LHCC Poster Session - CERN, 5 March 2014

Mixing and CP violation in the B_s system with ATLAS

1. Motivation

In the Standard Model *CP* violation is described by a phase in the CKM matrix. One of the manifestations of this complex phase is a phase shift between direct and mixing-mediated B_s decays producing a common final state. In the case of $B_s \rightarrow J/\psi\Phi$ this phase shift is predicted to be small: Φ_s = 0.0368 ± 0.0018 rad. New physics can enhance Φ_s whilst satisfying all existing constraints.

2. *CP* violation in B_s system

To distinguish between different *CP* violating effects three categories are defined:

- **CP violation in decay:** decay amplitudes of *B*-meson and anti *B*-meson are different
- **CP violation in mixing:** asymmetry in the particle antiparticle oscillations (*CP* eigenstates are not equivalent to the mass eigenstates)
- in the $B_s \rightarrow J/\psi\Phi$ channel the CP violation occurs in **interference of mixing and decay**:

$$\begin{tikzcd} B_s \arrow[rr] \arrow[dr] & & J/\psi\Phi \\ & \overline{B_s} \arrow[ur] & \end{tikzcd} \quad \text{or} \quad \begin{tikzcd} \overline{B_s} \arrow[rr] \arrow[dr] & & J/\psi\Phi \\ & B_s \arrow[ur] & \end{tikzcd}$$

4. Flavour tagging

- inclusion of the B_s meson flavor at production enhances the fit sensitivity to Φ_s
- initial flavour of (neutral) B_s can be inferred using the other *B*-meson, typically produced in the event (Opposite-Side Tagging)
- calibration by decays of $B^{\pm} \rightarrow J/\psi K^{\pm}$ from the entire 2011 run period (same data quality selections)

Muon tagging:
- use semi-leptonic decay of the *B*-meson
- combined and segment-tagged muons are used (*)
- momentum weighed charge of muon and tracks around
- diluted through $b \rightarrow c \rightarrow \mu$, but even so it has good separation power

Jet-charge tagging:
- used if the additional muon is absent
- momentum-weighted track-charge in jet

(*) *Combined muons* have a full track in the muon spectrometer that is matched to a full track in the inner detector.
Segment tagged muons have a full track in the inner detector that is matched to track segments in the muon spectrometer.

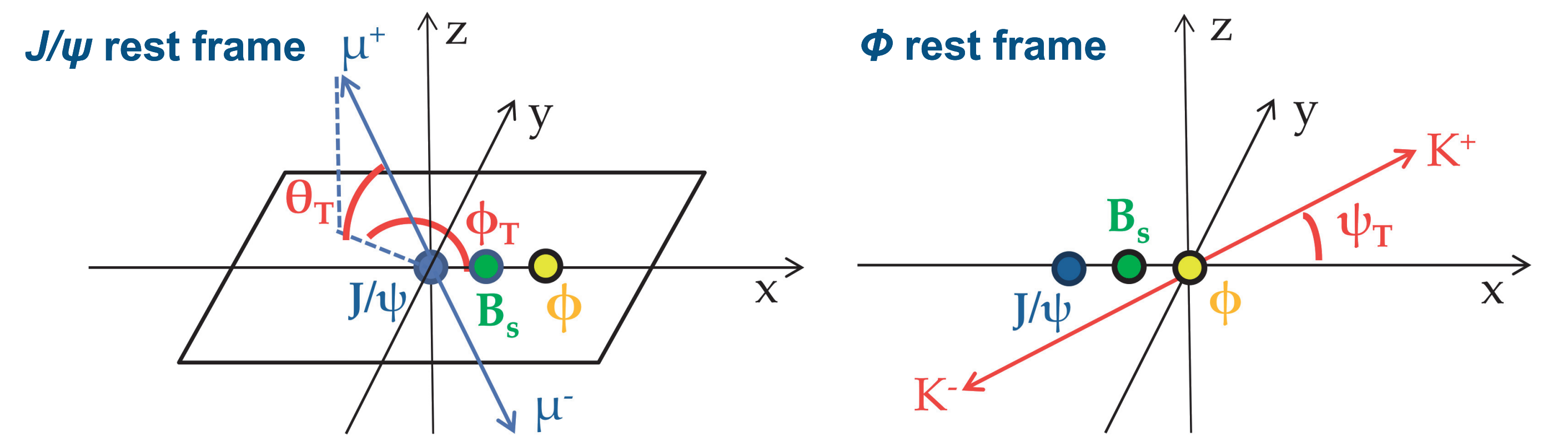
Tagging performance for the different tagging methods (statistical uncertainties only):

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

Initial flavour is expressed as probability that an event has a signal decay containing a $\overline{b}$ quark.

5. Angular analysis

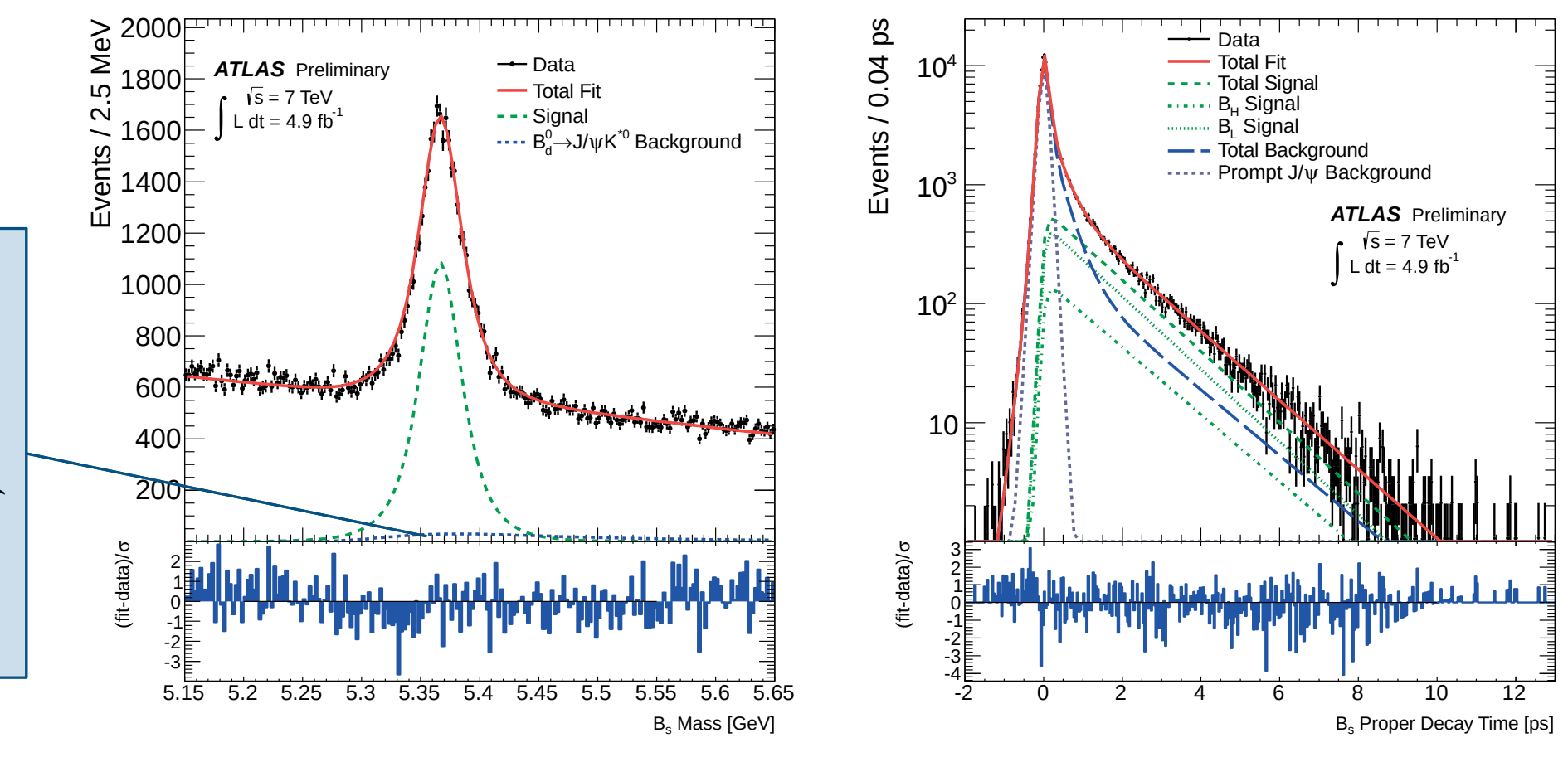
While the initial *B*-meson is a pseudoscalar, final-state particles are vectors. This results in an admixture of *CP*-odd and *CP*-even final states, with orbital angular momentum *L* = 0, 1 or 2. The *CP* states are separated statistically through the study of the distribution of the angular variables of the final state as a function of the B_s lifetime. This is performed through a combined lifetime-angular event-by-event fit.



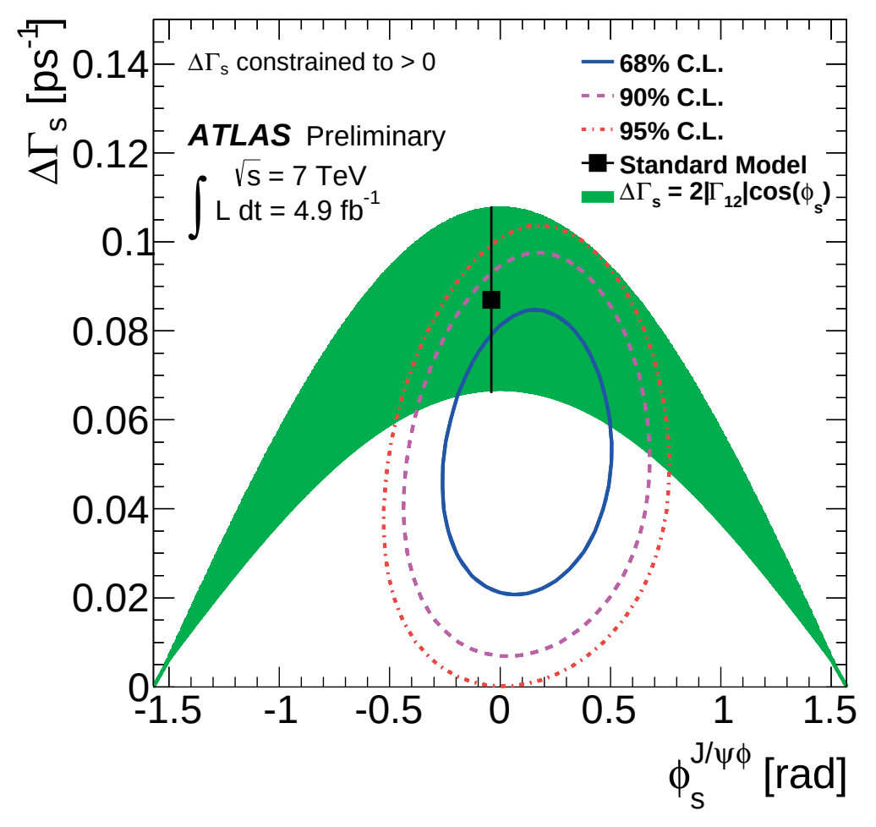
8. Fit projections and Φ_s - $\Delta\Gamma$ contour plot

Mass and lifetime:

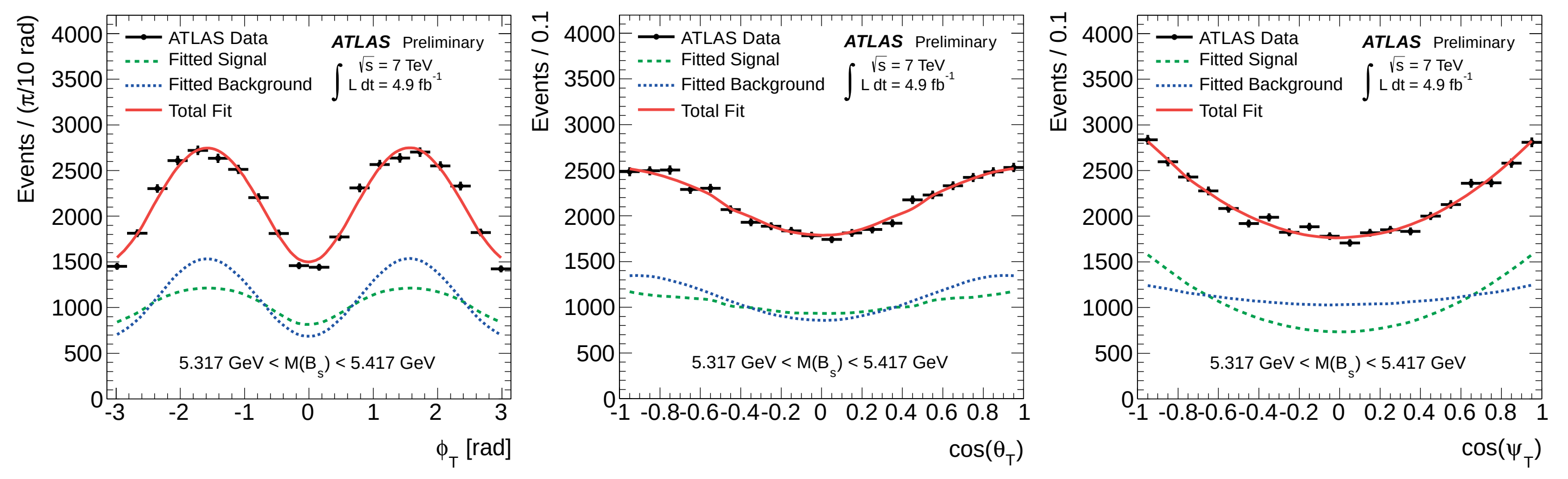
B_d background only (combinatorial background not shown)



Φ_s - $\Delta\Gamma$:



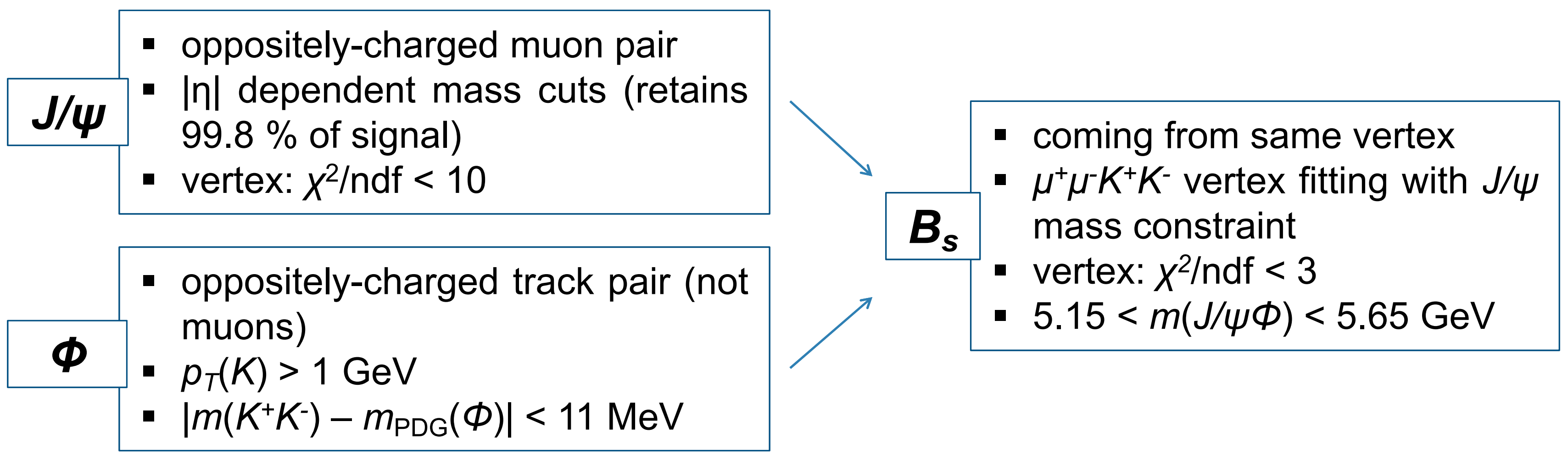
Transversity angles between final-state particles:



3. Used data and candidate selection

- 2011 data, 4.9 fb^{-1} of 7 TeV proton-proton collisions
- single and di-muon triggers based on the identification of $J/\psi \rightarrow \mu^+\mu^-$ decays with muon thresholds as low as 4 GeV

Offline candidate reconstruction:



J/ψ
- oppositely-charged muon pair
- |η| dependent mass cuts (retains 99.8 % of signal)
- vertex: χ^2/ndf < 10

Φ
- oppositely-charged track pair (not muons)
- $p_T(K)$ > 1 GeV
- $|m(K^+K^-) - m_{PDG}(\Phi)|$ < 11 MeV

B_s
- coming from same vertex
- $\mu^+\mu^-K^+K^-$ vertex fitting with J/ψ mass constraint
- vertex: χ^2/ndf < 3
- 5.15 < $m(J/\psi\Phi)$ < 5.65 GeV

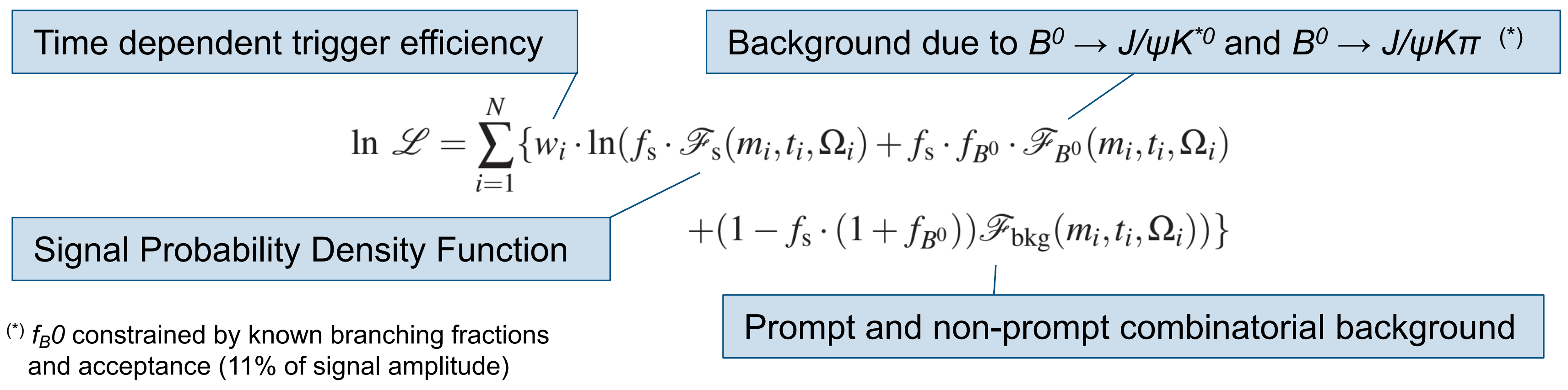
- in total 131k B_s candidates were collected and used in the analysis

Monte Carlo:
- 12 million $B_s \rightarrow J/\psi\Phi$ events
- background decay $B_d \rightarrow J/\psi K^{0*}$ (these events can be mis-reconstructed as $B_s \rightarrow J/\psi\Phi$)
- more general backgrounds $bb \rightarrow J/\psi X$ and $pp \rightarrow J/\psi X$

6. Fitting model

An unbinned maximum likelihood fit was performed, using these per-candidate variables:
- B_s mass m_i and proper decay time t_i and their uncertainties
- 3 angles between final-state particles in transversity basis $\Omega_i(\theta_{Ti}, \Phi_{Ti}, \psi_{Ti})$
- B_s momentum p_{Ti}
- B_s tag probability and tagging method

Fit determines 9 physics variables that describe $B_s \rightarrow J/\psi\Phi$ and S-wave ($B_s \rightarrow J/\psi K^+K^-$ (or f_0)) component: $\Delta\Gamma$, Φ_s, Γ_s, $|A_0(0)|^2$, $|A_{||}(0)|^2$, $|A_S(0)|^2$, $\delta_{||}$, $\delta_{\perp}$, δ_S



Time dependent trigger efficiency

Background due to $B^0 \rightarrow J/\psi K^{*0}$ and $B^0 \rightarrow J/\psi K\pi$ (*)

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

Signal Probability Density Function

Prompt and non-prompt combinatorial background

(*) f_B0 constrained by known branching fractions and acceptance (11% of signal amplitude)

Tag probabilities for the signal and background are different and since the background cannot be factorized out, extra PDF terms are included into account.

7. Systematic uncertainties

Effect of residual misalignment (studied in signal MC)

Uncertainty in the relative fraction of B_d background (contaminations from $B_d \rightarrow J/\psi K^{0*}$ and $B_d \rightarrow J/\psi K\pi$ events mis-reconstructed as $B_s \rightarrow J/\psi\Phi$)

Uncertainty in the calibration of the tag probability

Uncertainties of fit model derived in pseudo-experiment studies

	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

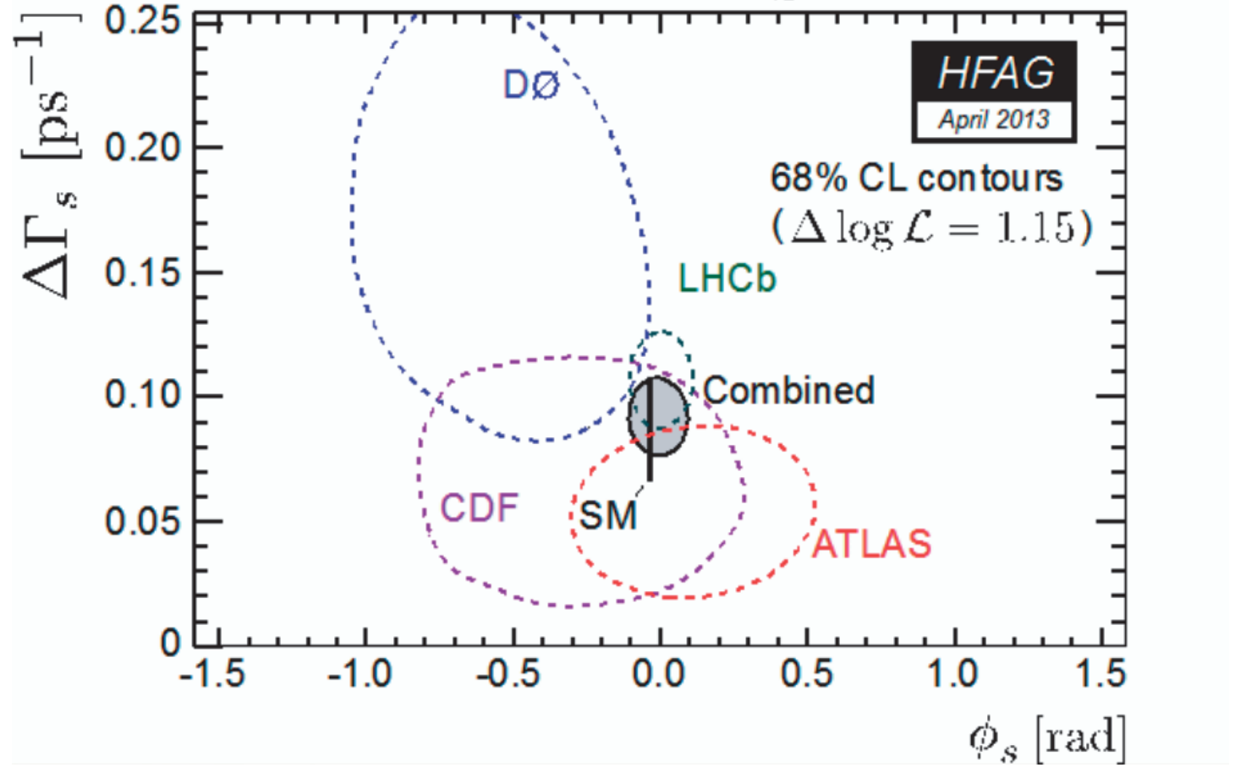
9. Results

Since the PDF describing the $B_s \rightarrow J/\psi\Phi$ decay is invariant under the transformations (Φ_s, $\Delta\Gamma_s$, $\delta_{\perp}$, $\delta_{||}$) → (π − Φ_s, −$\Delta\Gamma_s$, π − $\delta_{\perp}$, 2π − $\delta_{||}$), we consider only solutions with positive $\Delta\Gamma_s$ (according to other experiments).

- 22,670 ± 150 signal B_s from fit
- Φ_s and other parameters are consistent with the Standard Model prediction
- S-wave amplitude is consistent with 0

$$\begin{aligned} \phi_s &= 0.12 \pm 0.25\ (\text{stat.}) \pm 0.11\ (\text{syst.})\ \text{rad} \\ \Delta\Gamma_s &= 0.053 \pm 0.021\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{ps}^{-1} \\ \Gamma_s &= 0.677 \pm 0.007\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1} \\ |A_0(0)|^2 &= 0.529 \pm 0.006\ (\text{stat.}) \pm 0.011\ (\text{syst.}) \\ |A_{\parallel}(0)|^2 &= 0.220 \pm 0.008\ (\text{stat.}) \pm 0.009\ (\text{syst.}) \\ \delta_{\perp} &= 3.89 \pm 0.46\ (\text{stat.}) \pm 0.13\ (\text{syst.})\ \text{rad} \end{aligned}$$

Comparison with other experiments



Reference: ATLAS-CONF-2013-039

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