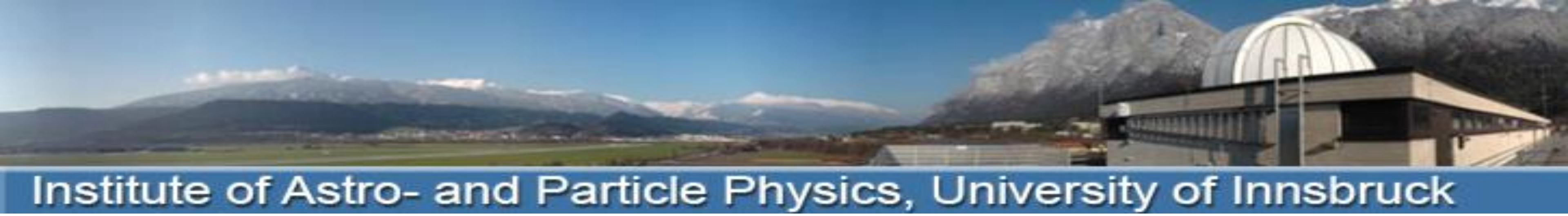


Measurement of CP violation with the ATLAS experiment

"Determination of ϕ_s and $\Delta\Gamma_s$ from the Decay $B_S \rightarrow J/\psi\ \phi$"

E. Kneringer – University of Innsbruck
and member of the ATLAS collaboration

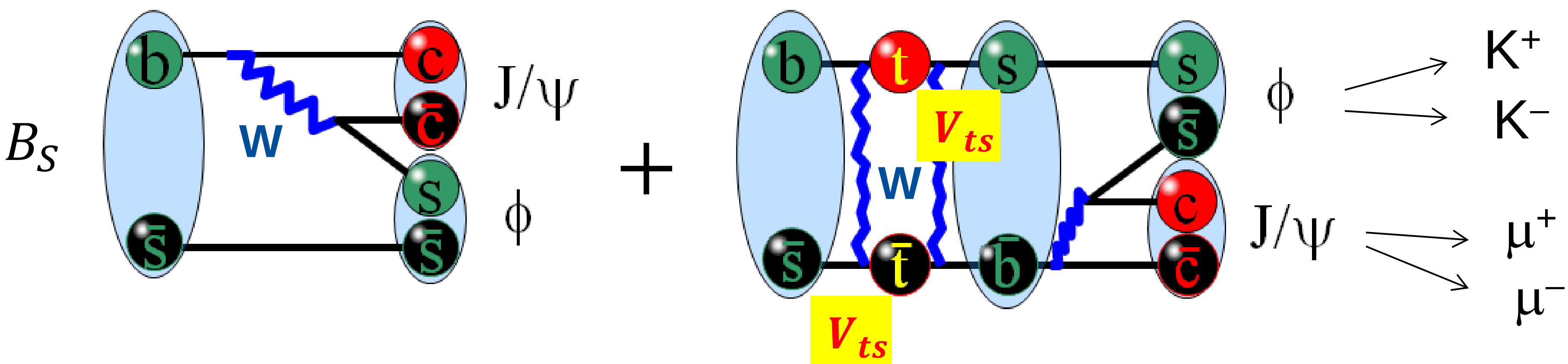
ÖPG/SPS meeting, 28/08/2019, Zürich

The decay $B_s \to J/\psi\, \phi$ and ϕ_s

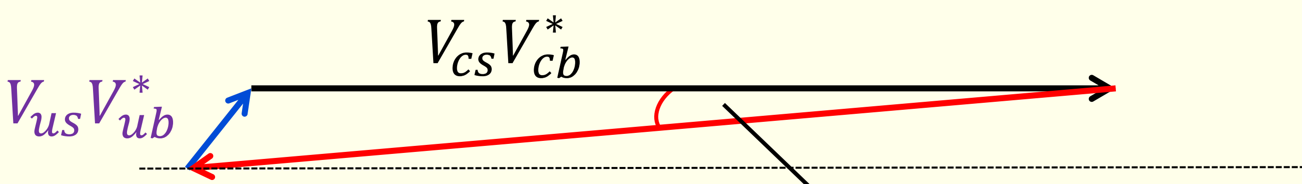
- CP violation in this decay arises from the quantum interference of these two diagrams:

tree diagram

box diagram + tree diagram



Unitarity triangle of CKM matrix: $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$



$\beta_s = \arg[-V_{ts}\cdot 1] = O(1°)$

Experimenters prefer: $\boxed{\phi_s \cong -2\,\beta_s}$

SM prediction: $\phi_s = -2.1°$ (= −37 ± 1 mrad)

Phenomenology of the $B_S, \overline{B}_S$ system

- Mass eigenstates B_L, B_H are linear combinations of flavor eigenstates $B_S, \overline{B}_S$:

$$\begin{aligned} B_L &= pB_S + q\overline{B}_S \\ B_H &= pB_S - q\overline{B}_S \end{aligned}$$

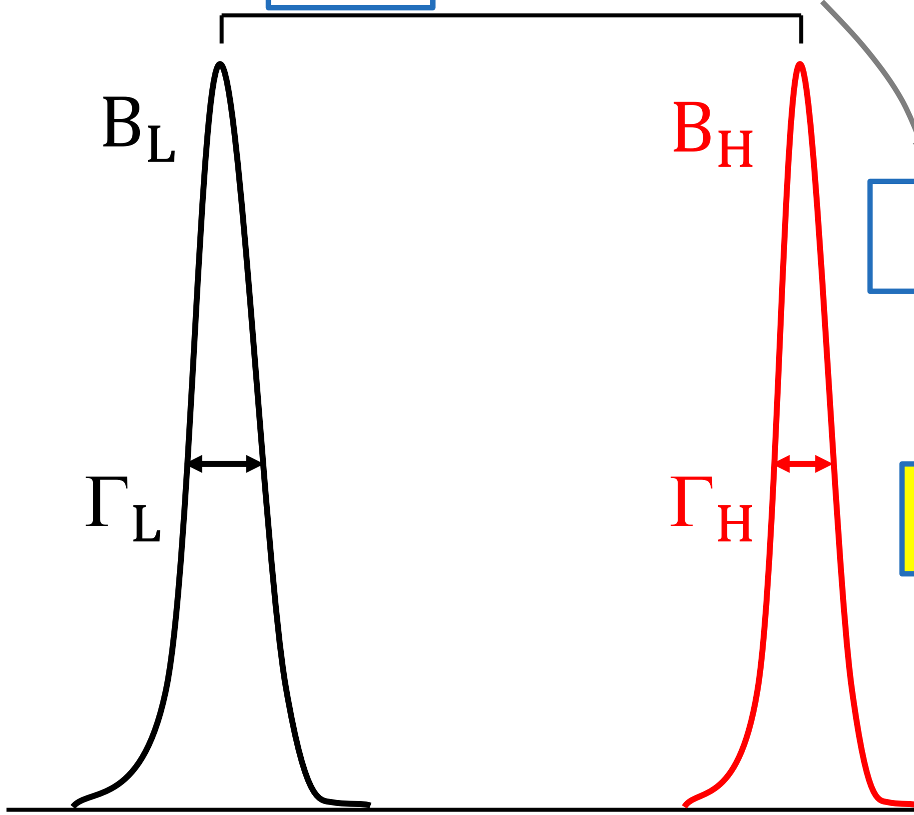
$$\boxed{\Delta m_s} = 17.8\ \mathrm{ps}^{-1} \approx 0.01\ \mathrm{eV}$$

factor 25

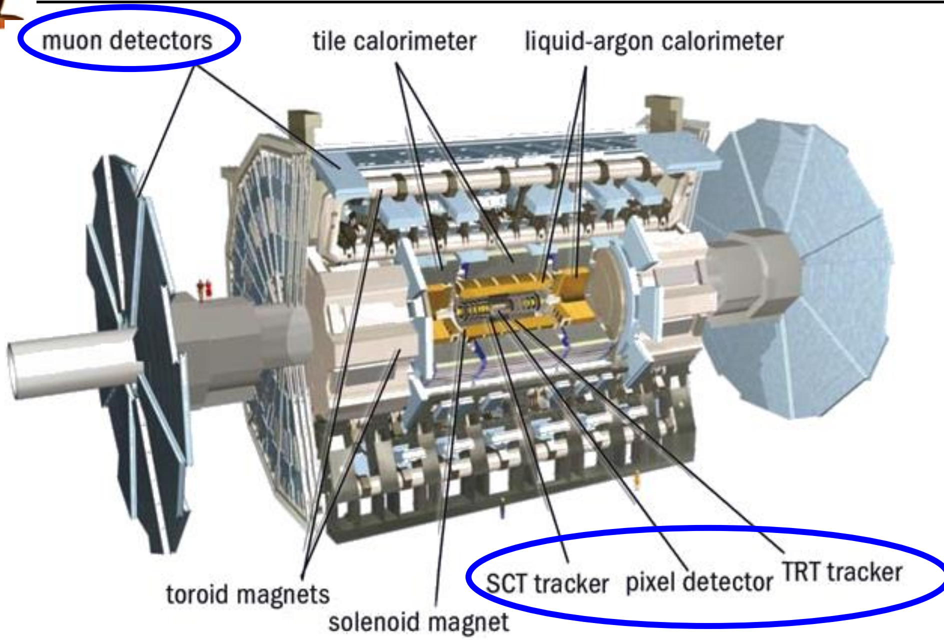
$$\boxed{\Gamma_s} = \tfrac{1}{2}(\overleftrightarrow{\Gamma_L} + \overleftrightarrow{\Gamma_H}) \approx \overleftrightarrow{0.7}\ \mathrm{ps}^{-1}$$

factor 10

$$\boxed{\Delta\Gamma_s} = \overleftrightarrow{\Gamma_L} - \overleftrightarrow{\Gamma_H} \approx 0.\overleftrightarrow{0}7\ \mathrm{ps}^{-1}$$



The ATLAS experiment

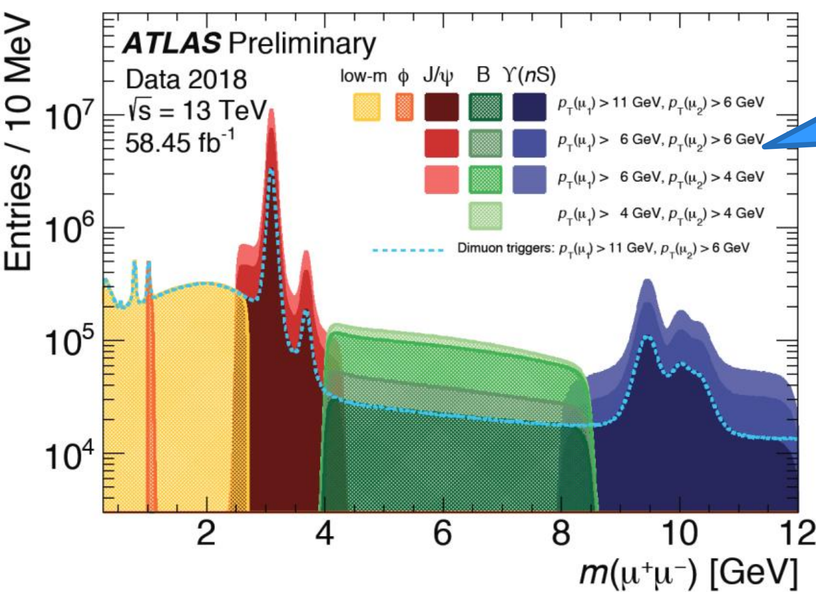


The ATLAS collaboration

38 Countries
183 Institutions
~2900 Scientific Authors

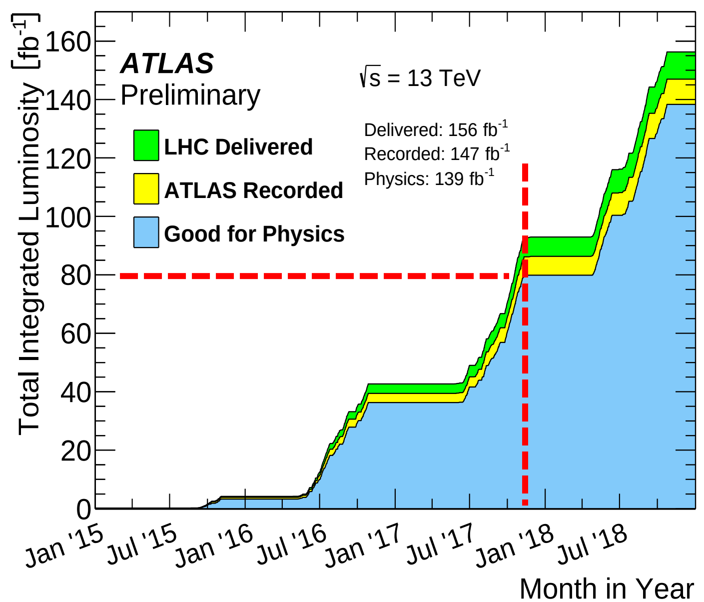
data recorded

run 1 : 26 fb^{-1}
run 2 : 147 fb^{-1}

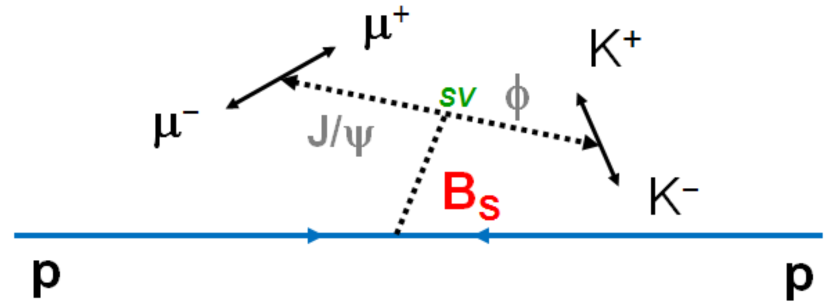


muon triggers

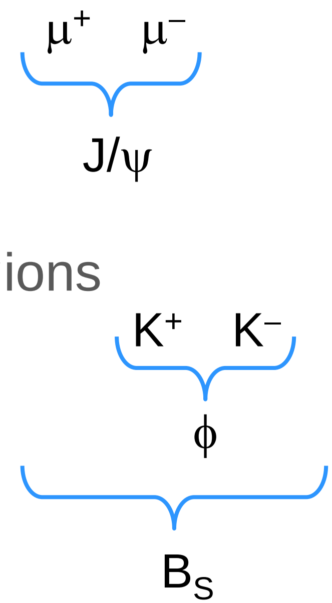
← run 2 →



The run 2 measurement



1. Trigger
   - using 80.5 fb^{-1} of data collected 2015-2017
   - events selected by various **muon triggers**
     - p_T threshold for muons: 4 – 10 GeV

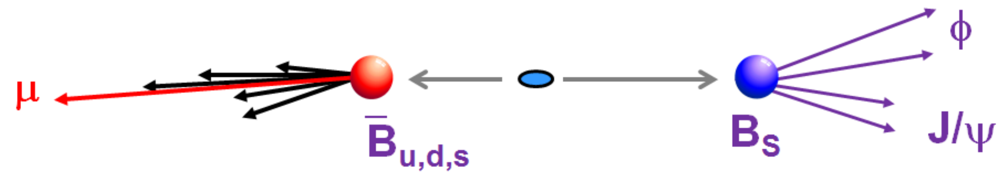


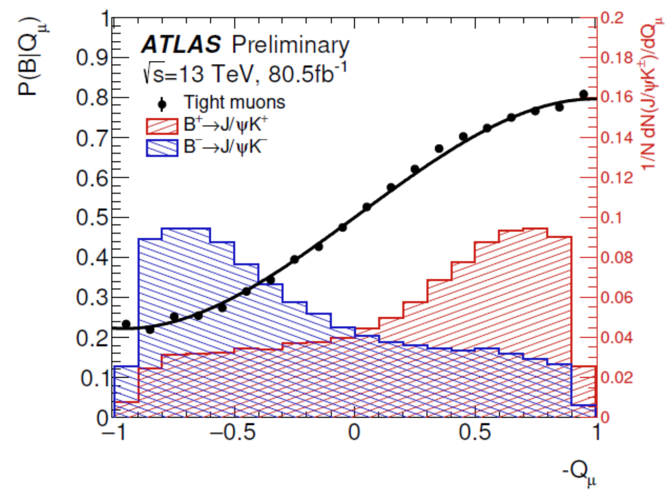
2. Selection cuts (tracks + event)
   - different $J/\psi(\mu^+\mu^-)$ **mass windows** for barrel/endcap regions
     - since mass resolution depends on $|\eta|$ of muons
   - $\phi(K^+K^-)$ invariant **mass window** (22 MeV)
     - p_T (kaons) > 1 GeV
   - B-meson **secondary vertex fit**: χ^2/dof < 3

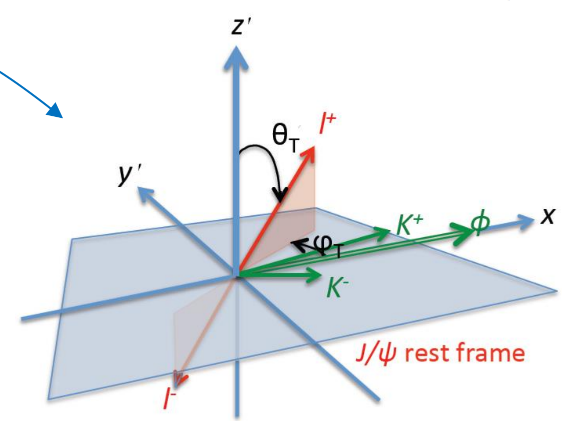
     gives → mass m_i, proper decay time t_i (in transverse plane), angles
3. Acceptance calculated on large samples of signal and **background** Monte Carlo events
   - e.g. $B^0 \rightarrow J/\psi\ K^{0*}$, $bb \rightarrow J/\psi\ X$, $pp \rightarrow J/\psi\ X$

More on the analysis

- B-charge flavor tagging
  - Identification of B_S flavor at production vertex through opposite side tagging (OST)
  - Self tagging calibration sample
    - $B^{\pm} \rightarrow J/\psi\ K^{\pm}$
- Measured kinematic variables
  - $(m,\ \sigma_m),\ (t,\ \sigma_t)$
  - decay angles $(\psi_T, \theta_T, \phi_T) \equiv \Omega$ in the transversity basis
- Unbinned Maximum Likelihood fit
  - extract 9 physics parameters describing the neutral B_S system
    - $\phi_S,\ \Delta\Gamma_S,\ \Gamma_S$
    - transversity amplitudes $|A_0|, |A_{||}|, |A_S|$
    - strong phases $\delta_{\perp}, \delta_{||}, \delta_S$

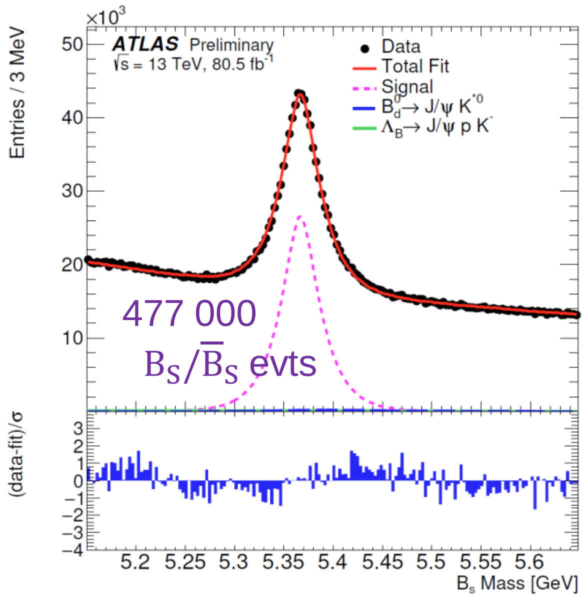




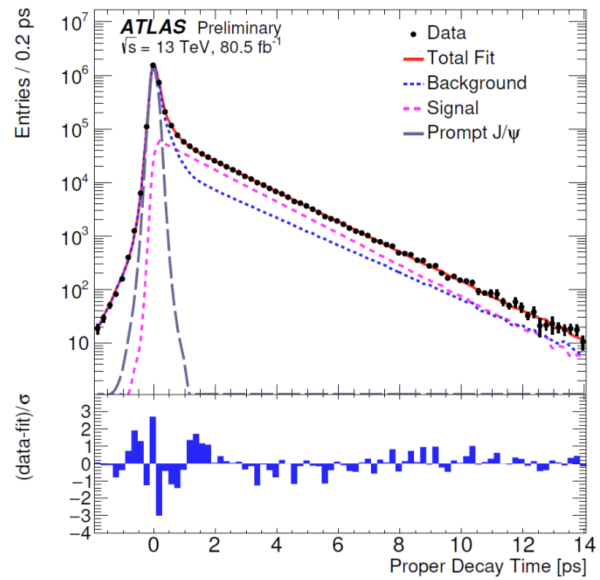


Result of the fit: fit projections

B_S meson mass

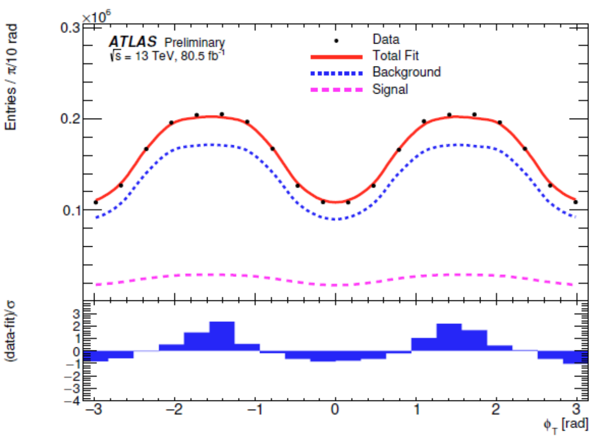


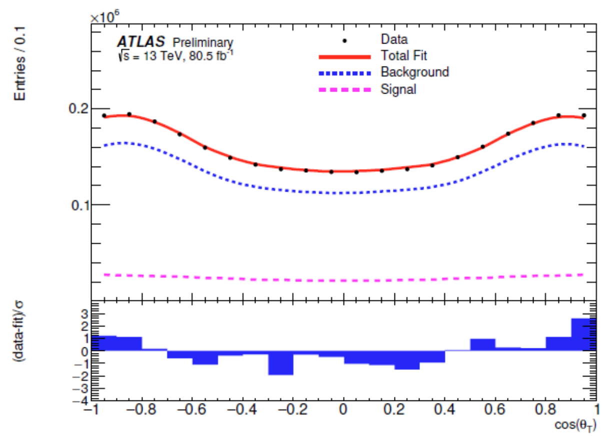
proper decay time

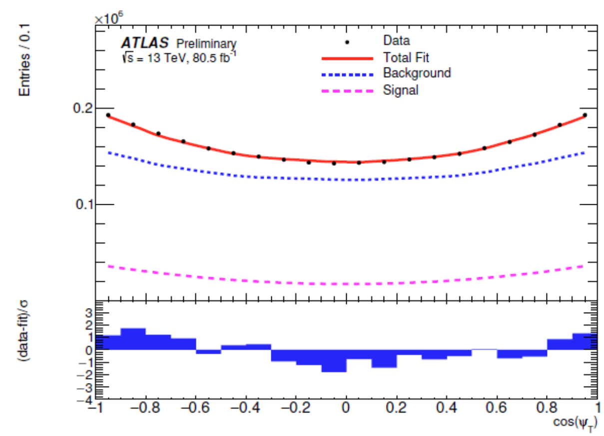


Fit range chosen such as to have enough background events in side bands to allow a high precision determination of background events properties.

3 angles $(\psi_T, \theta_T, \phi_T)$







Systematic uncertainties

- They are calculated using **different techniques**, including
  - changes in detector simulation (alignment),
  - studies based on data (efficiencies),
  - Monte Carlo pseudo experiments (mass models, fit model)
  - and variations in analysis methods and assumptions.

	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	1.7×10^{-2}	0.4×10^{-3}	0.3×10^{-3}	0.2×10^{-3}	0.2×10^{-3}	2.3×10^{-3}	1.9×10^{-2}	2.2×10^{-2}	2.2×10^{-3}
Acceptance	0.7×10^{-3}	$<10^{-4}$	$<10^{-4}$	0.8×10^{-3}	0.7×10^{-3}	2.4×10^{-3}	3.3×10^{-2}	1.4×10^{-2}	2.6×10^{-3}
ID alignment	0.7×10^{-3}	0.1×10^{-3}	0.5×10^{-3}	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	1.0×10^{-2}	7.2×10^{-3}	$<10^{-4}$
S–wave phase	0.2×10^{-3}	$<10^{-4}$	$<10^{-4}$	0.3×10^{-3}	$<10^{-4}$	0.3×10^{-3}	1.1×10^{-2}	2.1×10^{-2}	8.3×10^{-3}
Background angles model:									
Choice of fit function	1.8×10^{-3}	0.8×10^{-3}	$<10^{-4}$	1.4×10^{-3}	0.7×10^{-3}	0.2×10^{-3}	8.5×10^{-2}	1.9×10^{-1}	1.8×10^{-3}
Choice of p_T bins	1.3×10^{-3}	0.5×10^{-3}	$<10^{-4}$	0.4×10^{-3}	0.5×10^{-3}	1.2×10^{-3}	1.5×10^{-3}	7.2×10^{-3}	1.0×10^{-3}
Choice of mass interval	0.4×10^{-3}	0.1×10^{-3}	0.1×10^{-3}	0.3×10^{-3}	0.3×10^{-3}	1.3×10^{-3}	4.4×10^{-3}	7.4×10^{-3}	2.3×10^{-3}
Dedicated backgrounds:									
B_d^0	2.3×10^{-3}	1.1×10^{-3}	$<10^{-4}$	0.2×10^{-3}	3.1×10^{-3}	1.4×10^{-3}	1.0×10^{-2}	2.3×10^{-2}	2.1×10^{-3}
Λ_b	1.6×10^{-3}	0.4×10^{-3}	0.2×10^{-3}	0.5×10^{-3}	1.2×10^{-3}	1.8×10^{-3}	1.4×10^{-2}	2.9×10^{-2}	0.8×10^{-3}
Fit model:									
Time res. sig frac	1.4×10^{-3}	1.1×10^{-3}	$<10^{-4}$	0.5×10^{-3}	0.6×10^{-3}	0.6×10^{-3}	1.2×10^{-2}	3.0×10^{-2}	0.4×10^{-3}
Time res. p_T bins	3.3×10^{-3}	1.4×10^{-3}	0.1×10^{-2}	$<10^{-4}$	$<10^{-4}$	0.5×10^{-3}	6.2×10^{-3}	5.2×10^{-3}	1.1×10^{-3}
Total	1.8×10^{-2}	0.2×10^{-2}	0.1×10^{-2}	0.2×10^{-2}	0.4×10^{-2}	0.4×10^{-2}	9.7×10^{-2}	2.0×10^{-1}	0.1×10^{-1}

Final results in numbers

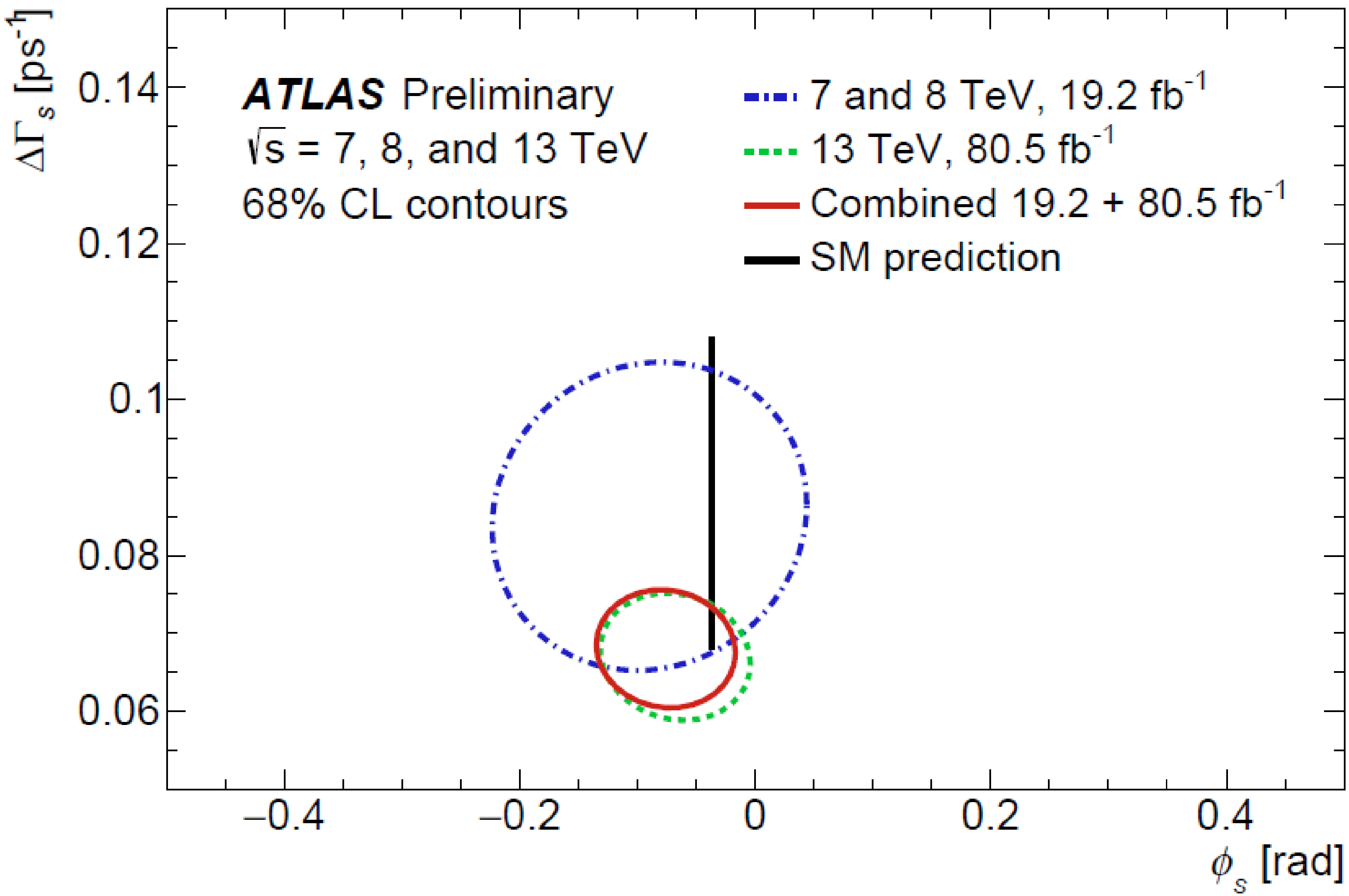
- Statistical error for ϕ_S rather large because of limited proper decay time resolution of ATLAS
  - Almost competitive with LHCb results

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	−0.076	0.034	0.019
$\Delta\Gamma_s$[ps^{-1}]	0.068	0.004	0.003
Γ_s[ps^{-1}]	0.669	0.001	0.001
$\|A_{\|\|}(0)\|^2$	0.220	0.002	0.002
$\|A_0(0)\|^2$	0.517	0.001	0.004
$\|A_S\|^2$	0.043	0.004	0.004
$\delta_\perp$ [rad]	3.075	0.096	0.091
$\delta_{\|\|}$ [rad]	3.295	0.079	0.202
$\delta_\perp - \delta_S$ [rad]	−0.216	0.037	0.010

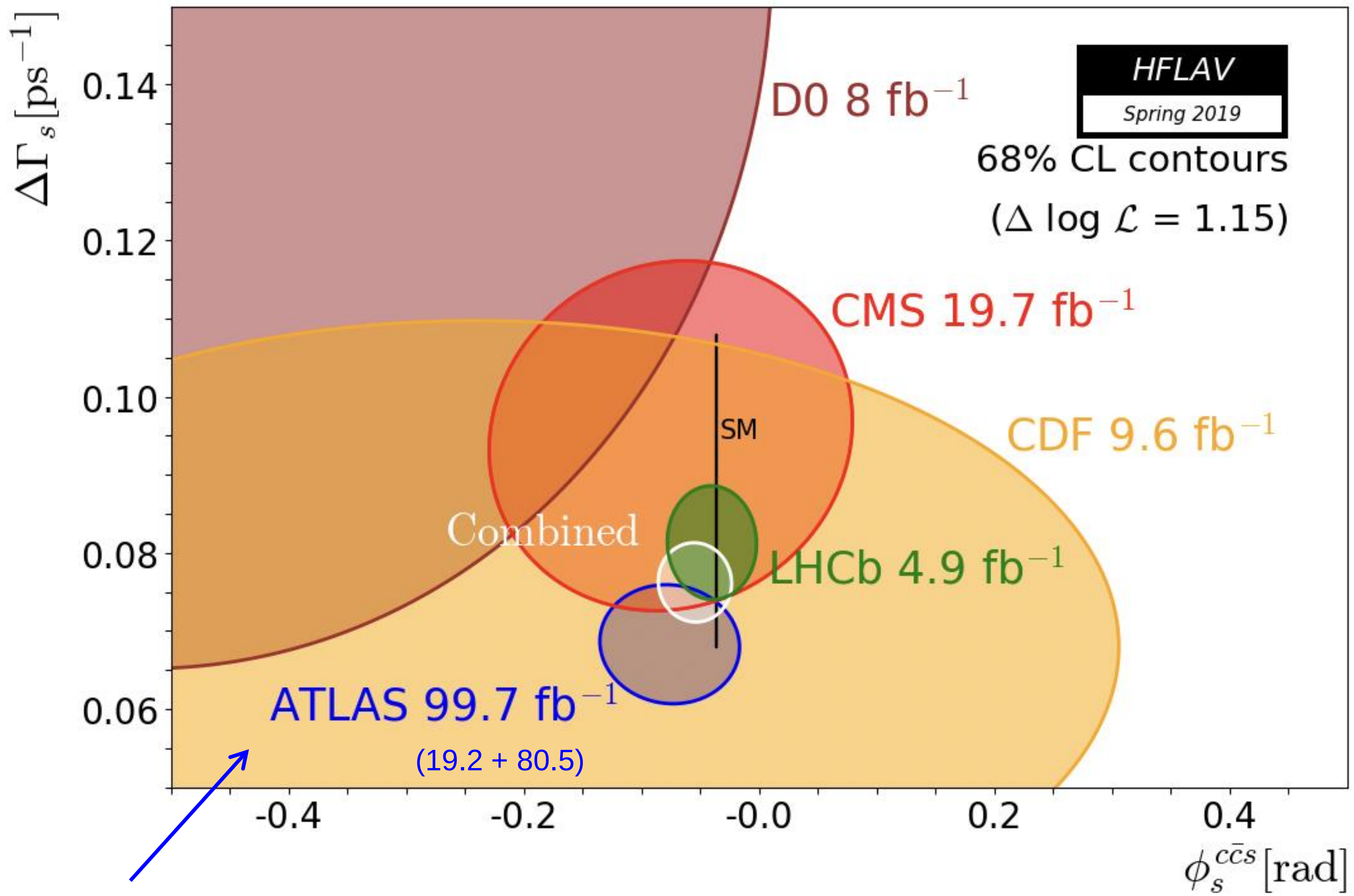
Combination: run 1 + run 2 (57%)

$\phi_S - \Delta\Gamma_S$ plane

ATLAS-CONF-2019-009

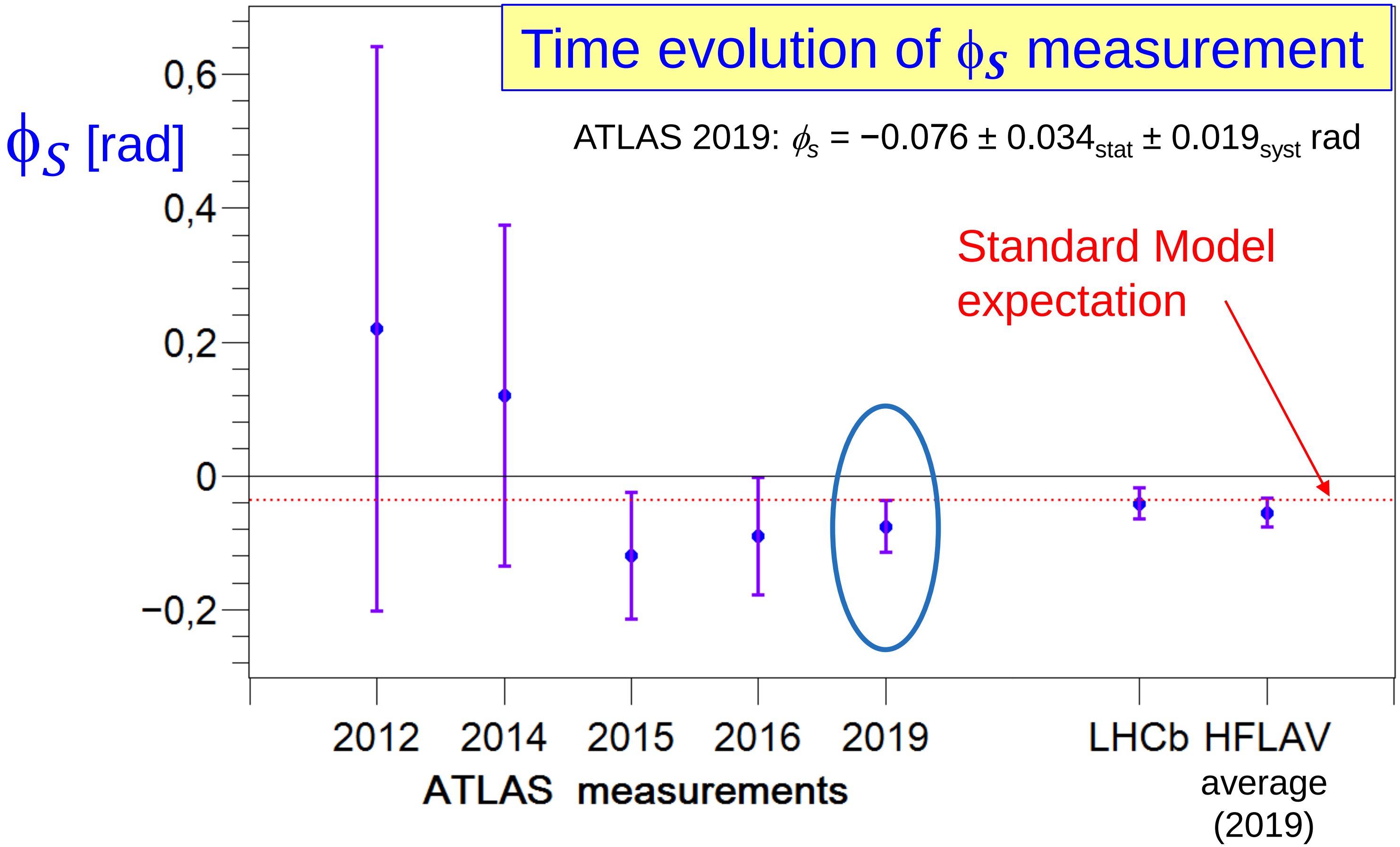


Comparison with other experiments



- New ATLAS result consistent with other experiments and SM prediction.

Summary and Outlook

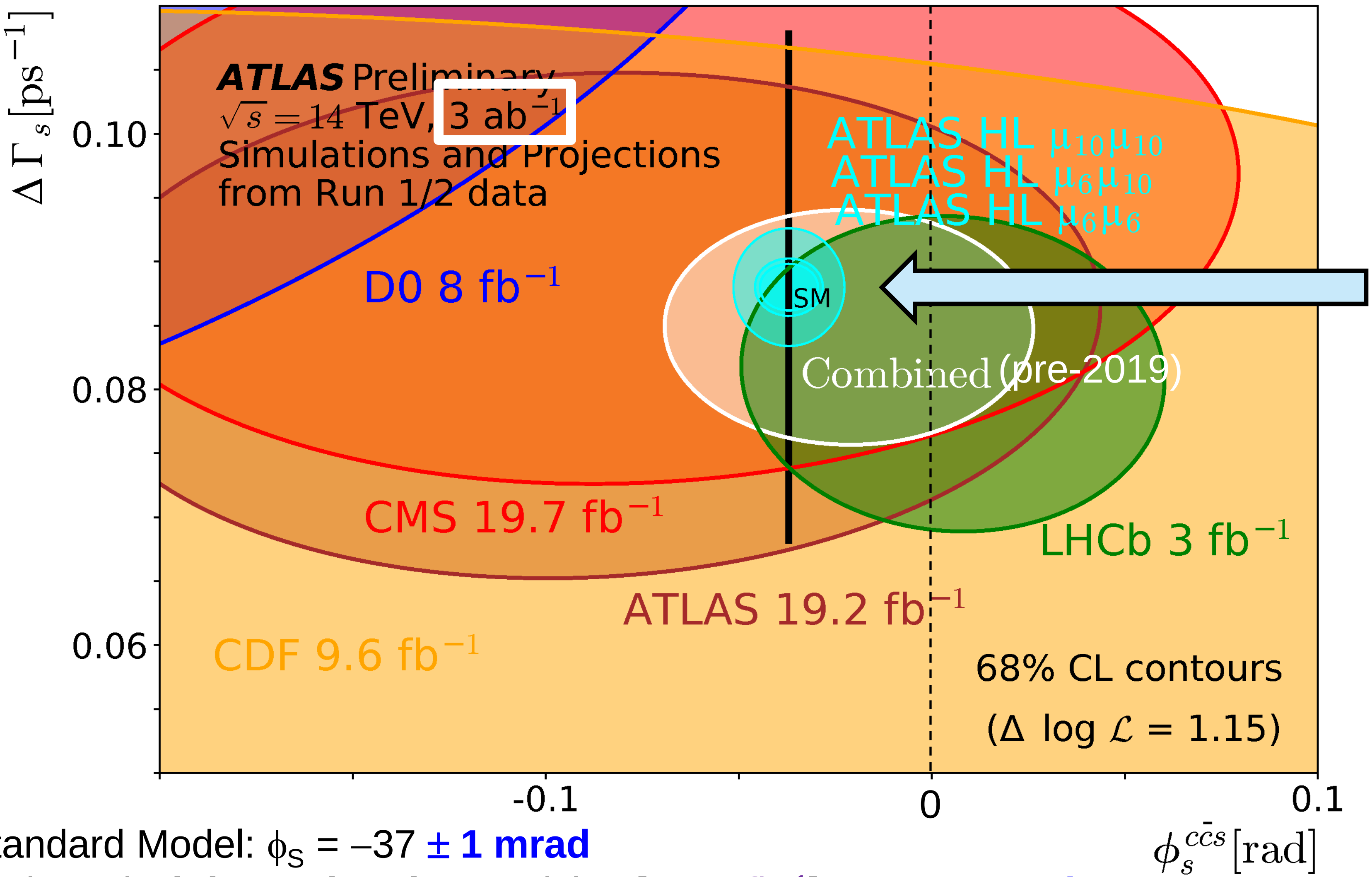


- The analysis will continue with additional data from last year (2018) and improvements in tagging.
- **Precision** expected by ATLAS at High-Luminosity-LHC: **5 to 10 mrad** (compared to 39 mrad now).

backup slides

Future prospects

ATL-PHYS-PUB-2018-041



Standard Model: ϕ_S = –37 **± 1 mrad**
Projected **High Luminosity** precision [3000 fb^{-1}]: **5 to 10 mrad**
(depending on various trigger scenarios)

Summary in numbers

- ATLAS has measured ϕ_s with the full run-1 (19.2/fb) and partial run-2 (80.5/fb) datasets, combining data at 7, 8 and 13 TeV.
  - The main results are consistent with Standard Model predictions as well as measurements from other experiments.

$$
\begin{aligned}
\phi_s &= -0.076 \pm 0.034\,(\text{stat.}) \pm 0.019\,(\text{syst.})\ \text{rad} \\
\Delta\Gamma_s &= 0.068 \pm 0.004\,(\text{stat.}) \pm 0.003\,(\text{syst.})\ \text{ps}^{-1} \\
\Gamma_s &= 0.669 \pm 0.001\,(\text{stat.}) \pm 0.001\,(\text{syst.})\ \text{ps}^{-1}
\end{aligned}
$$

- The analysis will continue with additional data from 2018 and improvements in tagging.

Construction of the Likelihood function $\mathcal{L}$

- Measured variables ($vars$)
  - (m_i, σ_{m_i}), (t_i, σ_{t_i}), Ω_i
  - w_i = trigger selection efficiency re-weighting factor (~ 1% effect)
  - set of nuisance parameters to describe background
- 27 parameters in the full fit ($pars$)
  - 9 physics parameters
    - 3 parameters of the B_s,$\bar{B}_s$ system: ϕ_s, $\Delta\Gamma_s$, Γ_s (not Δm_s)
    - 3 transversity amplitudes: $|A_0|$, $|A_{||}|$, $|A_S|$ ($A_\perp$ from normalization)
    - 3 strong phases: $\delta_\perp$, $\delta_{||}$, δ_S
  - signal fraction $f_s \rightarrow$ number of signal events
  - parameters describing various distributions
    - the J/ψ signal mass distribution, angular background distributions, estimated decay time uncertainty distributions for signal and background events, scale factors

Unbinned Maximum Likelihood fit:

max $\mathcal{L}(pars; vars) \rightarrow$ best fit parameters

Angular and proper time distributions

- Differential decay rate $$\frac{d^4\Gamma}{dt\ d\Omega} = \sum_{k=1}^{10} \mathcal{O}^{(k)}(t) g^{(k)}(\theta_T, \psi_T, \varphi_T)$$

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

CP	polarization state
+1	long.
+1	trans.
−1	trans.

interference terms

Terms related to non-resonant and via the f_0 state K^+K^- production (S-wave) → small

Normalization: $|A_0(0)|^2 + |A_\parallel(0)|^2 + |A_\perp(0)|^2 = 1$
Each amplitude A_X comes with its strong phase δ_X.
Define strong phases relative to $A_0(0)$: choose $\delta_0 = 0$
→ 3 amplitudes + 3 strong phases = 6 parameters for the fit!

$\sin\phi_S \approx \phi_S$
$\cos\phi_S = 1 + O(\phi_S^2)$

New Physics in $B_S - \overline{B}_S$ mixing

- Would change the off-diagonal element M_{12} of the **mass matrix** (but not significantly affect the corresponding decay matrix element Γ_{12})
  - parametrization: $M_{12}^s \equiv M_{12}^{\mathrm{SM},s} \cdot \Delta_s, \qquad \Delta_s \equiv |\Delta_s| e^{i\phi_s^\Delta}.$
  - correction adds linearly to the weak phase, like in $\sin\left(\phi_s^{\mathrm{SM}} + \phi_s^\Delta\right)$
  - for small ϕ_S only contributes quadratically to $\Delta\Gamma_S$:
    $\Delta\Gamma_s = 2|\Gamma_{12}^s| \cos\left(\phi_s^{\mathrm{SM}} + \phi_s^\Delta\right)$
  - magnitude measurable through oscillation frequency:
    $\Delta M_s = \Delta M_s^{\mathrm{SM}} |\Delta_s|$