ATLAS measurements of CP violation and rare decays processes with beauty mesons.

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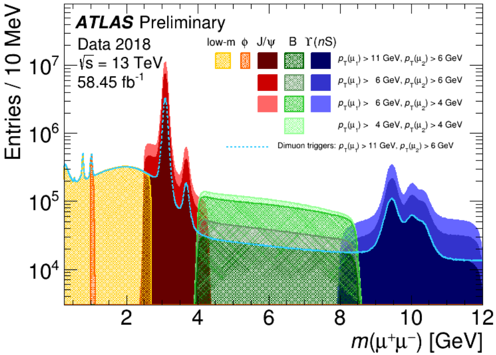
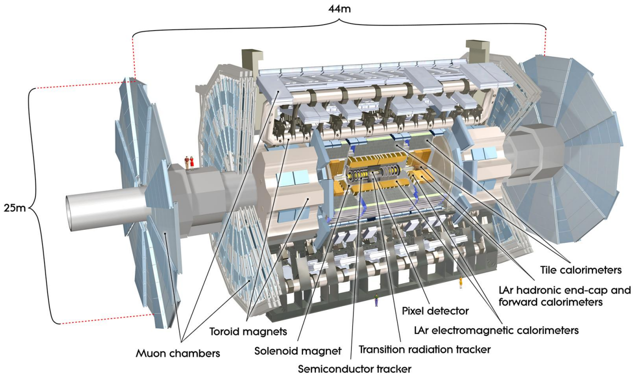
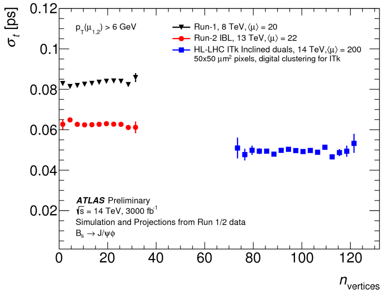
ATLAS data in B-physics analysis

- ATLAS has collected 139 fb^{-1} of data in Run 2, and 25 fb^{-1} in Run 1
- Focus mostly on final states with muons
- Typical triggers di-muons with p_T thresholds of either 4 GeV or 6 GeV (vary over run periods)
- Additional trigger selections are applied, e.g. on di-muon masses, targeting different analysis, as shown in Fig.





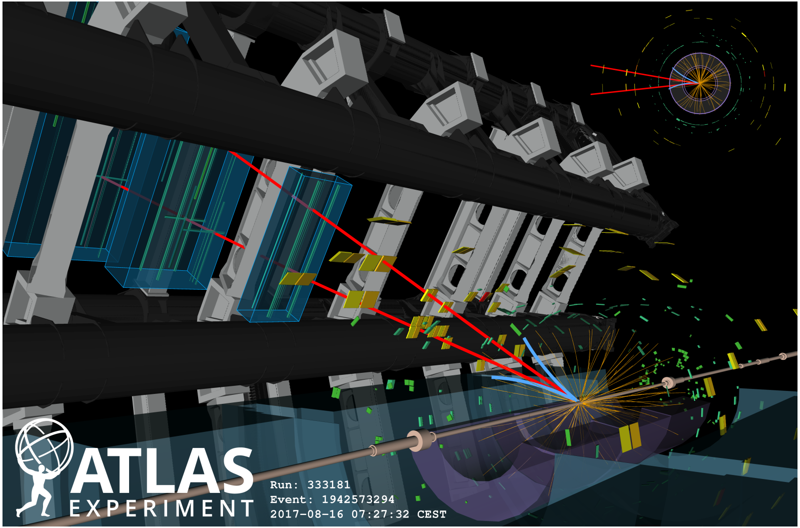


Time resolution of $B_s^0 \to J/\psi\phi$ for different numbers of reconstructed PV in the same bunch crossing.

- Inner Detector: PIX, SCT and TRT, $p_T > 0.4$ GeV, $|\eta| < 2.5$
  - Run2: new IBL 25% improvement of time resolution with respect to Run1.
  - Time, mass resolutions remain stable within increasing pileup in Run 2
- Muon Spectrometer: triggering ($|\eta| < 2.4$), precision tracking ($|\eta| < 2.7$)

CP violation in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

- Eur. Phys. J. C 81 (2021) 342, arXiv:2001.07115



Motivation

- $B_s^0 \to J/\psi\phi$ is used to measure CP-violation phase ϕ_s potentially sensitive to New Physics (NP)
- In SM ϕ_s is related to the CKM elements $\phi_s \simeq 2\arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$ and predicted with high precision
  - $\phi_s = -0.03696^{+0.00072}_{-0.00082}$ rad by CKMFitter group PhysRevD.91.073007
  - $\phi_s = -0.03700 \pm 0.00104$ rad according to UTfit Collaboration arXiv: hep-ph/0606167 [hep-ph].
- LHC combined 2021: $\phi_s = -0.050 \pm 0.019$ rad, consistent with SM, however SM precision still 20 times better - room for New physics.
- Other quantity related to B_s^0 mixing is $\Delta\Gamma_s = \Gamma_s^L - \Gamma_s^H$, Γ_s^L and Γ_s^H are the decay widths of the mass eigenstates. $\Delta\Gamma_s$ was calculated in SM arXiv:1912.07621v2 [hep-ph], 2020 and new experimental results are important to tighten uncertainties and eventually get sensitivity to NP

ATLAS data in this analysis

- Results presented here use $80.5\,\text{fb}^{-1}$ of 2015-2017 data, statistically combined with $19.2\,\text{fb}^{-1}$ Run1.
- Use $J/\psi \to \mu^+\mu^-$ triggers, with cuts on di-muon mass window. No low-limit cuts on L_{xy}, or on the impact parameter applied to avoid biasing B_s^0 proper-decay time
- Events selected for analysis contained $453\,570 \pm 740$ $B_s^0 \to J/\psi\phi$ signals.

- $B_s^0 \to J/\psi\phi$ = pseudoscalar to vector-vector
- Final state: admixture of *CP*-odd ($L = 1$) and *CP*-even ($L = 0, 2$) states
- Distinguishable through time-dependent angular analysis
- Non-resonant *S*-wave decay $B_s^0 \to J/\psi K^+K^-$ contribute to the final state
- Included in the differential decay rate due to interference with the $B_s^0 \to J/\psi(\mu^+\mu^-)\psi(K^+K^-)$ decay

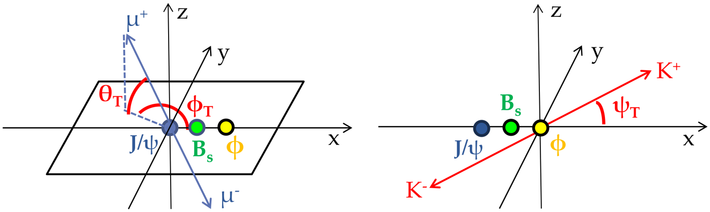


Figure: Angles between final state particles in transversity basis.

Mass-lifetime-angular fit

We perform unbinned maximum likelihood fit simultaneously for B_s^0 mass, decay time and the decay angles:

$$\begin{aligned}\ln\ \mathcal{L} = \sum_{i=1}^{N}\{ & w_i \cdot \ln(f_\mathrm{s} \cdot \mathcal{F}_\mathrm{s}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{\mathrm{T}_i}) \\ & + f_\mathrm{s} \cdot f_{B_d^0} \cdot \mathcal{F}_{B_d^0}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{\mathrm{T}_i}) \\ & + f_\mathrm{s} \cdot f_{\Lambda_b} \cdot \mathcal{F}_{\Lambda_b}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{\mathrm{T}_i}) \\ & + (1 - f_\mathrm{s} \cdot (1 + f_{B_d^0} + f_{\Lambda_b})) \cdot \mathcal{F}_\mathrm{bkg}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{\mathrm{T}_i}))\}\end{aligned}$$

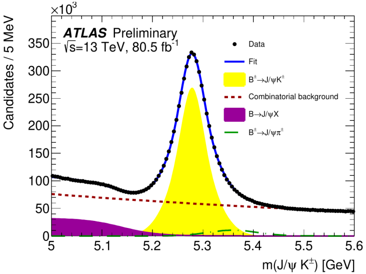
Physics parameters

- CPV phase ϕ_s
- Decay widths: $\Delta\Gamma_s$, Γ_s
- Decay amplitudes: $|A_0(0)|^2$, $|A_{\|}(0)|^2$, $\delta_{\|}$, $\delta_{\perp}$
- S-wave: $|A_S(0)|^2$, δ_S
- Δm_s fixed to PDG

Observables

- Basic observables : m_i, t_i, Ω_i
- Conditional observables per-candidate:
  - resolutions: σ_{m_i}, σ_{t_i}
  - tagging probability and method: $P(B|Q)$

- Opposite side tagging
- Use Muon or Electron
  - $b \to l$ transitions are clean tagging method
  - $b \to c \to l$ and neutral B-meson oscillations dilute the tagging
- Jet-Charge
  - information from tracks in b-tagged jet, when no lepton is found
- Calibration using $B^{\pm} \to J/\psi K^{\pm}$ data

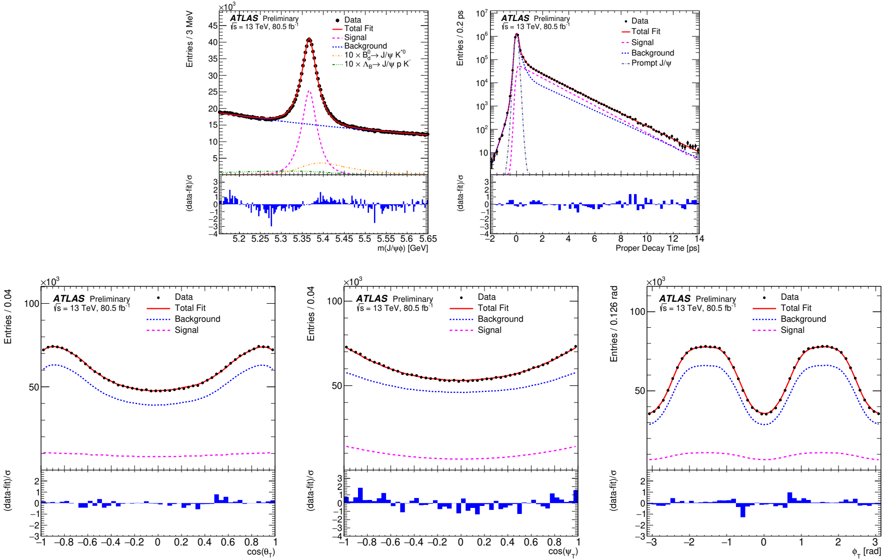


Inv. mass $B^{\pm} \to J/\psi K^{\pm}$. Data shown as points, overall fit result blue curve, other curves signal and background fits.

Tag method	Efficiency [%]	Effective Dilution [%]	Tagging Power [%]
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low-p_T muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	5.54 ± 0.01	20.4 ± 0.1	0.231 ± 0.005
Total	14.74 ± 0.02	33.4 ± 0.1	1.65 ± 0.01

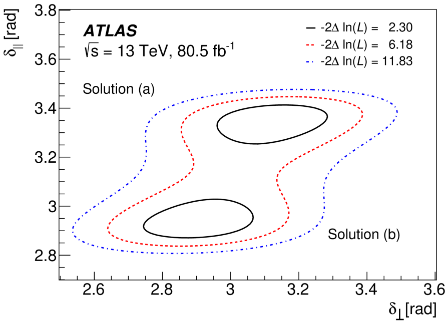
Efficiency: $\varepsilon = \frac{N_{\text{tagged}}}{N_{\text{Bcand}}}$, Dilution: $D = (1 - 2w)$, w is the miss-tag probability, Tagging Power: $TP = \varepsilon D^2$

Results 2015-2017 data: Projections of the mass-lifetime-angular fit



Results 2015-2017 data: fit parameters

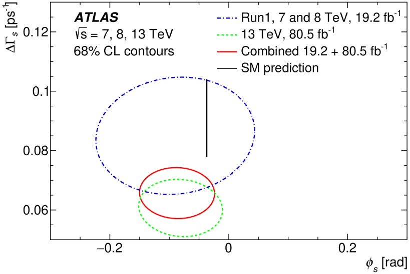
- While for most of the physics parameters, including ϕ_s , $\Delta\Gamma_s$, Γ_s, the fit determines a single solution, for the strong-phases $\delta_{||}$ and $\delta_{\perp}$ two well separated local maxima of the likelihood are found, and shown as solution (a) and (b) in table of results
- The difference in likelihoods, $-2\Delta\ln(L)$, between the two solutions is equal to 0.03, favouring (a) but without ruling out (b).

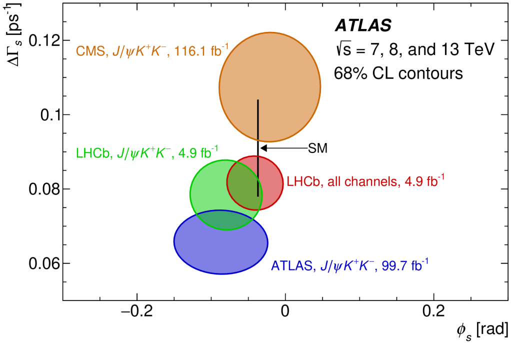


Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.081	0.041	0.022
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0043
Γ_s [ps^{-1}]	0.6687	0.0015	0.0022
$\lvert A_{\parallel}(0)\rvert^2$	0.2213	0.0019	0.0023
$\lvert A_0(0)\rvert^2$	0.5131	0.0013	0.0038
$\lvert A_S(0)\rvert^2$	0.0321	0.0033	0.0046
$\delta_{\perp} - \delta_S$ [rad]	−0.25	0.05	0.04
Solution (a)			
$\delta_{\perp}$ [rad]	3.12	0.11	0.06
$\delta_{\parallel}$ [rad]	3.35	0.05	0.09
Solution (b)			
$\delta_{\perp}$ [rad]	2.91	0.11	0.06
$\delta_{\parallel}$ [rad]	2.94	0.05	0.09

ATLAS $B_s^0 \to J/\psi\phi$ Combination Run2 + 1. Comparison with CMS and LHCb

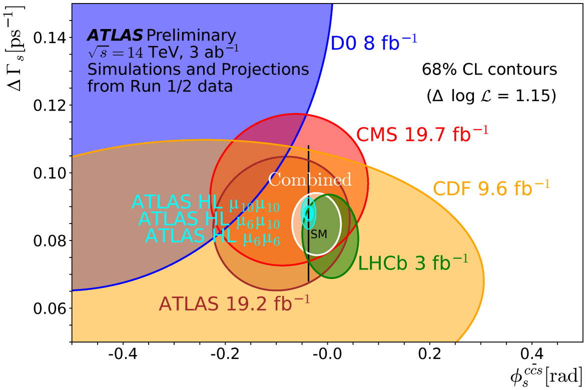
Parameter	Solution (a)		
	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.087	0.036	0.021
$\Delta\Gamma_s$ [ps^{-1}]	0.0657	0.0043	0.0037
Γ_s [ps^{-1}]	0.6703	0.0014	0.0018
$\lvert A_{\parallel}(0)\rvert^2$	0.2220	0.0017	0.0021
$\lvert A_0(0)\rvert^2$	0.5152	0.0012	0.0034
$\lvert A_S\rvert^2$	0.0343	0.0031	0.0045
$\delta_\perp$ [rad]	3.22	0.10	0.05
$\delta_\parallel$ [rad]	3.36	0.05	0.09
$\delta_\perp - \delta_S$ [rad]	−0.24	0.05	0.04



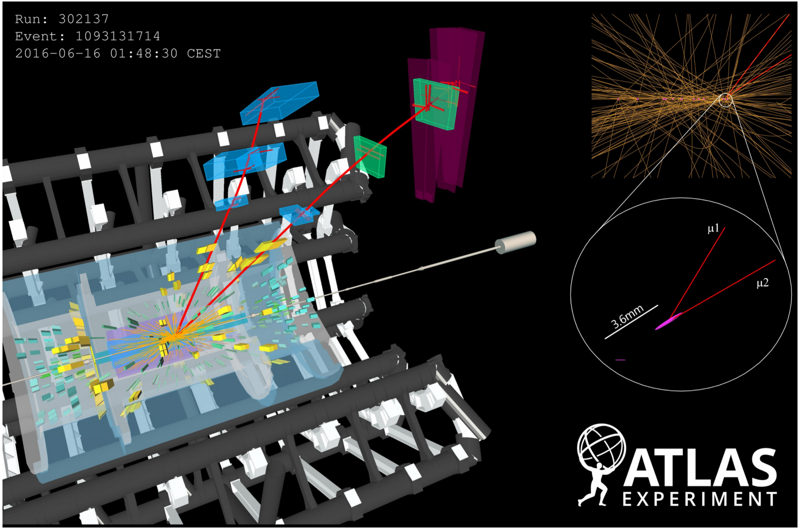


- ϕ_s result consistent with results from CMS, LHCb and SM
- Competitive single measurement of $\Delta\Gamma_s$, Γ_s and helicity parameters
- Still to add 60 fb^{-1} from 2018

- ATL-PHYS-PUB-2018-041
- Inner Detector upgrade: proper decay time resolution improved by 21% w.r.t. Run 2
- Three trigger scenarios for muon momenta thresholds
- ϕ_s precision improves (9 - 20) times w.r.t.Run1, or (4 - 9) times w.r.t. current result combining Run1 and Run2 99.7 fb^{-1}



- JHEP 04 (2019) 098, arXiv:1812.03017



Physics Motivation

- Multiple suppressions: FCNC current, CKM and Helicity
- New physics models predict higher, also lower rate.
- SM prediction very precise 6-8% uncertainties

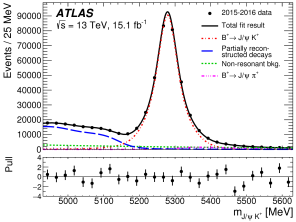
Run2 Analysis JHEP 04 (2019) 098 arXiv:1812.03017

- Use 2015-16 data
- Di-μ triggers with p_T thresholds 4 GeV and 6 GeV or higher. L_{xy} cuts applied online.

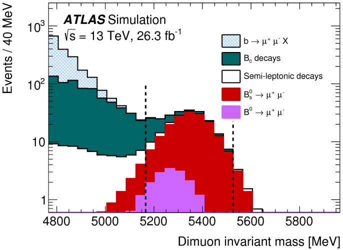
Normalisation B yield extraction

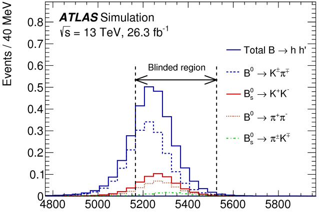
$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{N_{d(s)}}{\varepsilon_{\mu^+\mu^-}} \times \frac{\varepsilon_{J/\psi K^+}}{N_{J/\psi K^+}} \times \frac{f_u}{f_{d(s)}} \times [\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)]$$

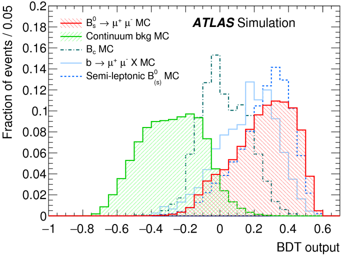
Unbinned maximum likelihood fit of the invariant mass $J/\psi K$



- Continuum Bg: μ's produced independently from fragmentation/decay-chains of b, $\bar{b}$ quarks.
  - Reduced by boosted decision tree (BDT) with 15 variables.
- Partially reconstructed decays:
  - same side - cascades $b \to c\mu X \to s(d)\mu X'$;
  - same vertex e.g. $B^0_{(s)} \to K^*\mu^+\mu^-$, $B \to J/\psi\mu X$, $B_c \to J/\psi(\mu^+\mu^-)\mu\nu$
  - Semileptonic with a hadron misidentified as a μ
- Peaking background $B \to h^+h^-$ two hadrons misidentified as μ.
  - tight μ criteria: profile of energy deposits in the calorimeters, tighter ID–MS matching

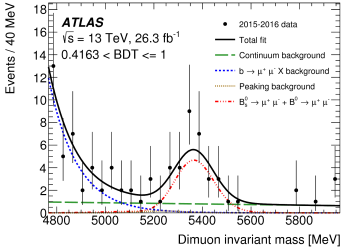




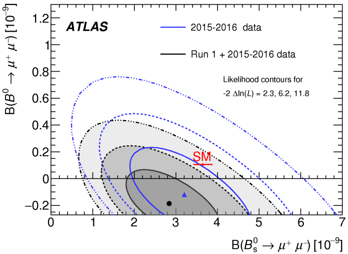


Extraction of the Signal yield

- Simultaneous likelihood fit to di-μ mass in 4 BDT bins, chosen to give equal sig efficiency 18%
- Signal model from MC: two Double-Gauss centred at B_d and B_s mass.
- Non-peaking backgrounds: common exponential - from data in low mass sideband
- Peaking backgrounds $B \to h^+ h^-$ - Double-Gauss from MC



Likelihood contours for the simultaneous fit to B($B_s \to \mu^+\mu^-$) and B($B_d \to \mu^+\mu^-$), for $-2\Delta\ \ln(L)$= 2.3, 6.2, 11.8



Results

- 2015-16 yields: Ns =80 $\pm$ 22 and Nd =-12$\pm$ 20 (expected from SM Ns =91 and Nd =10)
- Run2 (2015-16) + Run1 branching fractions:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9} \text{ and } \mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$$

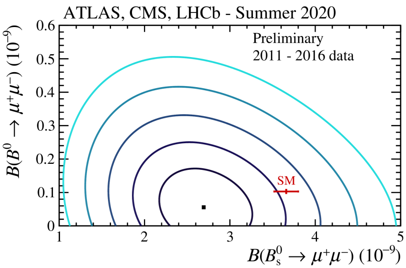
- Compatible with SM within 2.4 σ

$B^0_{(s)} \to \mu^+\mu^-$ LHC combination 2020 ATLAS-CONF-2020-049

- Combination from binned 2D profile likelihoods
- Independent systematics, except for ratio of fragmentation fractions f_d/f_s, treated individually
- Compatible with SM within 2.1 σ (latest LHCb result not included)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(2.69\,^{+0.37}_{-0.35}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) \; < \; 1.9 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

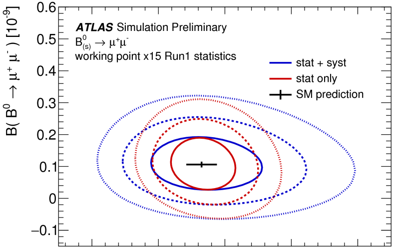
Likelihood contours correspond to $-2\Delta \ln(L)$= 2.3, 6.2, 11.8, 19.3, 30.2



$B^0_{(s)} \to \mu^+\mu^-$ HL-LHC Prospects in ATLAS, ATL-PHYS-PUB-2018-005

- 3 trigger scenarios for thresholds $p_T(\mu_1)$, $p_T(\mu_2)$
- Conservative (10-10) GeV (x15 Run1); Intermediate (6-10) GeV (x60 Run1); High-yield (6-6) GeV (x75 Run1).

Likelihood contours for 68.3%, 95.5%, and 99.7% confidence levels



Summary

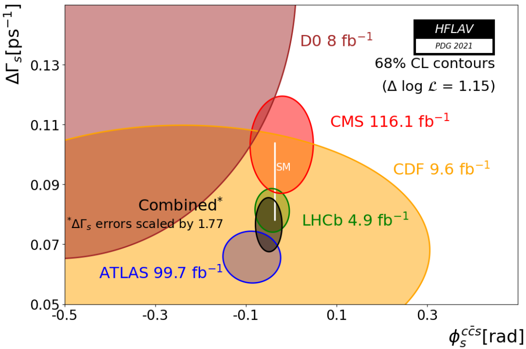
- ATLAS analysis of $B_s^0 \to J/\psi\phi$ combining Run1 and Run2 99.7 fb^{-1} show the CP violation phase ϕ_s compatible with SM. The search continues to include 2018 data and is prepared for Run3 data taking.
- At HL-LHC ATLAS ϕ_s precision will improve by (4 - 9) times w.r.t. current result. The measurement will benefit from both statistics and from improved time-resolution in upgraded ATLAS ID.

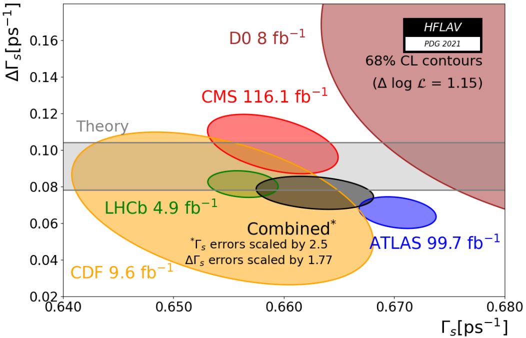
- In rare decays $B_{(s)}^0 \to \mu^+\mu^-$ combining 2015-16 and Run1 data, ATLAS arrives to a result compatible with SM within 2.4 σ
- LHC 2020 combination for rare decays $B_{(s)}^0 \to \mu^+\mu^-$ shows a compatibility with SM within 2.1 σ
- ATLAS continues analysing 2017-2018 data and is prepare for Run3.
- At HL-LHC ATLAS will increase $B_{(s)}^0 \to \mu^+\mu^-$ statistical precisions (3-5) times w.r.t. results expected from Total Run1+Run2, while uncertainties will still be statistically dominated.

- ATLAS B-physics program well prepared for Run3. HL-LHC studies done for principal B-physics channels, showing that ATLAS B-physics will benefit from the upgrade.

Backup Slides

$B_s^0 \to J/\psi\phi$ world combination 2021





World combined 2021: $\phi_s = -0.050 \pm 0.019$ rad, consistent with SM.

Because of tensions between the measurements, the errors on Γ_s and $\Delta\Gamma_s$ have been scaled by 2.5 and 1.77, respectively (the ellipses representing the results of each experiment are shown before scaling, while the combined ellipses include the scale factors).