CP violation in the B_s^0 system

Marcos Romero Lamas
on behalf of the ATLAS, CMS and LHC*b*
collaborations

The Galician Institute of the High Energy Physics (IGFAE)
Santiago de Compostela

FPCP 2022
Oxford, Mississippi (USA), May 24th

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Introduction

Kobayasi-Maskawa mechanism

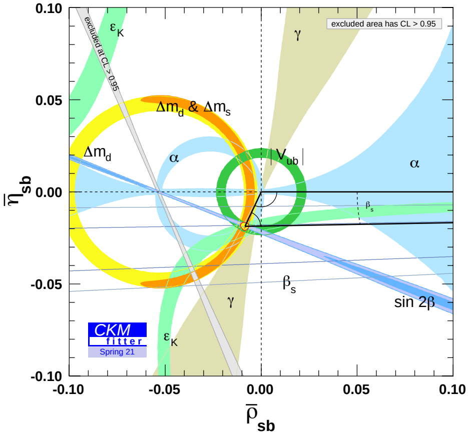
Describes the quark mixing in weak charged transitions by means of

$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix} =$$

$$= \begin{bmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)\,.$$

One can build triangles from the unitary condition,

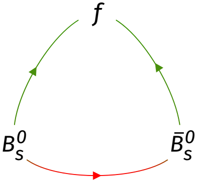
$$\beta_s = \arg\left(-\frac{V_{ts}}{V_{cs}}\frac{V_{tb}^*}{V_{cb}^*}\right).$$



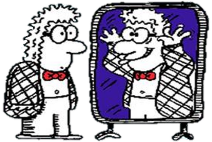
CP violation

Requires at least 2 competitive interfering amplitudes with different weak (*CP*-odd) phases. CP violating effects depend on

$$\lambda_f = |\lambda_f| e^{i\phi_s} = \frac{q}{p}\frac{\bar{A}_f}{A_f}.$$



1. **CPV in decay** Direct CPV corresponds $\Gamma(B_s^0 \to f) \neq \Gamma(\overline{B}_s^0 \to \overline{f})$ and requires both weak and strong (*CP*-even) phases to be different, resulting in $|A|^2 \neq |\overline{A}|^2$.
2. **CPV in mixing** $\Gamma(B_s^0 \to \overline{B}_s^0) \neq \Gamma(\overline{B}_s^0 \to B_s^0)$, thus $|q/p| \neq 1$.
3. **CPV in interference** Where $\Gamma(B_s^0 \to f) \neq \Gamma(B_s^0 \to \overline{B}_s^0 \to f)$, thus $\arg(\lambda) \neq 0$. Final state f usually (but not always) a *CP* eigenstate.



CP violation

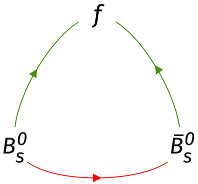
The time dependent CP asymmetry writes:

$$A_{CP}(t) = \frac{\Gamma(\overline{B} \to f) - \Gamma(B \to f)}{\Gamma(\overline{B} \to f) + \Gamma(B \to f)} = \frac{-\overbrace{\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}}^{C_f \text{ direct CPV}} \cos(\Delta m_s t) + \overbrace{\frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}}^{S_f \text{ mixing-induced CPV}} \sin(\Delta m_s t)}{\cosh\left(\frac{\Delta\Gamma_s}{2} t\right) + \underbrace{\frac{2\mathrm{Re}\lambda_f}{1+|\lambda_f|^2}}_{A_f^{\Delta\Gamma}} \sinh\left(\frac{\Delta\Gamma_s}{2} t\right).}.$$

- The mixing-induced CP violation phase is ϕ_s , in $\mathrm{Im}\lambda_f = \sin\phi_s$.
- ϕ_s is very sensitive to physics beyond the SM.
- Can be directly related with V_{CKM} elements

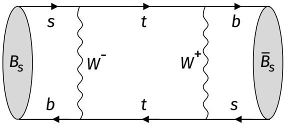
$$\phi_s^{SM} = -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right).$$

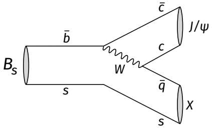
Measuring ϕ_s



- Assuming only SM tree level contributions (penguins seem small De Bruyn & Fleischer),

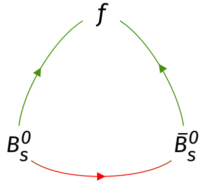
$$\phi_s^{SM} = -\arg(\lambda_f) = \phi_M^{SM} - 2\phi_D^{SM}$$



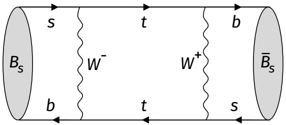


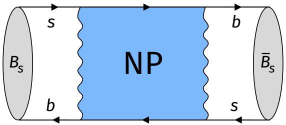
Measuring ϕ_s

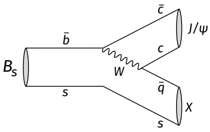
- Assuming only SM tree level contributions (penguins seem small De Bruyn & Fleischer),
- NP could enter in B_s^0 mixing.
- Can constrain BSM physics in rare decays such as $B \to K^* \ell\ell$.



$$\phi_s = -\arg(\lambda_f) = \phi_M^{SM} + \Delta\phi_{NP} - 2\phi_D^{SM}$$



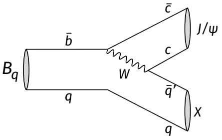




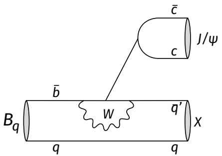
Measuring ϕ_s

- ϕ_s is most precisely measured in $b \to c\bar{c}s$ processes, where (SM) penguin pollution is small.
- $B_s^0 \to J/\psi\phi$ golden channel used to measure ϕ_s
    - No direct CPV
    - Only one weak phase
    - High signal/noise reconstruction.
- Higher order penguin contributions can also appear in ϕ_s.
    - Need to control penguin pollution $\phi_s = -2\beta_s + \Delta\phi_s^{\text{peng}} + \Delta\phi_s^{NP}$.
    - For $B_s^0 \to J/\psi\phi$, $SU(3)$ counterparts where $T \sim P$ ($B_s^0 \to J/\psi\{\rho, K^{*0}\}$) are used to estimate penguin contributions.

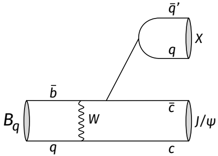
Tree



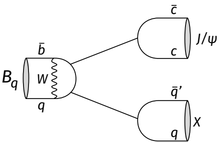
Penguin



Exchange



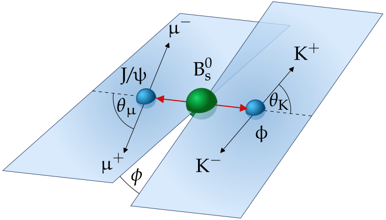
Penguin-annihilation



Phenomenology

Time-dependent angular fit to disentangle *CP*-even and -odd components

$$\frac{d^4\Gamma}{d\Omega dt} = \sum_{u,v=S,0,\perp,\parallel} A_u \bar{A}_v \, h_{u,v}(t) \, f_{u,v}(\theta_K, \theta_\mu, \phi_h)$$



This corresponds to LHC*b* formalism, a bit different for ATLAS and CMS

where

$$h_{u,v}^{B_s^0}(t) = e^{-\Gamma_s t}\left[a_{u,v}\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + b_{u,v}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right) + c_{u,v}\cos\left(\Delta m_s t\right) + d_{u,v}\sin\left(\Delta m_s t\right)\right]$$

and

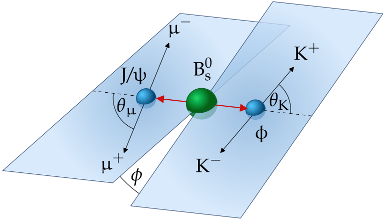
$$h_{u,v}^{\bar{B}_s^0}(t) = e^{-\Gamma_s t}\left[a_{u,v}\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + b_{u,v}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right) - c_{u,v}\cos\left(\Delta m_s t\right) - d_{u,v}\sin\left(\Delta m_s t\right)\right].$$

Phenomenology

Time-dependent angular fit to disentangle *CP*-even and -odd components

$$\frac{d^4\Gamma}{d\Omega dt} = \sum_{u,v=S,0,\perp,\parallel} A_u \bar{A}_v \, h_{u,v}(t) \, f_{u,v}(\theta_K, \theta_\mu, \phi_h)$$

where



This corresponds to LHC*b* formalism, a bit different for ATLAS and CMS

u	v	$f_{u,v}$	$a_{u,v}$	$b_{u,v}$	$c_{u,v}$	$d_{u,v}$
0	0	$c_K^2 s_l^2$	$\frac{1}{2}(1+\lvert\lambda\rvert^2)$	$-\lvert\lambda\rvert\cos(\phi_s)$	$\frac{1}{2}(1-\lvert\lambda\rvert^2)$	$\lvert\lambda\rvert\sin(\phi_s)$
$\parallel$	$\parallel$	$\frac{1}{2}s_K^2(1-c_\phi^2 s_l^2)$	$\frac{1}{2}(1+\lvert\lambda\rvert^2)$	$-\lvert\lambda\rvert\cos(\phi_s)$	$\frac{1}{2}(1-\lvert\lambda\rvert^2)$	$\lvert\lambda\rvert\sin(\phi_s)$
$\perp$	$\perp$	$\frac{1}{2}s_K^2(1-s_\phi^2 s_l^2)$	$\frac{1}{2}(1+\lvert\lambda\rvert^2)$	$\lvert\lambda\rvert\cos(\phi_s)$	$\frac{1}{2}(1-\lvert\lambda\rvert^2)$	$-\lvert\lambda\rvert\sin(\phi_s)$
$\perp$	$\parallel$	$s_K^2 s_l^2 s_\phi c_\phi$	$\frac{1}{2}(1-\lvert\lambda\rvert^2)\sin(\delta_\perp-\delta_\parallel)$	$-\lvert\lambda\rvert\cos(\delta_\perp-\delta_\parallel)\sin(\phi_s)$	$\frac{1}{2}(1+\lvert\lambda\rvert^2)\sin(\delta_\perp-\delta_\parallel)$	$-\lvert\lambda\rvert\cos(\delta_\perp-\delta_\parallel)\cos(\phi_s)$
0	$\parallel$	$\sqrt{2}s_K c_K s_l c_l c_\phi$	$\frac{1}{2}(1+\lvert\lambda\rvert^2)\cos(\delta_0-\delta_\parallel)$	$-\lvert\lambda\rvert\cos(\delta_0-\delta_\parallel)\cos(\phi_s)$	$\frac{1}{2}(1-\lvert\lambda\rvert^2)\cos(\delta_0-\delta_\parallel)$	$\lvert\lambda\rvert\cos(\delta_0-\delta_\parallel)\sin(\phi_s)$
0	$\perp$	$-\sqrt{2}s_K c_K s_l c_l s_\phi$	$-\frac{1}{2}(1-\lvert\lambda\rvert^2)\sin(\delta_0-\delta_\perp)$	$-\lvert\lambda\rvert\cos(\delta_0-\delta_\perp)\sin(\phi_s)$	$-\frac{1}{2}(1+\lvert\lambda\rvert^2)\sin(\delta_0-\delta_\perp)$	$-\lvert\lambda\rvert\cos(\delta_0-\delta_\perp)\cos(\phi_s)$
S	S	$\frac{1}{3}s_l^2$	$\frac{1}{2}(1+\lvert\lambda\rvert^2)$	$\lvert\lambda\rvert\cos(\phi_s)$	$\frac{1}{2}(1-\lvert\lambda\rvert^2)$	$-\lvert\lambda\rvert\sin(\phi_s)$
S	$\parallel$	$\frac{2}{\sqrt{6}}s_K s_l c_l c_\phi$	$\frac{1}{2}(1-\lvert\lambda\rvert^2)\cos(\delta_S-\delta_\parallel)$	$\lvert\lambda\rvert\sin(\delta_S-\delta_\parallel)\sin(\phi_s)$	$\frac{1}{2}(1+\lvert\lambda\rvert^2)\cos(\delta_S-\delta_\parallel)$	$\lvert\lambda\rvert\sin(\delta_S-\delta_\parallel)\cos(\phi_s)$
S	$\perp$	$-\frac{2}{\sqrt{6}}s_K s_l c_l s_\phi$	$-\frac{1}{2}(1+\lvert\lambda\rvert^2)\sin(\delta_S-\delta_\perp)$	$-\lvert\lambda\rvert\sin(\delta_S-\delta_\perp)\cos(\phi_s)$	$-\frac{1}{2}(1-\lvert\lambda\rvert^2)\sin(\delta_S-\delta_\perp)$	$-\lvert\lambda\rvert\sin(\delta_\perp-\delta_S)\sin(\phi_s)$
S	0	$\frac{2}{\sqrt{3}}c_K s_l^2$	$\frac{1}{2}(1-\lvert\lambda\rvert^2)\cos(\delta_S-\delta_0)$	$\lvert\lambda\rvert\sin(\delta_S-\delta_0)\sin(\phi_s)$	$\frac{1}{2}(1+\lvert\lambda\rvert^2)\cos(\delta_S-\delta_0)$	$\lvert\lambda\rvert\sin(\delta_S-\delta_0)\cos(\phi_s)$

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

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

- ATLAS measurement of ϕ_s in $B_s^0 \to J/\psi\phi$ at 13 TeV with 80.5 fb^{-1} of data collected between 2015 and 2017. Eur. Phys. J. C 81 (2021) 342
- CMS measurement of ϕ_s in $B_s^0 \to J/\psi\phi$ at 13 TeV with 96.4 fb^{-1} of data collected in 2017 and 2018. Phys. Lett. B 816 (2021) 136188
- LHC*b* measurement of ϕ_s in $B_s^0 \to J/\psi$ KK at 13 TeV with 1.9 fb^{-1} of data collected in 2015 and 2016. Eur. Phys. J. C 79 (2019) 706

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

Datasets and selection

ATLAS

- Mixture of triggers based on $J/\psi \to \mu\mu$ with muon p_T thresholds.
- No lifetime or impact parameter cut applied at HLT level.
- Vertex fit performed with J/ψ mass constraint.

Variable	Cut
$p_T(\mu^\pm)$	$> 4\ (/6)$ GeV
$p_T(K^\pm)$	> 1 GeV
$\chi^2/\mathrm{ndof}(all)$	< 3
t	[-2, 14] ps

CMS

- Trigger on $J/\psi \to \mu^+\mu^- + \mu$ (for tagging)
- No displacement cut at HLT level.
- Vertex fit performed with J/ψ mass constraint.

Variable	Cut
$p_T(\mu^\pm)$	> 3.5 GeV
$p_T(K^\pm)$	> 1.2 GeV
t	[0.23, 16.17] ps

LHCb

- Two triggers based on $J/\psi \to \mu\mu$.
- BDT-based selection.
- Λ_b is subtracted injecting negative-weighted Λ_b MC events.
- $B_d^0 \to J/\psi K\pi$ is neglected (assigned syst.)
- Vertex fit performed with J/ψ mass constraint.

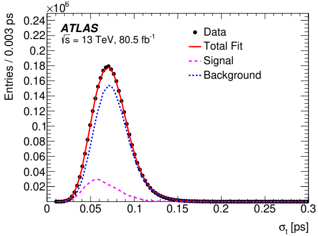
Variable	Cut
$p_T(\mu^\pm)$	> 0.5 GeV
$p_T(K^\pm)$	> 0.5 GeV
$\chi^2/\mathrm{ndof}(all)$	< 3
t	[0.3, 15] ps

Decay-time resolution

The value and uncertainty of the decay-time resolution strongly affects the relative precision on ϕ_s .

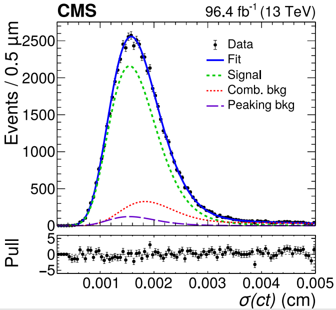
ATLAS

- Per-candidate uncertainty on proper decay time is modelled with a gaussian resolution model.
- σ_{eff} ~ 69 fs.



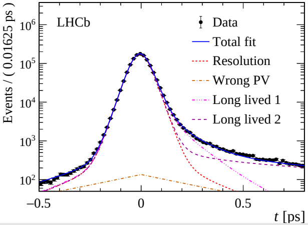
CMS

- Data driven, with scaling factor to correct for decay-lenght uncertainty.
- Scaling factor from MC.



LHC*b*

- Per-candidate decay-time uncertainty is calibrated on a J/ψ -prompt sample.
- Seminumerical estimation of the dilution.
- σ_{eff} = 45.54 ± 0.05 fs.



Decay-time acceptance

Cuts and trigger efficiencies affect the decay-time distribution and they are corrected differently between the experiments.

ATLAS

- Proper decay time dependence corrected reweighting to

$$\frac{1}{w} = p_0\left(1 - p_1\left(Erf\left(\frac{t - p_3}{p_2}\right) + 1\right)\right).$$

- Inefficiency taken from MC comparisons of proper decay time distribution obtained before and after applying the trigger selection.

CMS

- Per year.
- Computed as $\frac{ct_{MC}^{\Delta\Gamma=0}}{ct_{GEN} \otimes \delta(ct)}$, where $\delta(ct) = ct_{GEN} - ct_{MC}$ is the lifetime resolution.
- Modeled as $\epsilon(ct) = e^{-a \cdot ct}\text{Cheby}(ct, 4)$.
- Procedure is validated measuring τ_u in eight subsamples of $B_u^+ \to J/\psi K^+$.

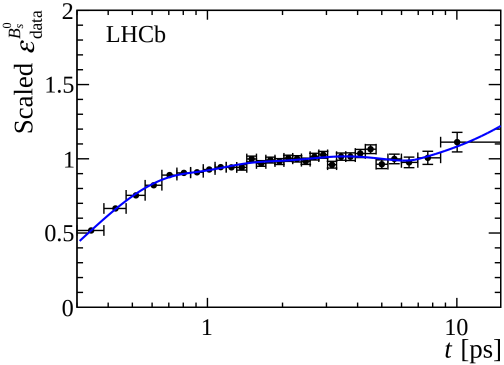
LHC*b*

- Per year and trigger category.
- Use $B_d^0 \to J/\psi K^*$, corrected with MC ratio, as control channel to get efficiency shape

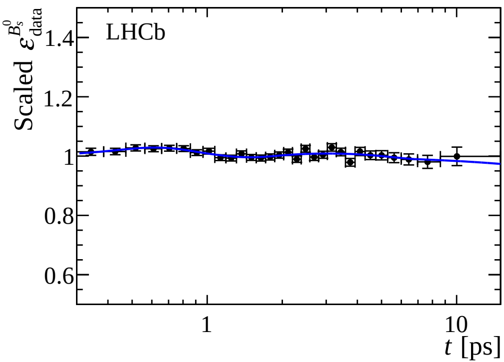
$$\epsilon_{\text{data}}^{B_s^0} = \epsilon_{\text{data}}^{B_d^0} \times \frac{\epsilon_{\text{MC}}^{B_s^0}}{\epsilon_{\text{MC}}^{B_d^0}}$$

- Procedure is validated measuring τ_d and τ_u/τ_d.

Decay-time acceptance



Biased (2016) LHC*b* trigger category time acceptance with a drop at low decay times because of the impact parameter cut.



Unbiased (2016) LHC*b* trigger category time acceptance is much flatter.

Flavor tagging

Tagging is crucial to measure ϕ_s . The experiments use different taggers.

ATLAS

- Uses OS tagging
- Profits from $b - \bar{b}$–pair correlation to infer initial signal flavor.
- 4 tagging methods:
    - tight muons
    - electrons
    - low-p_T muons
    - jet, in b-tagged jet when there are no leptons
- Calibrated in $B_u^+ \to J/\psi K^+$
- Tagging power is ~ 1.75%

CMS

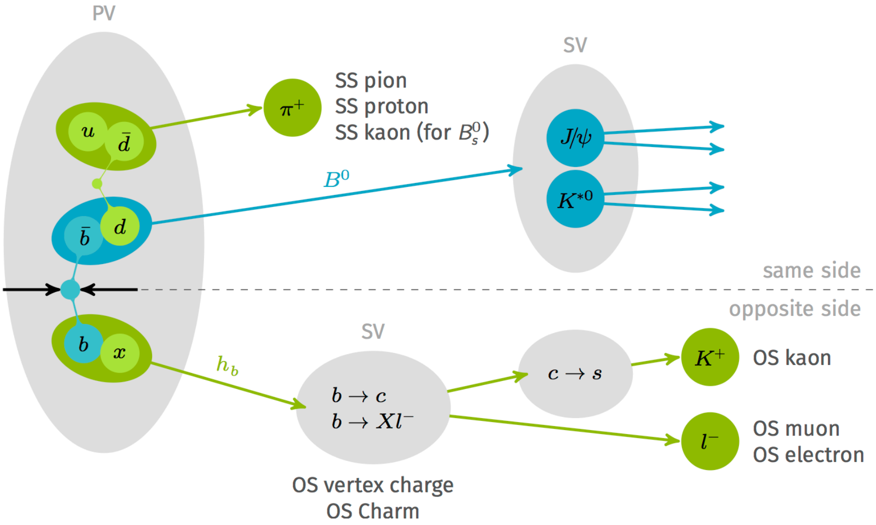
- OS tagging using muon charge (trigger level selected).
- Optimized for $B_s^0 \to J/\psi\phi$ and linearly calibrated on $B_u^+ \to J/\psi K^+$.
- Per-event mistag probability evaluated with DNN.
- Tagging power is ~ 10%.

LHC*b*

- OS (calibrated on $B_u^+ \to J/\psi K^+$) and SS (calibrated on $B_s^0 \to D_s\pi$) tagging algorithms.
- True mistag is linearly-calibrated: $\omega = p_0 + p_1\eta$.
- Tagging power is ~ 4.73% tagging power.

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

Flavor tagging



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

Angular acceptance

ATLAS

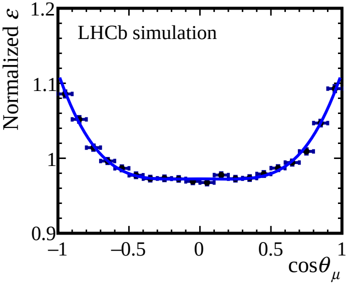
- Calculated from a binned fit to MC simulated data ratio.
- Event by event efficiency depending on the 3 angles and the p_T.

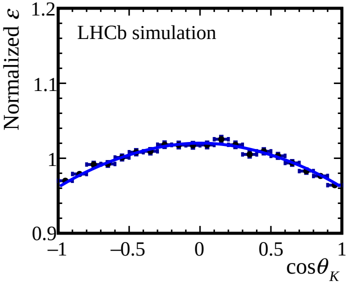
CMS

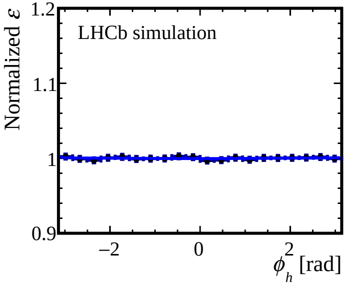
- Obtained from MC in 70 bins per year.
- Parametrized with Legendre polynomials and Spherical Harmonics up to order 6.

LHC*b*

- Per year and trigger.
- Iterative correcting and weighting MC to match RD.
- It is applied in the integral of the full pdf as normalization weights.







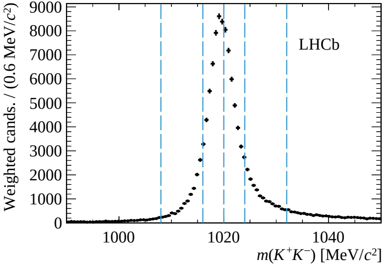
S+P-wave interference

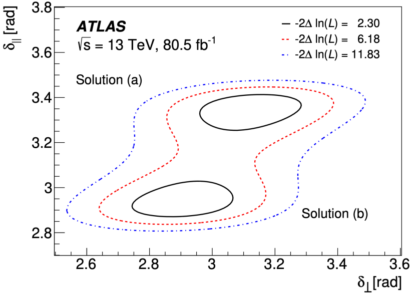
- S and P wave amplitudes are fitted.
- The interference is taken into account with a factor C_{SP} multiplying the amplitudes:

$$C_{SP}e^{-i\theta_{SP}} = \frac{\int_{m_{KK}^L}^{m_{KK}^H} p(m_{KK}) \times s(m_{KK})^* \; dm_{KK}}{\sqrt{\int_{m_{KK}^L}^{m_{KK}^H} |p(m_{KK})|^2 \; dm_{KK} \int_{m_{KK}^L}^{m_{KK}^H} |s(m_{KK})|^2 \; dm_{KK}}}.$$

- ATLAS and CMS have just **one** coefficient.
- LHC*b* splits the m_{KK} range in six bins, thus having **six** coefficients.
  - Can see the phase movement around the $\phi(1020)$ pole.
  - Resolve the twofold ambiguity in the decay rate:

$$(\delta_{\|}, \delta_{\perp}, \delta_S) \to (2\pi - \delta_{\|}, \delta_{\perp} + 2(\pi - \delta_{\|}), \delta_S + 2(\pi - \delta_{\|}))$$





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

Results: ATLAS **Eur. Phys. J. C 81 (2021) 342**

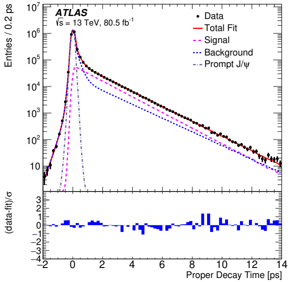
2015+2016+2017

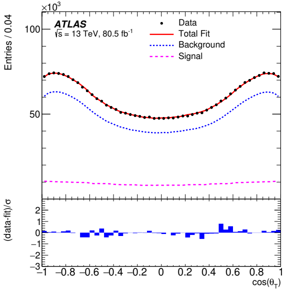
$$\phi_s = -0.081 \pm 0.041 \pm 0.022 \text{ rad}$$

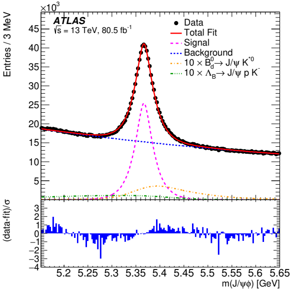
$$\Delta\Gamma_s = 0.0607 \pm 0.0047 \pm 0.0043 \text{ ps}^{-1}$$

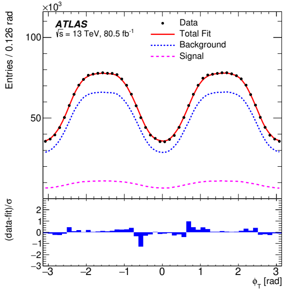
$$\Gamma_s = 0.6687 \pm 0.0015 \pm 0.0022 \text{ ps}^{-1}$$

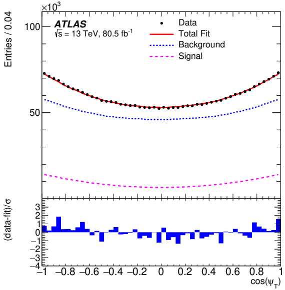
$$\Delta m_s = 17.757 \pm 0.021 (\text{fixed to PDG2018})$$











Results: CMS

Phys. Lett. B 816 (2021) 136188

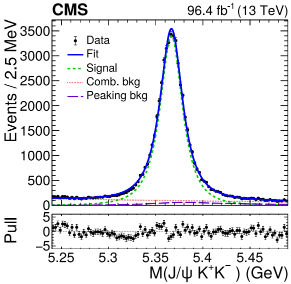
2017+2018

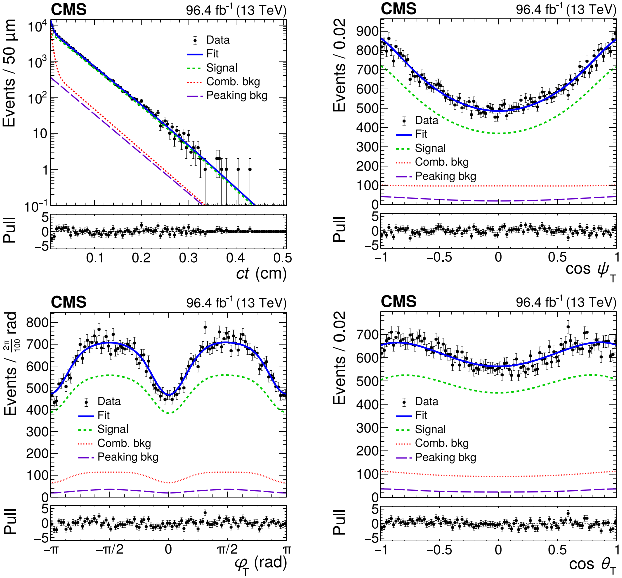
$$\phi_s = -0.011 \pm 0.050 \pm 0.010 \text{ rad}$$

$$\Delta\Gamma_s = 0.114 \pm 0.014 \pm 0.007 \text{ ps}^{-1}$$

$$\Gamma_s = 0.6531 \pm 0.0042 \pm 0.0026 \text{ ps}^{-1}$$

$$\Delta m_s = 17.51 \pm 0.10 \pm 0.03 \text{ ps}^{-1}$$





Results: LHC*b* Eur. Phys. J. C 79 (2019) 706

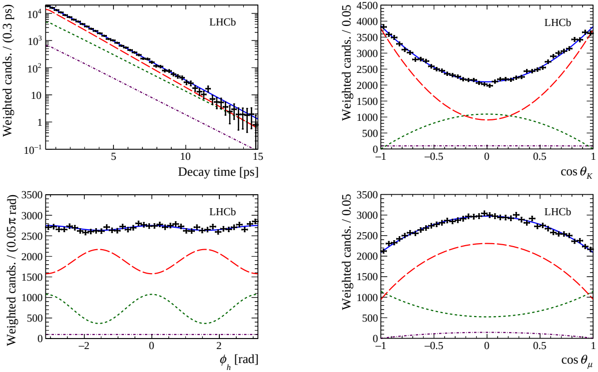
2015+2016

$$\phi_s = -0.083 \pm 0.041 \pm 0.006 \text{ rad}$$

$$\Delta\Gamma_s = 0.077 \pm 0.008 \pm 0.003 \text{ ps}^{-1}$$

$$\Gamma_s - \Gamma_d = -0.0041 \pm .0024 \pm 0.0015 \text{ ps}^{-1}$$

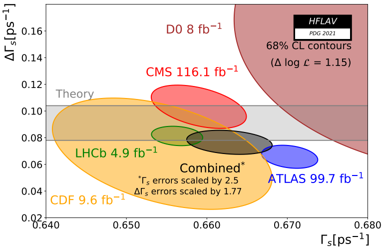
$$\Delta m_s = 17.703 \pm 0.059 \pm 0.018 \text{ ps}^{-1}$$

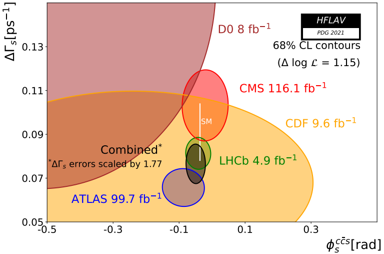


Current status

	ϕ_s [mrad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]
ATLAS	−87 ± 42	0.0657 ± 0.0057	0.6703 ± 0.0023
CMS	−21 ± 45	0.1073 ± 0.0097	0.6531 ± 0.0049
LHC*b* †	−41 ± 25	0.0816 ± 0.0048	0.6562 ± 0.0021
HFLAV	−50 ± 19	0.0756 ± 0.0059	0.6628 ± 0.0035
CKMfitter SM pred. ‡	$-36.96^{+0.84}_{-0.72}$	0.088 ± 0.020	0.6587 ± 0.0024

†:
LHC*b* combines other decay modes into this single measurement.
‡:
Theory predicts $\frac{\Gamma_s}{\Gamma_d}$ = 1.0006 ± 0.0025. Γ_s is computed using the current WA Γ_d = 1.519 ± 0.004



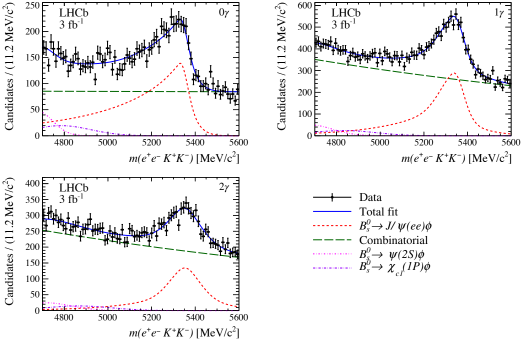


ϕ_s in $B_s^0 \to J/\psi(e^+e^-)\phi(K^+K^-)$ decays

Introduction

Eur. Phys. J. C (2021) 81: 1026

- First time-dependent angular analysis with dielectron final state.
- Run1 data (3fb^{-1}@7/8 TeV).
- Follows similar strategy as $B_s^0 \to J/\psi(\mu^+\mu^-)\phi$.
- Experimentally harder: resolution, reconstruction, bremsstrahlung...
- Has ~ 12% stats of the dimuon channel.
- BDT-based selection supresses combinatorial background.
- NN rejects K^+ that could be identified as p, thus suppressing the $\Lambda_b \to J/\psi p K^-$.



ϕ_s in $B_s^0 \to J/\psi(e^+e^-)\phi(K^+K^-)$ decays

Strategy

$$p.d.f. = \frac{\displaystyle\sum_{u,v=S,0,\parallel,\perp} A_u\overline{A}_v \;\; f_{u,v}[\Omega] \;\; \left\{(1+q^{OS}D[\eta^{OS}])(1+q^{OS}D[\eta^{OS}])h_{u,v}^{B_s^0}[t] + (1+q^{OS}D[\eta^{OS}])(1+q^{SS}D[\eta^{SS}])h_{u,v}^{\overline{B}^{s}_{0}}[t]\right\} \;\; \varepsilon[t] \otimes G[t,\sigma[t]]}{\displaystyle\int_{0.3\,\mathrm{ps}}^{14\,\mathrm{ps}} dt \sum_{u,v=S,0,\parallel,\perp} A_u\overline{A}_v \;\; \left\{(1+q^{OS}D[\eta^{OS}])(1+q^{SS}D[\eta^{SS}])h_{u,v}^{B_s^0}[t] + (1+q^{OS}D[\eta^{OS}])(1+q^{SS}D[\eta^{SS}])h_{u,v}^{\overline{B}^{s}_{0}}[t]\right\} \;\; \varepsilon[t] \otimes G[t,\sigma[t]] \;\; \omega_{u,v}}$$

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Flavor tagging

Need to know initial B_s^0 flavor. Experimentally limited by the mistag probability. SS and OS taggers with tagging power 5.07 ± 0.16%.

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MC iteratively corrected and reweighted to data to get a set of angular integral normalization weights.

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Mass dependence

Analysis performed in a single $m(KK) \in [990, 1050]$ MeV/c bin.

Strategy

Decay-time efficiency

Time-efficiency is modeled with splines fitted on B_d^0 control channel and corrected with B_s^0/B_d^0 MC ratio

$$p.d.f. = \frac{\displaystyle\sum_{u,v=S,0,\parallel,\perp} A_u\bar{A}_v \; f_{u,v}[\Omega] \; \left\{(1+q^{OS}D[\eta^{OS}])(1+q^{OS}D[\eta^{OS}])h_{u,v}^{B_s^0}[t] + (1+q^{OS}D[\eta^{OS}])(1+q^{SS}D[\eta^{SS}])h_{u,v}^{\bar{B}_0^s}[t]\right\} \; {\color{blue}\varepsilon[t]} \otimes G[t,\sigma[t]]}{\displaystyle\int_{0.3\,\text{ps}}^{14\,\text{ps}} dt \sum_{u,v=S,0,\parallel,\perp} A_u\bar{A}_v \; \left\{(1+q^{OS}D[\eta^{OS}])(1+q^{SS}D[\eta^{SS}])h_{u,v}^{B_s^0}[t] + (1+q^{OS}D[\eta^{OS}])(1+q^{SS}D[\eta^{SS}])h_{u,v}^{\bar{B}_0^s}[t]\right\} \; {\color{blue}\varepsilon[t]} \otimes G[t,\sigma[t]] \; \omega_{u,v}}$$

Strategy

Time resolution

B_s^0 oscillates fast, $T \sim 350\,\mathrm{fs}$. Need excellent time resolution, modeled with 2 gaussians.
$\sigma_{eff} = 45.6 \pm 0.5$ fs

$$p.d.f. = \frac{\displaystyle\sum_{u,v=S,0,\|,\perp} A_u\bar{A}_v \; f_{u,v}[\Omega] \; \left\{(1+q^{OS}D[\eta^{OS}])(1+q^{OS}D[\eta^{OS}])h_{u,v}^{B_s^0}[t] + (1+q^{OS}D[\eta^{OS}])(1+q^{SS}D[\eta^{SS}])h_{u,v}^{\overline{B}_0^s}[t]\right\} \; \varepsilon[t] \otimes G[t,\sigma[t]]}{\displaystyle\int_{0.3\,\mathrm{ps}}^{14\,\mathrm{ps}} dt \sum_{u,v=S,0,\|,\perp} A_u\bar{A}_v \; \left\{(1+q^{OS}D[\eta^{OS}])(1+q^{SS}D[\eta^{SS}])h_{u,v}^{B_s^0}[t] + (1+q^{OS}D[\eta^{OS}])(1+q^{SS}D[\eta^{SS}])h_{u,v}^{\overline{B}_0^s}[t]\right\} \; \varepsilon[t] \otimes G[t,\sigma[t]] \; \omega_{u,v}}$$

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CP disentanglement

Time-dependent angular analysis to disentangle CP-odd and CP-even addmixture of amplitudes in the final state

$$p.d.f. = \frac{\sum\limits_{u,v=S,0,\|,\perp} A_u\bar{A}_v \;\; f_{u,v}[\Omega] \;\; \Big\{(1+q^{OS}D[\eta^{OS}])(1+q^{OS}D[\eta^{OS}])h_{u,v}^{B_s^0}[t] + (1+q^{OS}D[\eta^{OS}])(1+q^{SS}D[\eta^{SS}])h_{u,v}^{\overline{B}_0^s}[t]\Big\} \;\; \varepsilon[t] \otimes G[t,\sigma[t]]}{\int_{0.3\,\mathrm{ps}}^{14\,\mathrm{ps}} dt \sum\limits_{u,v=S,0,\|,\perp} A_u\bar{A}_v \;\; \Big\{(1+q^{OS}D[\eta^{OS}])(1+q^{SS}D[\eta^{SS}])h_{u,v}^{B_s^0}[t] + (1+q^{OS}D[\eta^{OS}])(1+q^{SS}D[\eta^{SS}])h_{u,v}^{\overline{B}_0^s}[t]\Big\} \;\; \varepsilon[t] \otimes G[t,\sigma[t]] \;\; \omega_{u,v}}$$

ϕ_s in $B_s^0 \to J/\psi(e^+e^-)\phi(K^+K^-)$ decays

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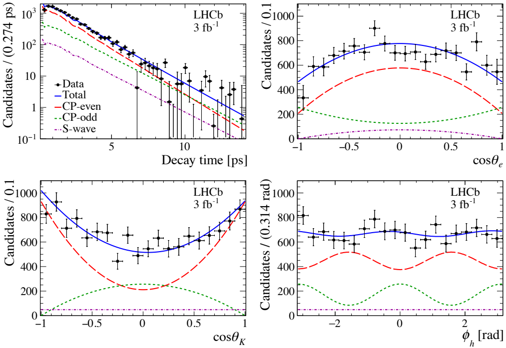
ϕ_s in $B_s^0 \to J/\psi(e^+e^-)\phi(K^+K^-)$ decays

Results

Eur. Phys. J. C (2021) 81: 1026

- Result is consistent with the SM predictions.
- Statistically limited.



First measurement of CP-violating phase in $B_s^0 \to J/\psi(e^+e^-)\phi$:

Measurements

$$\phi_s = 0.00 \pm 0.28 \pm 0.05\,\text{rad}$$

$$\Delta\Gamma_s = 0.115 \pm 0.045 \pm 0.011\,\text{ps}^{-1}$$

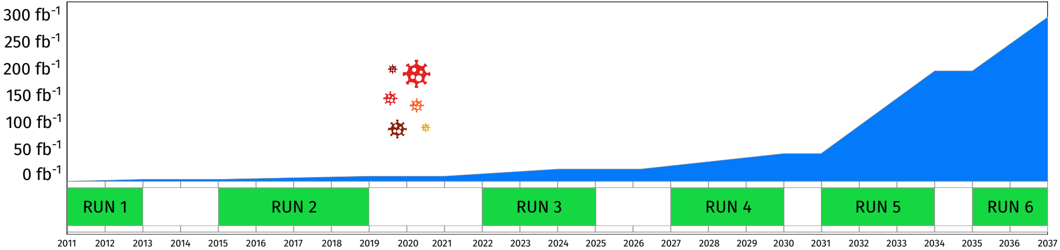
$$\Gamma_s = 0.608 \pm 0.018 \pm 0.011\,\text{ps}^{-1}$$

- Biggest systematic sources come from mass factorization, mass model and decay time resolution.
- Compatible with zero direct CPV.
- Compatible with no CPV in mixing.

Prospects

Prospects

- ATLAS to analyse remaining Run 2 data from 2018, ~ 59 fb^{1}.
- CMS to add triggers and taggers to their full Run 2 dataset.
- LHC*b* to analyse remaining Run 2 data from 2017 and 2018, ~ 4 fb^{-1}.
  - $B_s^0 \to J/\psi K^+K^-$ should get to $\sigma(\phi_s) \approx 22$ mrad from Run 1 + Run 2 alone.



With 300 fb^{-1} LHC*b* measurements of ϕ_s will be statistically dominated.

- $\sigma_{\text{stat.}}(\phi_s) \approx 4$ mrad with $B_s^0 \to J/\psi K^+K^-$ (≈ 3 mrad all modes combined).
- Improvements in trigger for $B_s^0 \to D_s^+D_s^-$ and adding other modes, i.e: $B_s^0 \to J/\psi(e^+e^-)K^+K^-$

CP violation in the B_s^0 system

Marcos Romero Lamas
on behalf of the ATLAS, CMS and LHC*b* collaborations

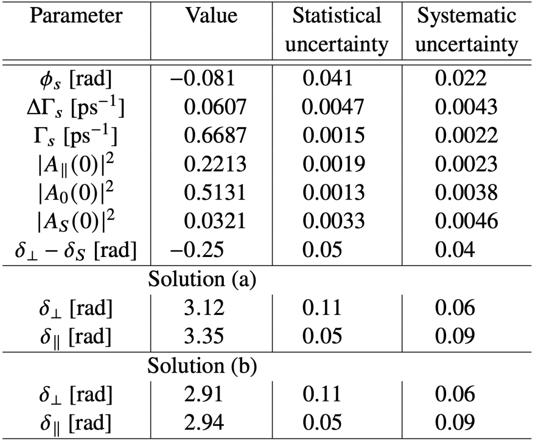
The Galician Institute of the High Energy Physics (IGFAE)
Santiago de Compostela

FPCP 2022
Oxford, Mississippi (USA), May 24th

- Time dependent analyses continue to be an important tool to study CP violation and test the Standard Model.
- LHC experiments opened the door to the systematic study of the B_s^0 system.
- Belle II will join the effort soon.
- Precision on ϕ_s is rapidly improving thanks to the many new measurements of B_s^0 decays.

+ please take a look at
CPV in B^0 decays
by D. Manuzzi

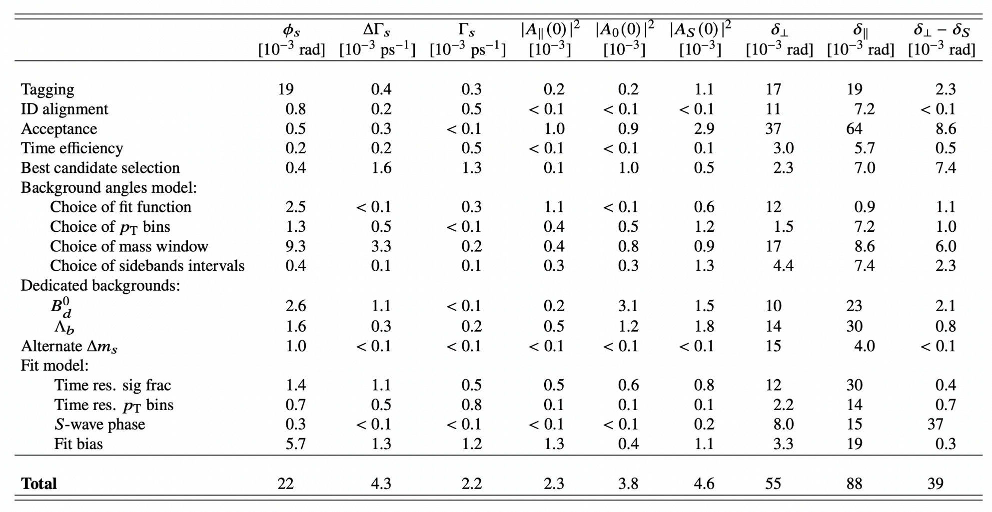
ϕ_s in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ tables: ATLAS



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

Backup

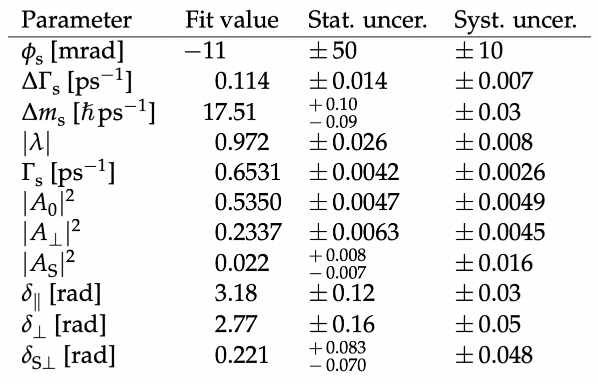
ϕ_s in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ tables: ATLAS



	ϕ_s [10^{-3} rad]	$\Delta\Gamma_s$ [10^{-3} ps^{-1}]	Γ_s [10^{-3} ps^{-1}]	$\lvert A_\parallel(0)\rvert^2$ [10^{-3}]	$\lvert A_0(0)\rvert^2$ [10^{-3}]	$\lvert A_S(0)\rvert^2$ [10^{-3}]	$\delta_\perp$ [10^{-3} rad]	$\delta_\parallel$ [10^{-3} rad]	$\delta_\perp - \delta_S$ [10^{-3} rad]
Tagging	19	0.4	0.3	0.2	0.2	1.1	17	19	2.3
ID alignment	0.8	0.2	0.5	< 0.1	< 0.1	< 0.1	11	7.2	< 0.1
Acceptance	0.5	0.3	< 0.1	1.0	0.9	2.9	37	64	8.6
Time efficiency	0.2	0.2	0.5	< 0.1	< 0.1	0.1	3.0	5.7	0.5
Best candidate selection	0.4	1.6	1.3	0.1	1.0	0.5	2.3	7.0	7.4
Background angles model:									
Choice of fit function	2.5	< 0.1	0.3	1.1	< 0.1	0.6	12	0.9	1.1
Choice of p_{T} bins	1.3	0.5	< 0.1	0.4	0.5	1.2	1.5	7.2	1.0
Choice of mass window	9.3	3.3	0.2	0.4	0.8	0.9	17	8.6	6.0
Choice of sidebands intervals	0.4	0.1	0.1	0.3	0.3	1.3	4.4	7.4	2.3
Dedicated backgrounds:									
B_d^0	2.6	1.1	< 0.1	0.2	3.1	1.5	10	23	2.1
Λ_b	1.6	0.3	0.2	0.5	1.2	1.8	14	30	0.8
Alternate Δm_s	1.0	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	15	4.0	< 0.1
Fit model:									
Time res. sig frac	1.4	1.1	0.5	0.5	0.6	0.8	12	30	0.4
Time res. p_{T} bins	0.7	0.5	0.8	0.1	0.1	0.1	2.2	14	0.7
S-wave phase	0.3	< 0.1	< 0.1	< 0.1	< 0.1	0.2	8.0	15	37
Fit bias	5.7	1.3	1.2	1.3	0.4	1.1	3.3	19	0.3
Total	22	4.3	2.2	2.3	3.8	4.6	55	88	39

Backup

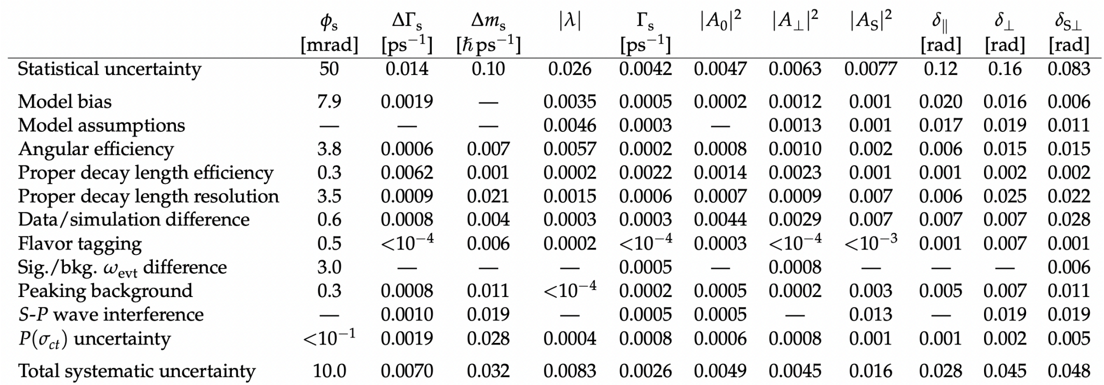
ϕ_s in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ tables: CMS



Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-11	± 50	± 10
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
Δm_s [$\hbar$ ps^{-1}]	17.51	$^{+0.10}_{-0.09}$	± 0.03
$\lvert\lambda\rvert$	0.972	± 0.026	± 0.008
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0026
$\lvert A_0\rvert^2$	0.5350	± 0.0047	± 0.0049
$\lvert A_\perp\rvert^2$	0.2337	± 0.0063	± 0.0045
$\lvert A_S\rvert^2$	0.022	$^{+0.008}_{-0.007}$	± 0.016
$\delta_\parallel$ [rad]	3.18	± 0.12	± 0.03
$\delta_\perp$ [rad]	2.77	± 0.16	± 0.05
$\delta_{S\perp}$ [rad]	0.221	$^{+0.083}_{-0.070}$	± 0.048

Backup

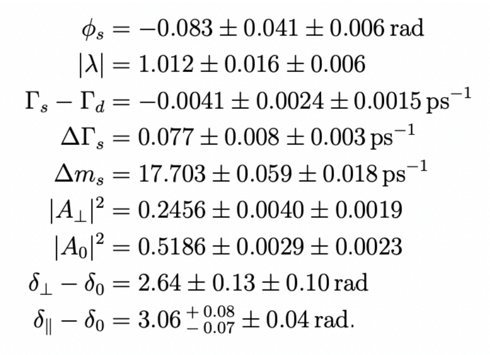
ϕ_s in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ tables: CMS



	ϕ_s [mrad]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [$\hbar$ ps^{-1}]	$\lvert\lambda\rvert$	Γ_s [ps^{-1}]	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	$\lvert A_S\rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]
Statistical uncertainty	50	0.014	0.10	0.026	0.0042	0.0047	0.0063	0.0077	0.12	0.16	0.083
Model bias	7.9	0.0019	—	0.0035	0.0005	0.0002	0.0012	0.001	0.020	0.016	0.006
Model assumptions	—	—	—	0.0046	0.0003	—	0.0013	0.001	0.017	0.019	0.011
Angular efficiency	3.8	0.0006	0.007	0.0057	0.0002	0.0008	0.0010	0.002	0.006	0.015	0.015
Proper decay length efficiency	0.3	0.0062	0.001	0.0002	0.0022	0.0014	0.0023	0.001	0.001	0.002	0.002
Proper decay length resolution	3.5	0.0009	0.021	0.0015	0.0006	0.0007	0.0009	0.007	0.006	0.025	0.022
Data/simulation difference	0.6	0.0008	0.004	0.0003	0.0003	0.0044	0.0029	0.007	0.007	0.007	0.028
Flavor tagging	0.5	$<10^{-4}$	0.006	0.0002	$<10^{-4}$	0.0003	$<10^{-4}$	$<10^{-3}$	0.001	0.007	0.001
Sig./bkg. ω_{evt} difference	3.0	—	—	—	0.0005	—	0.0008	—	—	—	0.006
Peaking background	0.3	0.0008	0.011	$<10^{-4}$	0.0002	0.0005	0.0002	0.003	0.005	0.007	0.011
S-*P* wave interference	—	0.0010	0.019	—	0.0005	0.0005	—	0.013	—	0.019	0.019
$P(\sigma_{ct})$ uncertainty	$<10^{-1}$	0.0019	0.028	0.0004	0.0008	0.0006	0.0008	0.001	0.001	0.002	0.005
Total systematic uncertainty	10.0	0.0070	0.032	0.0083	0.0026	0.0049	0.0045	0.016	0.028	0.045	0.048

Backup

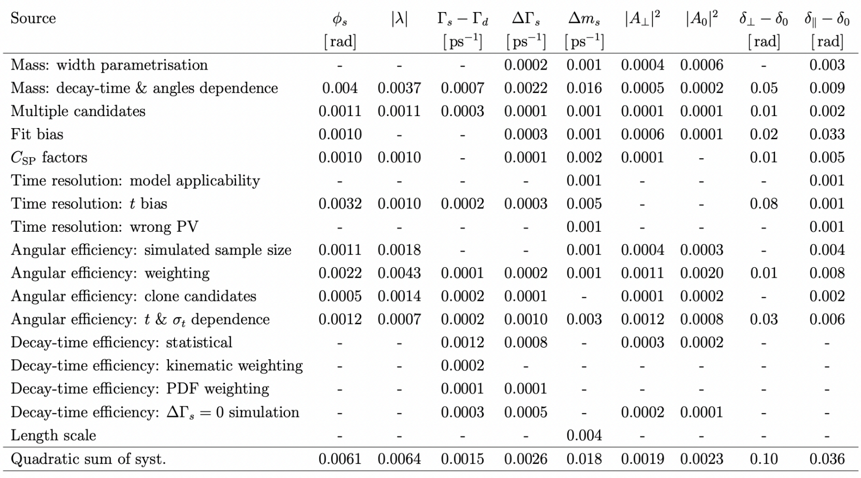
ϕ_s in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ tables: LHC*b*



$$\begin{aligned}
\phi_s &= -0.083 \pm 0.041 \pm 0.006\,\mathrm{rad} \\
|\lambda| &= 1.012 \pm 0.016 \pm 0.006 \\
\Gamma_s - \Gamma_d &= -0.0041 \pm 0.0024 \pm 0.0015\,\mathrm{ps}^{-1} \\
\Delta\Gamma_s &= 0.077 \pm 0.008 \pm 0.003\,\mathrm{ps}^{-1} \\
\Delta m_s &= 17.703 \pm 0.059 \pm 0.018\,\mathrm{ps}^{-1} \\
|A_\perp|^2 &= 0.2456 \pm 0.0040 \pm 0.0019 \\
|A_0|^2 &= 0.5186 \pm 0.0029 \pm 0.0023 \\
\delta_\perp - \delta_0 &= 2.64 \pm 0.13 \pm 0.10\,\mathrm{rad} \\
\delta_\parallel - \delta_0 &= 3.06\,{}^{+\,0.08}_{-\,0.07} \pm 0.04\,\mathrm{rad}.
\end{aligned}$$

Backup

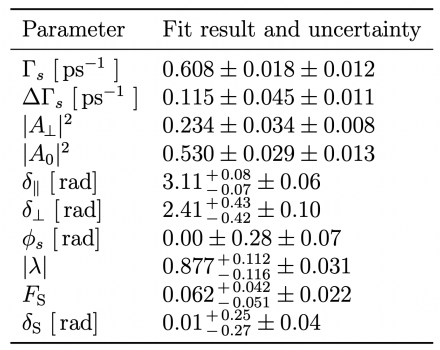
ϕ_s in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ tables: LHC*b*



Source	ϕ_s [rad]	$\lvert\lambda\rvert$	$\Gamma_s - \Gamma_d$ [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [ps^{-1}]	$\lvert A_\perp\rvert^2$	$\lvert A_0\rvert^2$	$\delta_\perp - \delta_0$ [rad]	$\delta_\parallel - \delta_0$ [rad]
Mass: width parametrisation	-	-	-	0.0002	0.001	0.0004	0.0006	-	0.003
Mass: decay-time & angles dependence	0.004	0.0037	0.0007	0.0022	0.016	0.0005	0.0002	0.05	0.009
Multiple candidates	0.0011	0.0011	0.0003	0.0001	0.001	0.0001	0.0001	0.01	0.002
Fit bias	0.0010	-	-	0.0003	0.001	0.0006	0.0001	0.02	0.033
C_{SP} factors	0.0010	0.0010	-	0.0001	0.002	0.0001	-	0.01	0.005
Time resolution: model applicability	-	-	-	-	0.001	-	-	-	0.001
Time resolution: t bias	0.0032	0.0010	0.0002	0.0003	0.005	-	-	0.08	0.001
Time resolution: wrong PV	-	-	-	-	0.001	-	-	-	0.001
Angular efficiency: simulated sample size	0.0011	0.0018	-	-	0.001	0.0004	0.0003	-	0.004
Angular efficiency: weighting	0.0022	0.0043	0.0001	0.0002	0.001	0.0011	0.0020	0.01	0.008
Angular efficiency: clone candidates	0.0005	0.0014	0.0002	0.0001	-	0.0001	0.0002	-	0.002
Angular efficiency: t & σ_t dependence	0.0012	0.0007	0.0002	0.0010	0.003	0.0012	0.0008	0.03	0.006
Decay-time efficiency: statistical	-	-	0.0012	0.0008	-	0.0003	0.0002	-	-
Decay-time efficiency: kinematic weighting	-	-	0.0002	-	-	-	-	-	-
Decay-time efficiency: PDF weighting	-	-	0.0001	0.0001	-	-	-	-	-
Decay-time efficiency: $\Delta\Gamma_s = 0$ simulation	-	-	0.0003	0.0005	-	0.0002	0.0001	-	-
Length scale	-	-	-	-	0.004	-	-	-	-
Quadratic sum of syst.	0.0061	0.0064	0.0015	0.0026	0.018	0.0019	0.0023	0.10	0.036

Backup

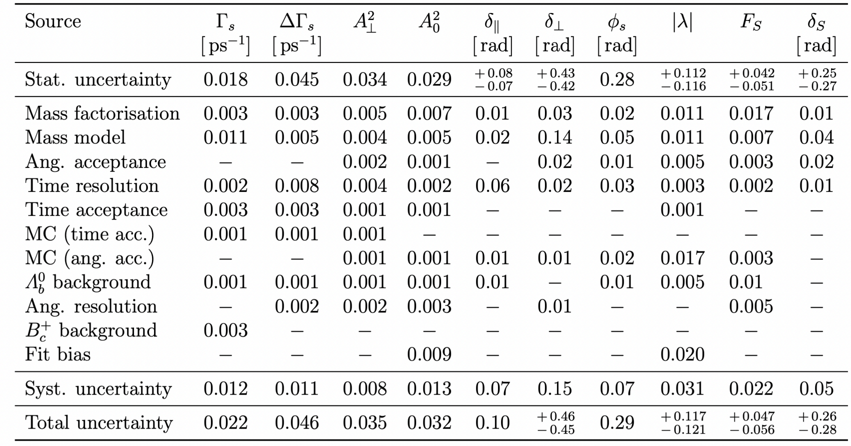
ϕ_s in $B_s^0 \to J/\psi(e^+e^-)\phi(K^+K^-)$ tables



Parameter	Fit result and uncertainty
$\Gamma_s\ [\mathrm{ps}^{-1}]$	$0.608 \pm 0.018 \pm 0.012$
$\Delta\Gamma_s\ [\mathrm{ps}^{-1}]$	$0.115 \pm 0.045 \pm 0.011$
$\|A_\perp\|^2$	$0.234 \pm 0.034 \pm 0.008$
$\|A_0\|^2$	$0.530 \pm 0.029 \pm 0.013$
$\delta_\parallel$ [rad]	$3.11\,^{+0.08}_{-0.07} \pm 0.06$
$\delta_\perp$ [rad]	$2.41\,^{+0.43}_{-0.42} \pm 0.10$
ϕ_s [rad]	$0.00 \pm 0.28 \pm 0.07$
$\|\lambda\|$	$0.877\,^{+0.112}_{-0.116} \pm 0.031$
F_S	$0.062\,^{+0.042}_{-0.051} \pm 0.022$
δ_S [rad]	$0.01\,^{+0.25}_{-0.27} \pm 0.04$

Backup

ϕ_s in $B_s^0 \to J/\psi(e^+e^-)\phi(K^+K^-)$ tables



Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$A_\perp^2$	A_0^2	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\lvert\lambda\rvert$	F_S	δ_S [rad]
Stat. uncertainty	0.018	0.045	0.034	0.029	$^{+0.08}_{-0.07}$	$^{+0.43}_{-0.42}$	0.28	$^{+0.112}_{-0.116}$	$^{+0.042}_{-0.051}$	$^{+0.25}_{-0.27}$
Mass factorisation	0.003	0.003	0.005	0.007	0.01	0.03	0.02	0.011	0.017	0.01
Mass model	0.011	0.005	0.004	0.005	0.02	0.14	0.05	0.011	0.007	0.04
Ang. acceptance	–	–	0.002	0.001	–	0.02	0.01	0.005	0.003	0.02
Time resolution	0.002	0.008	0.004	0.002	0.06	0.02	0.03	0.003	0.002	0.01
Time acceptance	0.003	0.003	0.001	0.001	–	–	–	0.001	–	–
MC (time acc.)	0.001	0.001	0.001	–	–	–	–	–	–	–
MC (ang. acc.)	–	–	0.001	0.001	0.01	0.01	0.02	0.017	0.003	–
Λ_b^0 background	0.001	0.001	0.001	0.001	0.01	–	0.01	0.005	0.01	–
Ang. resolution	–	0.002	0.002	0.003	–	0.01	–	–	0.005	–
B_c^+ background	0.003	–	–	–	–	–	–	–	–	–
Fit bias	–	–	–	0.009	–	–	–	0.020	–	–
Syst. uncertainty	0.012	0.011	0.008	0.013	0.07	0.15	0.07	0.031	0.022	0.05
Total uncertainty	0.022	0.046	0.035	0.032	0.10	$^{+0.46}_{-0.45}$	0.29	$^{+0.117}_{-0.121}$	$^{+0.047}_{-0.056}$	$^{+0.26}_{-0.28}$