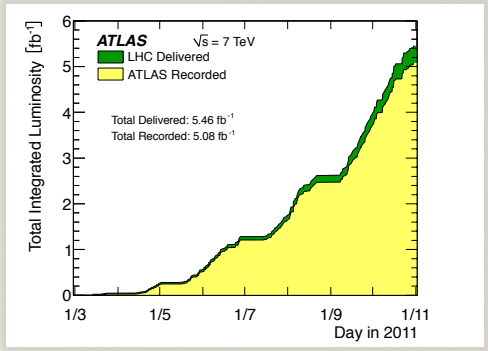
- Rare B decays for new physics
  - $B_s \to \mu^+\mu^-$
    - Status of Run-1 data analysis
  - $B_d \to K^*\mu^+\mu^-$
    - Status of Run-1 data analysis

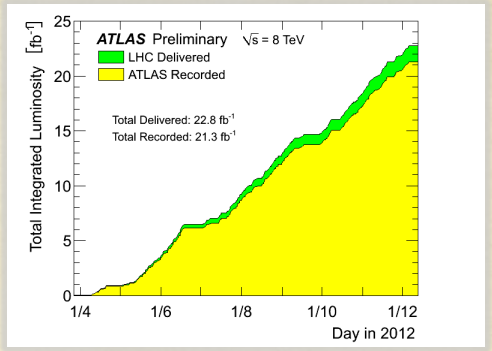
- Conclusions

The ATLAS detector

- ATLAS is a multipurpose experiment designed to achieve the highest possible flexibility in different sectors of the high energy physics

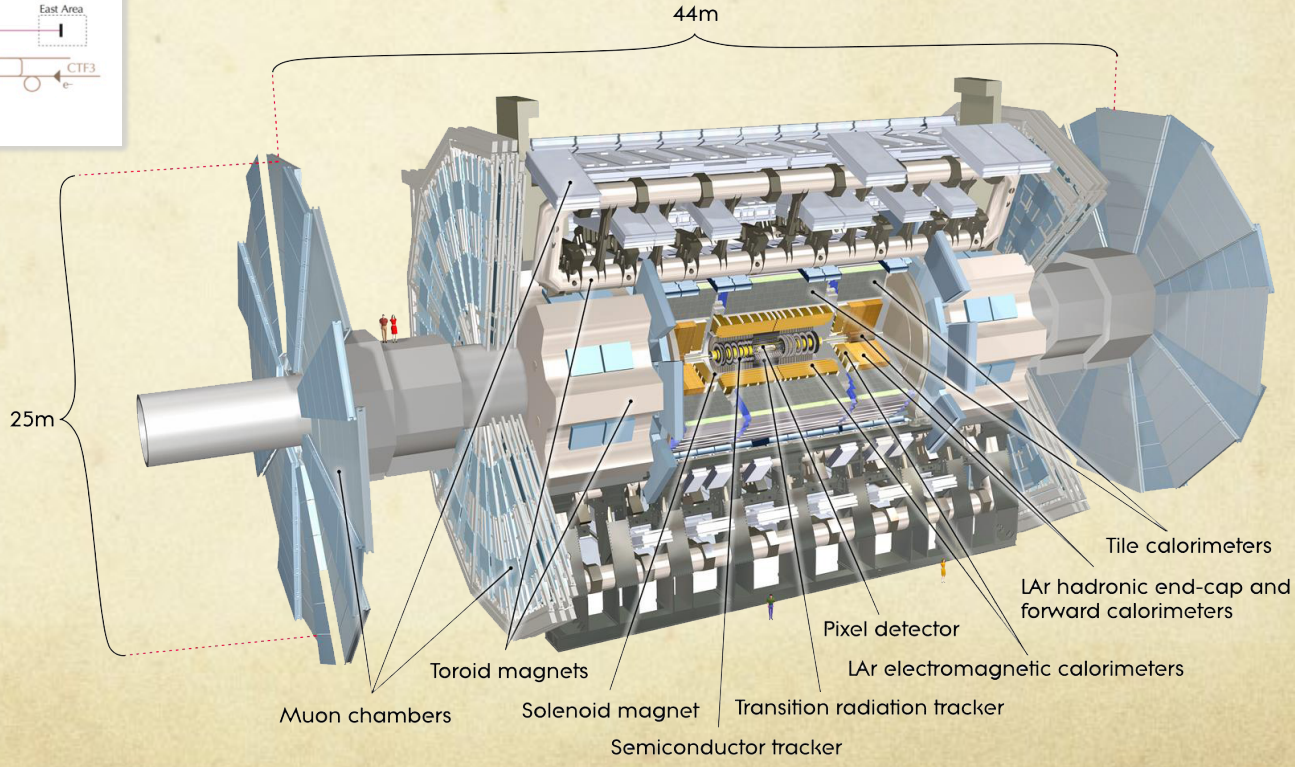






- Muon identification from combined Muon Spectrometer (MS) and Inner Detector (ID) tracking

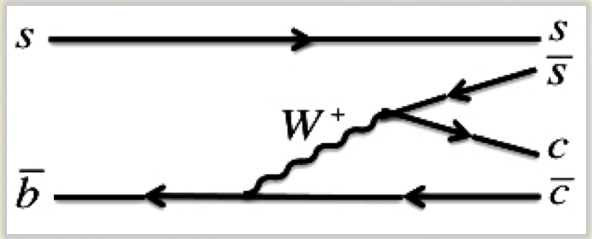
- ID tracks (from muons) provides **precision momentum and lifetime measurements for the range of momenta considered here**



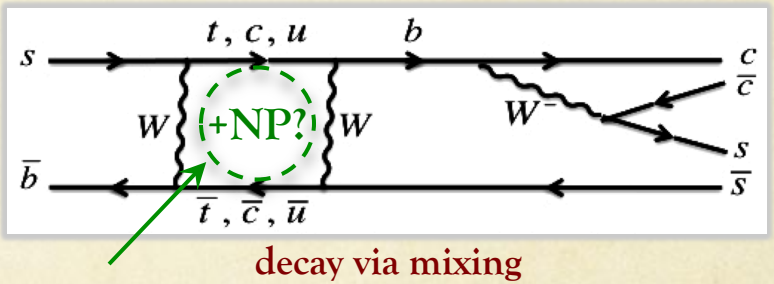
Flavour-tagged time-dependent angular analysis in $B_s \to J/\psi\phi$

Measurements of $\Delta\Gamma_s$ and ϕ_s from $B_s \to J/\psi\phi$

- CP violation in B decays may be altered by new phenomena beyond SM
- The time evolution of B_s meson mixing is characterised by
  - The mass difference $\Delta m_s = m_s^H - m_s^L$ of the heavy (B^H) and light (B^L) mass eigenstate ($\Delta m_s \sim 17.77\ ps^{-1}$)
  - The width difference $\Delta\Gamma_s = \Gamma_s^L - \Gamma_s^H \rightarrow \Delta\Gamma_s^{(SM)} = 0.087 \pm 0.021\ ps^{-1}$ [arXiv:1102.4274]
  - The CP-violating mixing phase ϕ_s
- Interference between direct decays and decays with B_s mixing gives rise to a measureable CP violating phase ϕ_s



direct decay



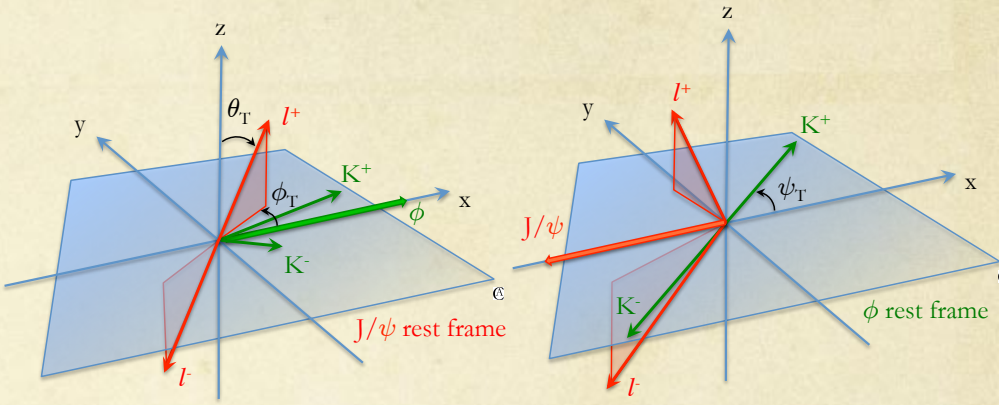
decay via mixing

  - Indirect determination via global fits to experimental data $\rightarrow \phi_s^{(SM)} = -0.0363^{+0.0012}_{-0.0014}$ rad
  - Small uncertainty makes **direct measurement interesting** since NP could modify ϕ_s and the ratio $\Delta\Gamma_s / \Delta m_s$ if new particles contributes to B_s /anti-B_s box diagrams

❖ **Updated measurement to *Phys. Rev. D 90 (2014) 052007* that includes 2012 data (14.3 fb^{-1})**

$B_s \to J/\psi\,\phi$: angular analysis

- Time dependent angular analysis necessary to disentangle the interesting eigenstates: CP-even (L=0,2) and CP-odd (L=1)
- 3 transversity angles (θ_T , Ψ_T , ϕ_T) used to describe the B_s decay angular distribution
- Each B candidate initial flavour is tagged → allows to improves accuracy
- Precision driven by proper-time resolution



- **Analysis on full Run-1 data**
- Un-binned maximum likelihood fit to extract Γ, $\Delta\Gamma$, ϕ_s → observables
  - m(J/ψ KK), τ, σ (τ)
  - Ω = (θ_T , Ψ_T , ϕ_T)
  - B_s momentum
  - Tagging probability

weights for proper decay time trigger efficiency

signal with amplitude f_s

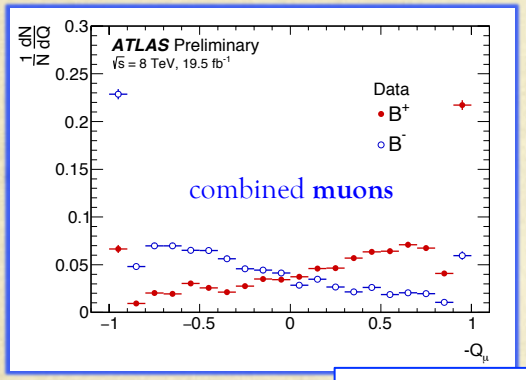
$$\ln \mathcal{L} = \sum_{i=1}^{N} \{ w_i \cdot \ln(f_s \cdot \mathcal{F}_s(m_i, t_i, \sigma_t, \Omega_i, P(B|Q)) + f_s \cdot f_{B^0} \cdot \mathcal{F}_{B^0}(m_i, t_i, \sigma_t, \Omega_i) + (1 - f_s \cdot (1 + f_{B^0})) \mathcal{F}_{bkg}(m_i, t_i, \Omega_i)) \}$$

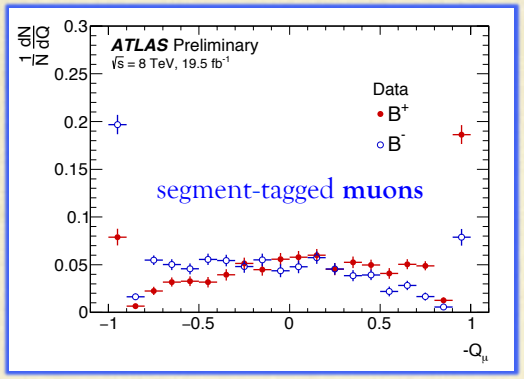
prompt and non-prompt combinatorial background described with empirical angular distribution (no K-π discrimination) – *parameters fitted in the likelihood*

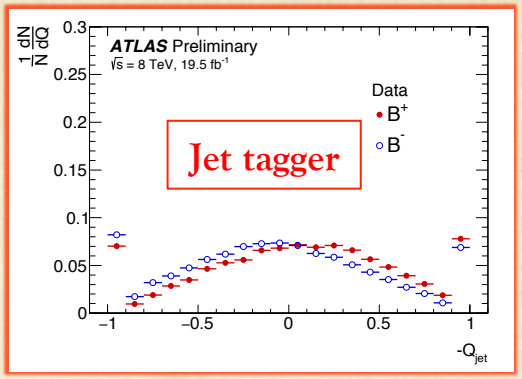
background from $B^0 \to J/\psi\, K^{*0}$ and $B^0 \to J/\psi\, K\, \pi$ with amplitude f_B - *fixed shapes*

$B_s \to J/\psi\,\phi$: flavour tagging

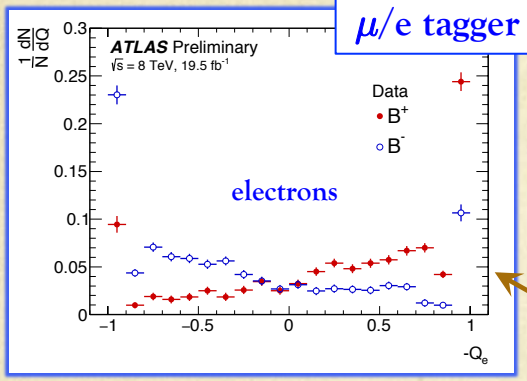
- Identification of B_s flavour at point of production improves the sensitivity
- The initial flavour of a neutral B meson can be determined using information from the other B meson that is typically produced from the other b quark in the event







μ/e tagger



- ✓ Muon/electron charge identified through semi-leptonic decay of B
- ✓ Evaluate μ/e cone charge $Q_{\mu/e}$

- ✓ Tracks associated to the jet from the same PV of signal decay
- ✓ Evaluate jet cone charge Q_{jet}

New! Not present in 2011 data analysis

Tagger	Tagging Power [%]
Combined muon	0.92 ± 0.02
Electrons	0.29 ± 0.01
Segment Tagged Muon	0.10 ± 0.01
Jet charge	0.19 ± 0.01
Total	1.49 ± 0.02

- **Two methods combined according to the hierarchy of performance**
- Probability that signal decay contains $\bar{b}$ as a function of $Q_{\mu/e}$ and Q_{jet} calibrated using $B^+ \to J/\psi\,K^+$ sample
- Un-binned maximum likelihood fit performed considering probability distribution and per-candidate probability (P=0.5 if no tagging information is available)

$B_s \to J/\psi\,\phi$: systematics

- **Background angular model**
  - Variation of the p_T and sideband mass regions defined in the analysis
  - Mis-reconstructed $B_d \to J/\psi\, K^{0*}$ accounted for in the main fit, angular shapes taken into account
  - Contributions from $B_d \to J/\psi\, K\pi$ contamination and interference with $B_d \to J/\psi\, K^{0*}$ included in the systematic
- **Tagging**
  - Uncertainty due to the finite size of the $B^+ \to J/\psi\, K^+$ calibration sample (treated in overall statistical error)
  - Systematic arising from the precision of the tagging calibration → alternate parameterisations of calibration curves
- **Assumption of the fit model** → variations of the model tested in pseudo-experiments
- **Angular acceptance method and trigger efficiency**

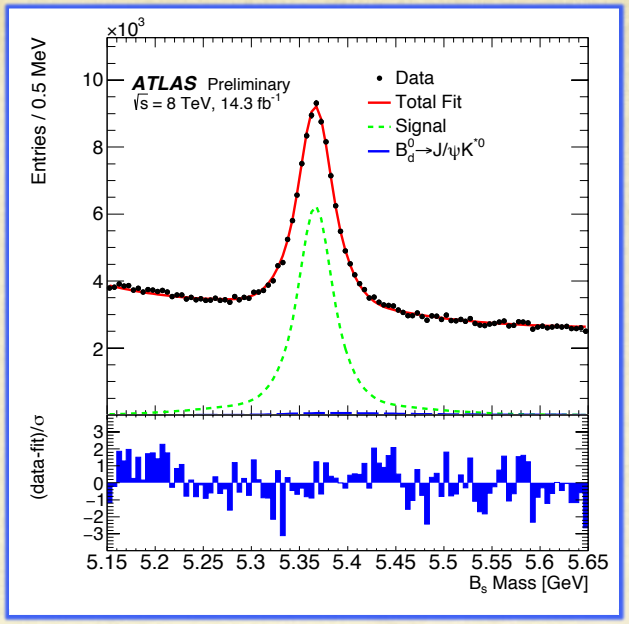
	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	$\lvert A_\parallel(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_\perp$ [rad]	$\delta_\parallel$ [rad]	$\delta_\perp - \delta_S$ [rad]
Tagging	0.026	0.003	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.001	0.238	0.014	0.004
Acceptance	$<10^{-3}$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

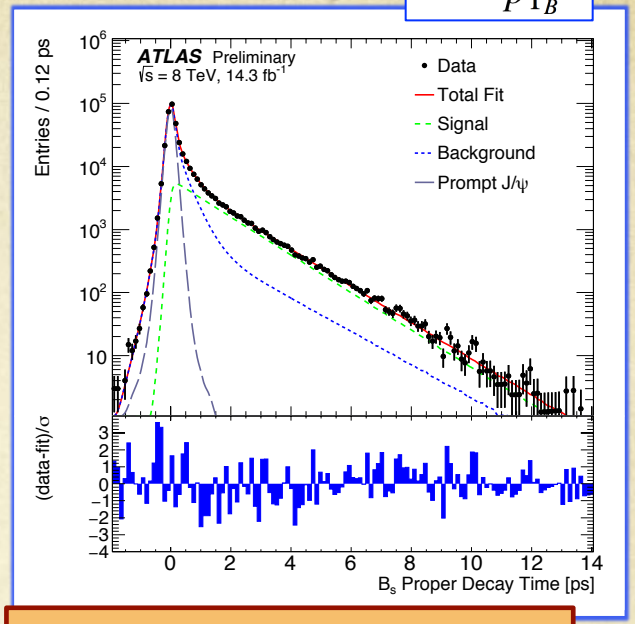
ATLAS Preliminary

$B_s \to J/\psi\,\phi$: fit with 8 TeV data

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

- **Projection on B_s mass and proper decay time**
- Signal component:
  - **Mass**: triple Gaussian
  - **Lifetime**: expo ⊗ Gaussian
- Invariant mass background described by an exponential

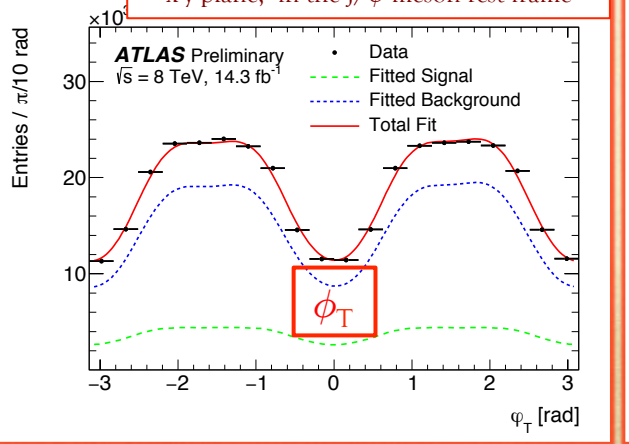




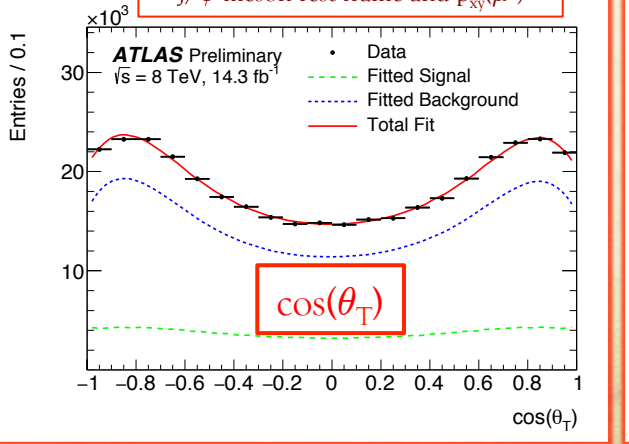
No cut on decay lifetime is applied

- **Projection on the three transversity angles**

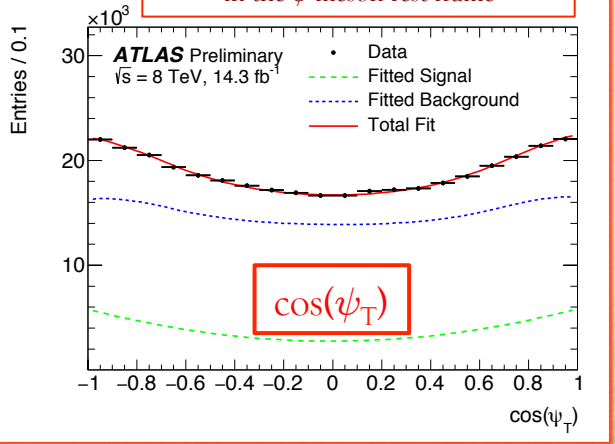
ϕ_T: angle between the x-axis and $p_{xy}(\mu^+)$, the projection of the μ^+ momentum in the x-y plane, in the J/ψ meson rest frame



θ_T: angle between the x-y plane in the J/ψ meson rest frame and $p_{xy}(\mu^+)$



ψ_T: angle between $p(K^+)$ and $-p(J/\psi)$ in the ϕ meson rest frame



$B_s \to J/\psi\,\phi$: results with 8 TeV data and combination

- **Results with 7 TeV data**
  - $\phi_s = -0.12 \pm 0.25$ (stat.) ± 0.05 (syst.) rad
  - $\Delta\Gamma_s = 0.053 \pm 0.021$ (stat.) ± 0.010 (syst.) ps^{-1}
- **Results with 8 TeV data**
  - $\phi_s = -0.119 \pm 0.088$ (stat.) ± 0.036 (syst.) rad
  - $\Delta\Gamma_s = 0.096 \pm 0.013$ (stat.) ± 0.007 (syst.) ps^{-1}

Statistical combination of the results

→ Best Linear Unbiased Estimate (BLUE) *[The European Physical Journal C 74 (2014) no. 8]* of 7 TeV and 8 TeV results → minimises the variance in the estimators

	Value	Stat.	Syst.	Unit		ϕ_s	$\Delta\Gamma_s$	Γ_s	$\lvert A_{\perp\perp}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_{\perp\perp}$	$\delta_\perp$	$\delta_\perp - \delta_S$
ϕ_s	-0.094	0.083	0.033	rad		1.000	0.094	-0.072	0.028	0.028	0.048	0.062	-0.016	-0.009
$\Delta\Gamma_s$	0.082	0.011	0.007	ps^{-1}			1.000	-0.377	0.113	0.145	0.068	0.012	0.012	-0.012
Γ_s	0.677	0.003	0.003	ps^{-1}				1.000	-0.126	-0.043	0.172	-0.026	-0.009	0.019
$\lvert A_{\perp\perp}(0)\rvert^2$	0.227	0.004	0.006						1.000	-0.326	0.081	0.095	0.024	-0.018
$\lvert A_0(0)\rvert^2$	0.515	0.004	0.002							1.000	0.220	-0.008	0.006	0.012
$\lvert A_S(0)\rvert^2$	0.086	0.007	0.012								1.000	-0.042	-0.002	0.050
$\delta_{\perp\perp}$	4.13	0.34	0.15	rad								1.000	0.165	-0.007
$\delta_\perp$	3.16	0.13	0.05	rad									1.000	0.016
$\delta_\perp - \delta_S$	-0.08	0.03	0.01	rad										1.000

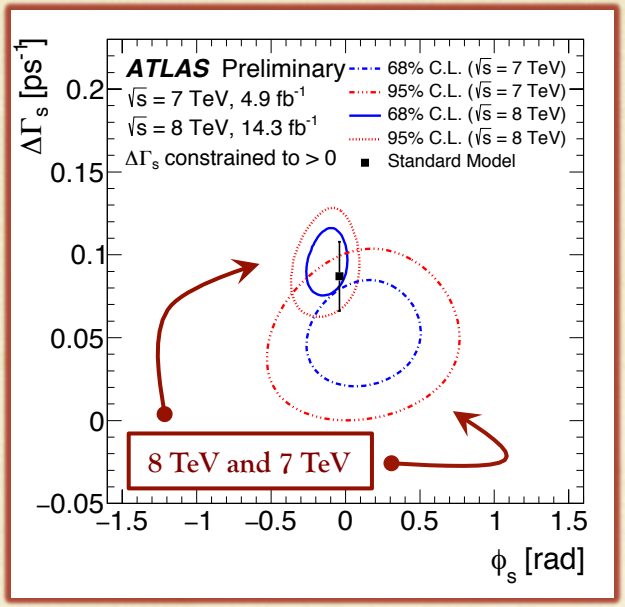
PRELIMINARY

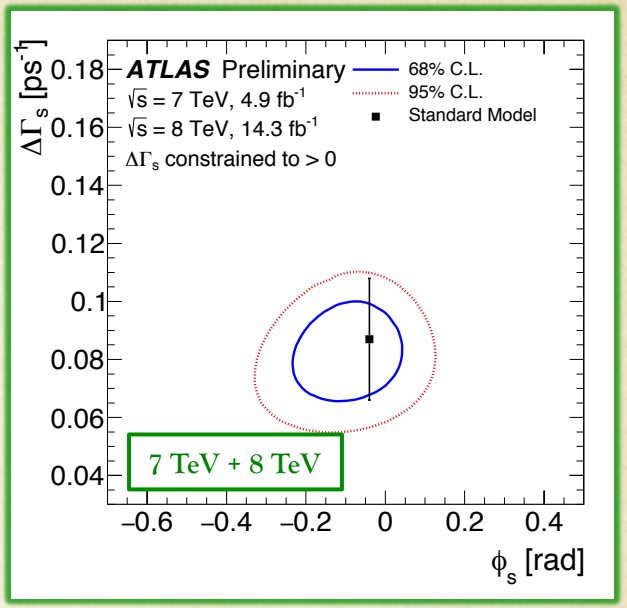
$B_s \to J/\psi\,\phi$: summary and conclusions

- Measurement of the time-dependent flavour-tagged CP asymmetry in decays $B_s \to J/\psi\,\phi$

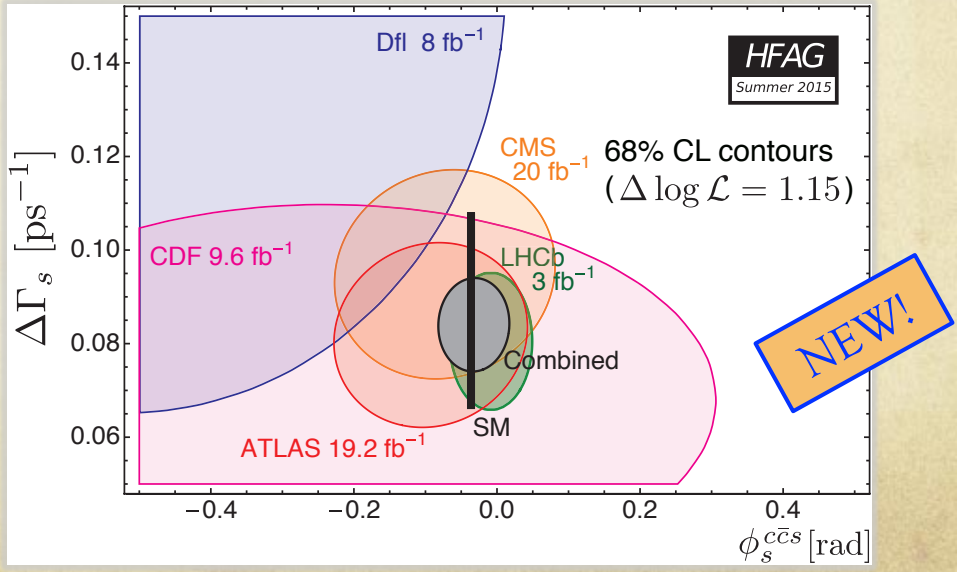
- 14.3 fb^{-1} from 8 TeV data collected in 2012 statistically combined with the results obtained from 4.9 fb^{-1} at 7 TeV

different plot axes!





- The **results obtained are consistent with the other experiments and with the SM predictions**
  - ✓ $\phi_s^{(SM)} = -0.0363^{+0.0012}_{-0.0014}$ rad
  - ✓ $\Delta\Gamma_s^{(SM)} = 0.087 \pm 0.021$ ps^{-1}

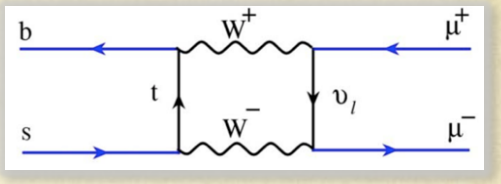


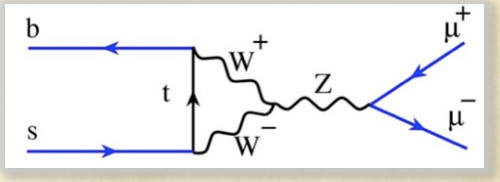
Rare B^0 decays

Rare B^0 decays: $B^0 \rightarrow \mu^+\mu^-$

- Flavour Changing Neutral Currents (FCNC) are highly suppressed in the SM
- **Rare decays $B^0 \rightarrow \mu^+\mu^-$**
  - BR expectation:
    - $B_s^0 : (3.65 \pm 0.23) \cdot 10^{-9}$
    - $B^0 : (1.06 \pm 0.09) \cdot 10^{-10}$

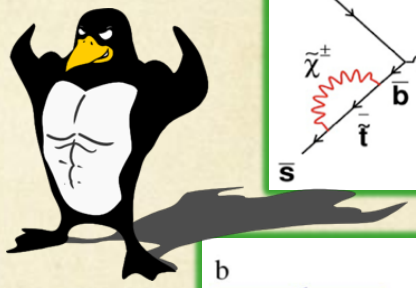
C. Bobeth et al., Phys. Rev. Lett. 112 (2014) 101801

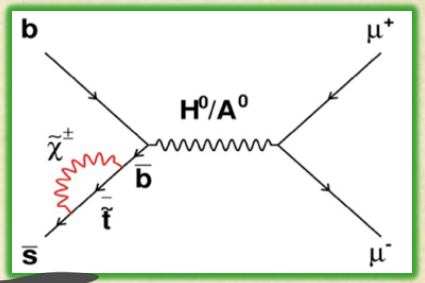




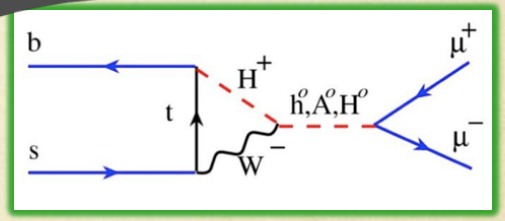
  - Evidence from LHCb and CMS (combined results):
    - $B_s^0 : (2.8 \pm 0.7) \cdot 10^{-9}$
    - $B^0 : (3.9 \pm 1.6) \cdot 10^{-9}$

Nature, 522 (2015) 7554, 68 [arXiv:1411.4413]





- Coupling to **non-SM particles** may **change the branching ratio**
- Indirect researches can reach higher scale w.r.t direct search
  → orthogonal search for physics beyond the SM



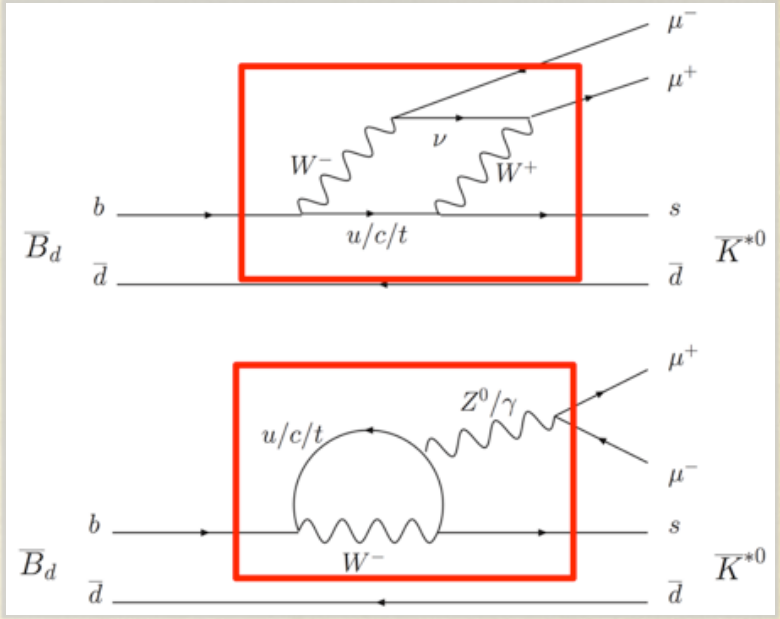
- ATLAS result on 4.9 fb^{-1} of data collected in 2011 ATLAS-CONF-2013-076

→ Analysis on full Run-1 data is going to be published very soon!

Rare B^0 decays: $B_d \to K^* \mu^+ \mu^-$

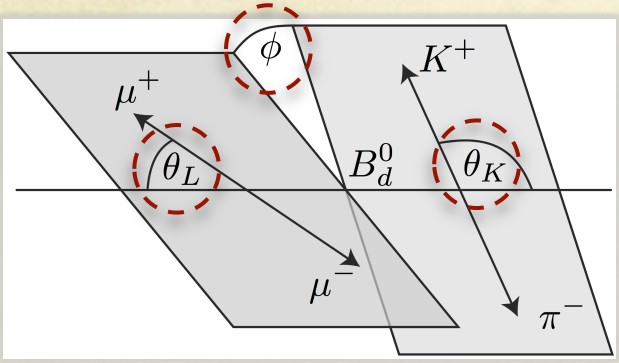
- Flavour Changing Neutral Currents (FCNC) are highly suppressed in the SM
- **Semi-leptonic rare decays $B_d \to K^* \mu^+ \mu^-$**
  - Studied through $b \to s$ transitions

BR : $(1.06 \pm 0.10) \cdot 10^{-6}$



- Angular distribution of the 4 final state particles and decay amplitudes sensible to NP for interference with SM diagrams

Th. prediction: C. Bobeth et al. arXiv:1105.2659



- Analysis on full Run-1 data is on-going
  - Plans to move toward an optimised observable parameterisation

(https://indico.cern.ch/event/341292/session/24/contribution/336/attachments/670318/921362/DIS2015_BPhysATLAS.pdf)

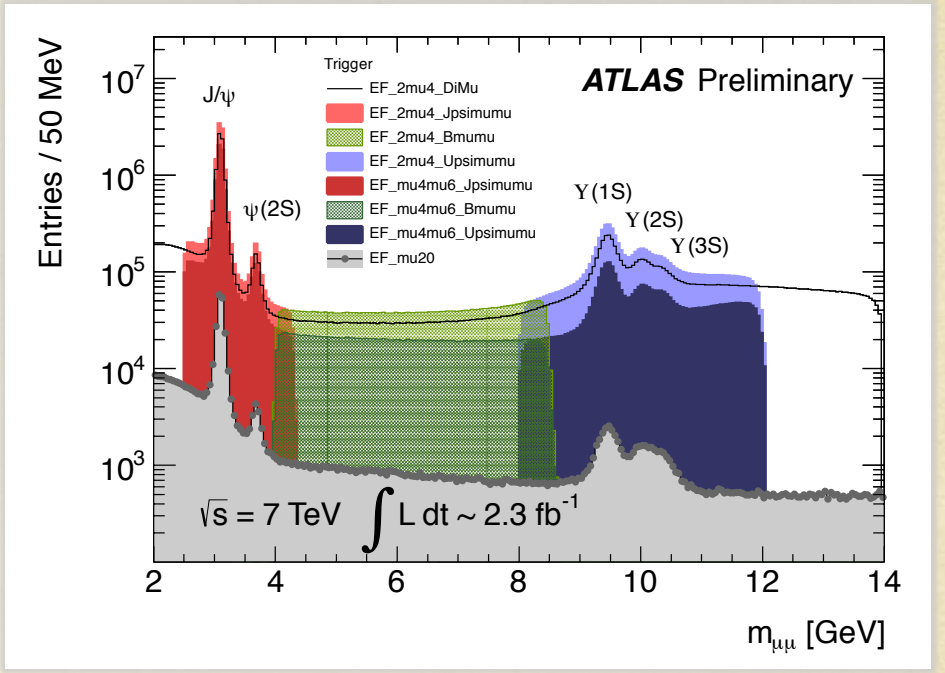
Conclusions

- ATLAS can provide high quality measurements in the B^0 system
  - $B_s \rightarrow J/\psi\,\phi$ measurements of CP violating phase ϕ_s and decay width difference $\Delta\Gamma_s$
    - Analysed 2012 data
    - Statistical combination 2011 + 2012 (4.9 + 14.3 fb^{-1})
      - $\phi_s = 0.094 \pm 0.083\ (stat.) \pm 0.033\ (syst.)$ rad
      - $\Gamma_s = 0.082 \pm 0.011 \pm 0.007\ ps^{-1}$
    - Results consistent with SM predictions
  - $B_s^0 \rightarrow \mu^+\mu^-$
    - Analysed 2011 data
    - The full Run-1 analysis is going to published soon
  - $B_d \rightarrow K^*\mu^+\mu^-$
    - The full Run-1 analysis is on-going

BACKUP

B-physics triggers

- Trigger system subdivided in 3 levels O(20 MHz) → O(200 Hz):
  - Level 1 → hardware O(75 KHz)
  - Level 2 and Event Filter
    - ✓ Software-based
    - ✓ Offline-like reconstruction
- B-physics statistics typically low-pT
- Primary B-physics triggers:
  - Two muon signals at L1
  - confirmed at L2/EF with vertexing and invariant mass criteria applied
  - Varying thresholds and prescaling applied to maximise signal rate
  - Two muons $p_T^{\mu} > 4$ GeV or > 6 GeV → $\mu 4\ \mu 4$ or $\mu 4\ \mu 6$



$B_s \to J/\psi\,\phi$: B_s candidate selection

- **Fit mass windows**
  - $5216 < m(B_s) < 5516$ MeV
- **Tracks**
  - Inner Detector (ID) tracks → $\geqslant 1$ hits in Pixel and $\geqslant 4$ hits on SCT detector
  - Muons → at least one combined (ID+muon spectrometer) muon in the pair
- **$\phi \to$ KK candidate selection**
  - Mass: $1009 < m(\phi) < 1031$ MeV
  - $K^{\pm}$ transverse momentum > 1 GeV
- **B_s candidate selection**
  - Vertex fit of all the 4 tracks with muons pair constrained to J/ψ PDG mass
  - All 4 tracks vertex fit $\chi^2/NDF < 3.0$ 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
- **$J/\psi \to \mu^+ + \mu^-$ candidates selection**
  - Vertex fit χ^2 / NDF < 10
- **3 invariant mass windows for both muons in barrel (BB), end-cap (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 retains 99.8 % of the signal

$B_s \to J/\psi\,\phi$: flavour tagging

- Identifying the charge of a muon through the semi-leptonic decay of the B meson provides strong power of separation
- The $b \to \mu$ transitions are diluted through neutral B meson oscillations, as well as by cascade decays $b \to c \to \mu$ which can alter the sign of the muon relative to the one coming from direct semi-leptonic decays $b \to \mu$
- The separation power of tag muons can be enhanced by
  - Considering a weighted sum of the charge of the tracks in a cone around the muon

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

  - Considering a weighted sum of charged tracks associated to the opposite side B meson

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

- Probability to tag a signal event as b-bar

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

$$P(\bar{B}|Q) = 1 - P(Q|B)$$

$B_s \to J/\psi\,\phi$: PDF

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

- N is the number of selected candidates
- w_i is a weighting factor to account for the trigger efficiency,
- f_s is the fraction of signal candidates
- f_{B0} is the fraction of B^0 mesons mis-identified as B_s^0 candidates calculated relative to the number of signal events; this parameter is fixed in the likelihood fit.
- The mass m_i, the proper decay time t_i and the decay angles Ω_i are the values measured from the data for each event i. F_s, F_{B0} and F_{bkg} are the probability density functions (PDF) modelling the signal, the specific B^0 background and the other background distributions, respectively.

$B_s \to J/\psi\,\phi$: signal PDF

Tagging probability term

Triple Gaussian

Angular sculpting term

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

Gamma functions

Joint distribution for the decay time t and the transversity angles Ω :

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

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

$B_s \to J/\psi\,\phi$: background PDF

$$\mathscr{F}_{\rm bkg}(m_i, t_i, \Omega_i) = P_{\rm b}(m_i) \cdot P_{\rm b}(t_i|\sigma_{t_i}) \cdot P_{\rm b}(\theta_T) \cdot P_{\rm b}(\varphi_T) \cdot P_{\rm b}(\psi_T) \cdot P_{\rm b}(\sigma_{t_i}) \cdot P_{\rm b}(p_{{\rm T}i})$$

Proper decay time → Gaussian distribution, two positive exponentials (fraction of longer-lived backgrounds with non-prompt J/ψ combined with hadrons from PV or from B/D hadron in the same event) and a negative exponential (events with poor vertex resolution), smeared with the same resolution function as the signal decay time-dependence.

Shapes of the background angular distributions arise from detector and kinematic sculpting effects → described by Legendre polynomial functions

$$Y_l^m(\cos\theta_T) = \sqrt{(2l+1)/(4\pi)}\,\sqrt{(l-m)!/(l+m)!}\,P_l^m(\cos\theta)$$

$$P_k(x) = \frac{1}{2^k k!}\frac{d^k}{dx^k}(x^2-1)^k$$

$$\mathscr{F}_{\rm bkg}(\theta_T, \Psi_T, \phi_T) = \sum_{k=0}^{6}\sum_{l=0}^{6}\sum_{m=-l}^{l} \begin{cases} a_i \sqrt{2} Y_l^m(\theta_T)\cos(m\phi_T) P_k(\cos\Psi_T) & \text{where } m>0 \\ a_i \sqrt{2} Y_l^{-m}(\theta_T)\sin(m\phi_T) P_k(\cos\Psi_T) & \text{where } m<0 \\ a_i \sqrt{2} Y_l^0(\theta_T) P_k(\cos\Psi_T) & \text{where } m=0 \end{cases}$$

where the **factors a_i are adjusted to give the best fit to the angular distributions** for events in the B_s^0 mass sidebands. These parameters are then fixed in the main fit. The B_s^0 mass interval used for the background fit is between 5150 and 5650 MeV excluding the signal mass region $|(m(B_s) - 5366| < 110$ MeV. The background mass model, $P_b(m)$ is an exponential function with a constant term added.