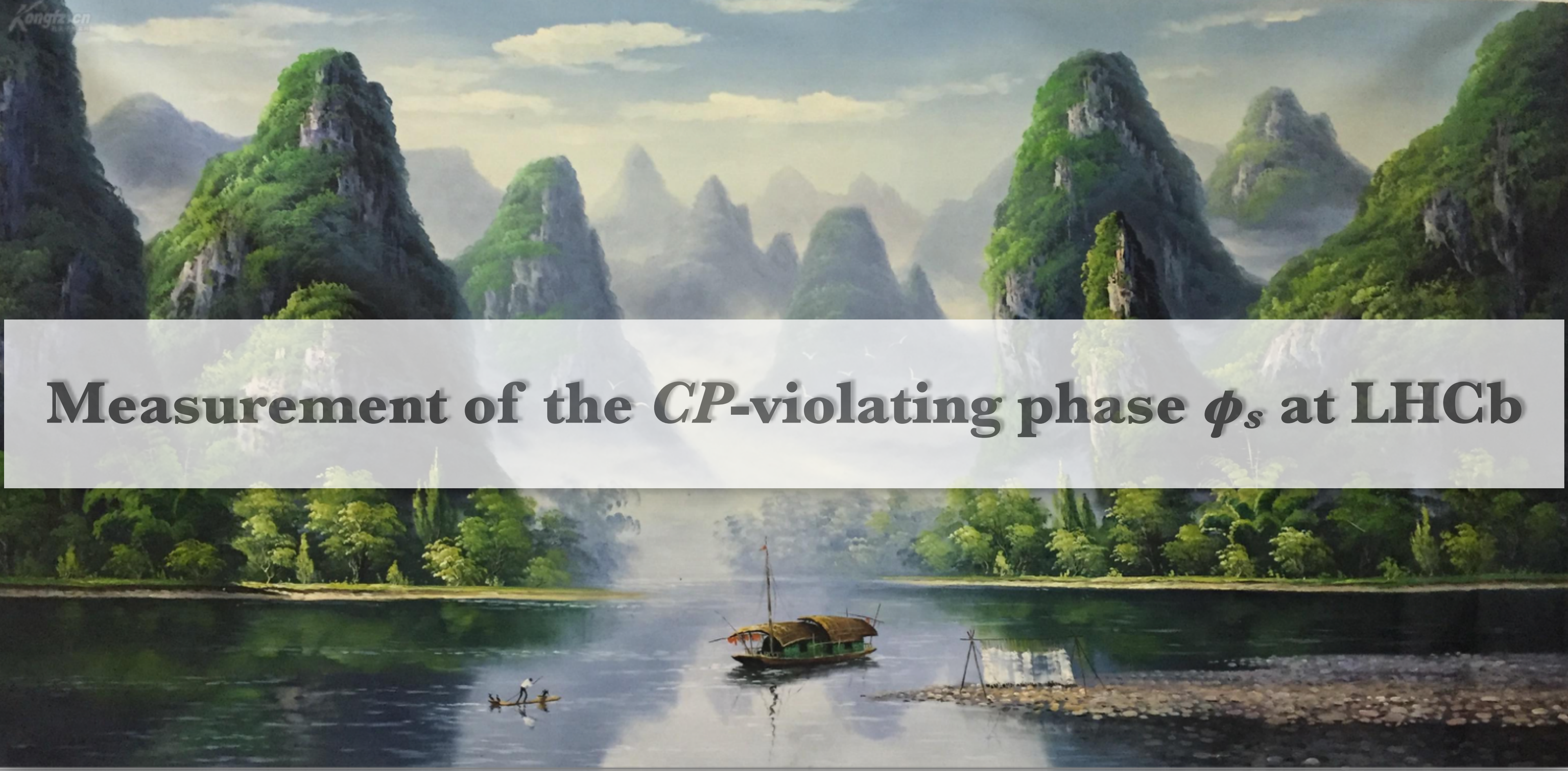
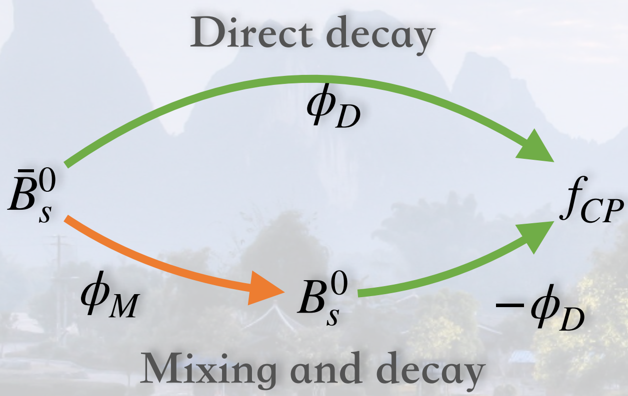
Measurement of the *CP*-violating phase ϕ_s at LHCb

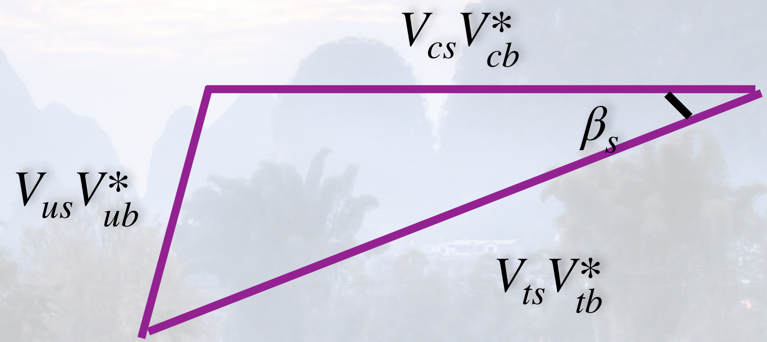


Xuesong Liu, on behalf of the LHCb collaboration
Tsinghua University

XVIII International Conference on Hadron Spectroscopy and Structure
August 2019, Guilin

CP-violation in B_s^0 mixing and decays, ϕ_s



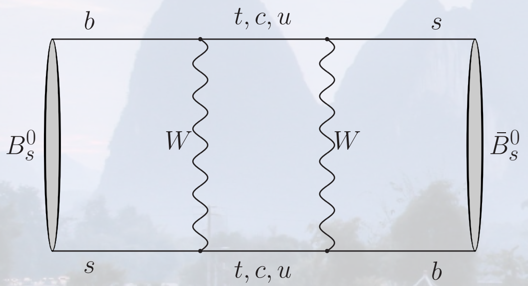


$$\phi_s = \phi_M - 2\phi_D$$

$$\beta_s = \frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}$$

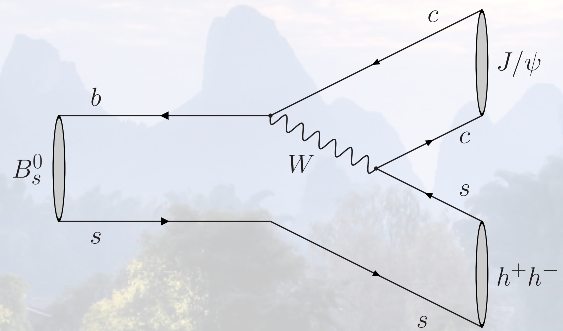
- $\phi_s = -\arg(\lambda_f),\ \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$ is a mixing-induced *CPV* phase in B_s^0 decays
- Assuming only SM tree level contribution, $\phi_s^{SM} = -2\beta_s$ - angle in B_s^0 system analogous to β in B^0 system
- Possibility measurement in interference between B_s^0 mixing and decay.
  - via $b \to c\bar{c}s$ transitions, with decays like $B_s^0 \to J/\psi h^+h^-(h = K, \pi)$

CP-violation in B_s^0 mixing and decays, ϕ_s



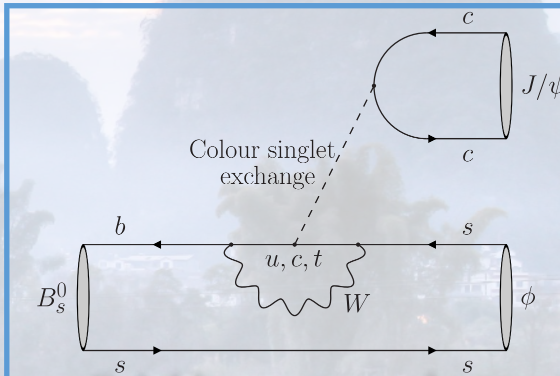
Mixing

+



Color-suppressed $b \to c\bar{c}s$ tree

+



Cabibbo-suppressed penguin

$B_{H,L} = pB_s^0 \pm q\bar{B}_s^0$

Golden mode: $B_s^0 \to J/\psi(\to \mu\mu)\phi(KK)$

+ smaller weak exchange and penguin annihilation diagrams

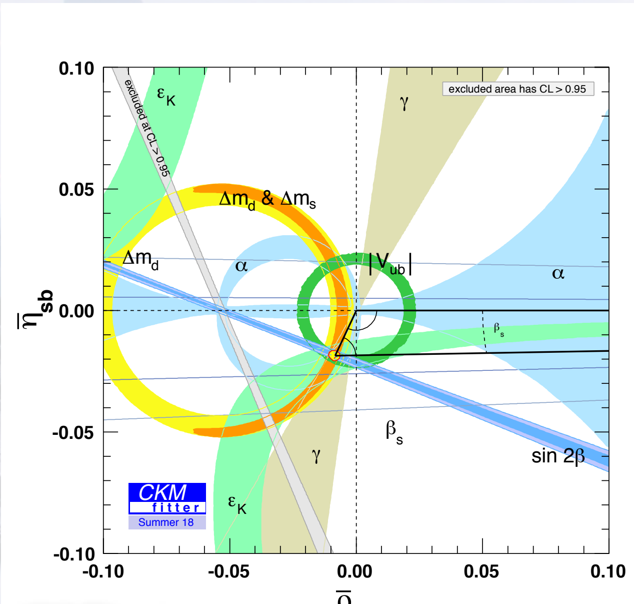
$$\phi_s = \phi_s^{\mathrm{SM}} + \Delta\phi_s^{\mathrm{peng}} + \Delta\phi_s^{\mathrm{NP}}$$

- ϕ_s is sensitive to New Physics in B_s^0 mixing,
- ϕ_s^{SM} determined via global fit to CKM matrix

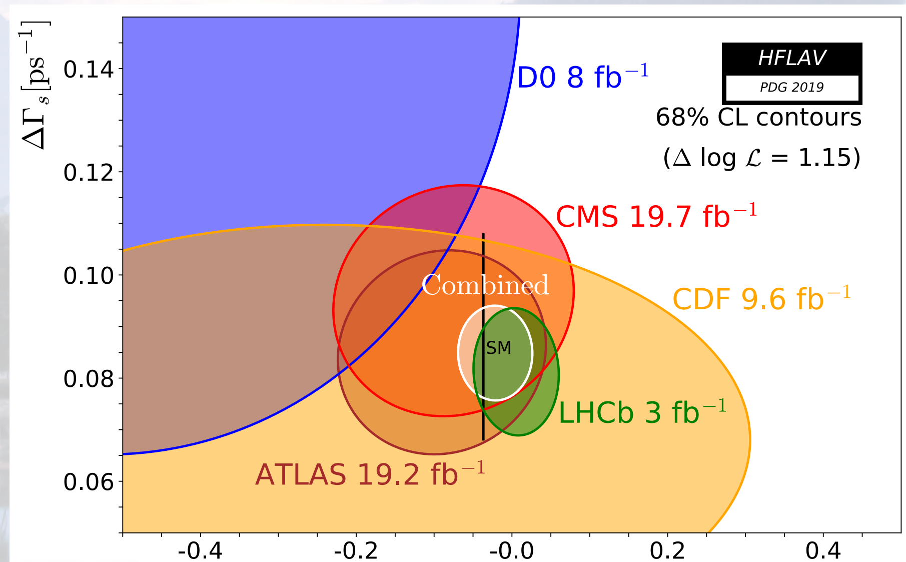
$$\phi_s^{\mathrm{SM}} = -0.0368^{+0.0010}_{-0.0008} \text{ rad}$$ [CKMFitter], no penguins

- If $\phi_s^{\mathrm{exp}} \neq \phi_s^{\mathrm{SM}}$, NP is found!

Status of ϕ_s before Spring 2019



[CKMFitter]



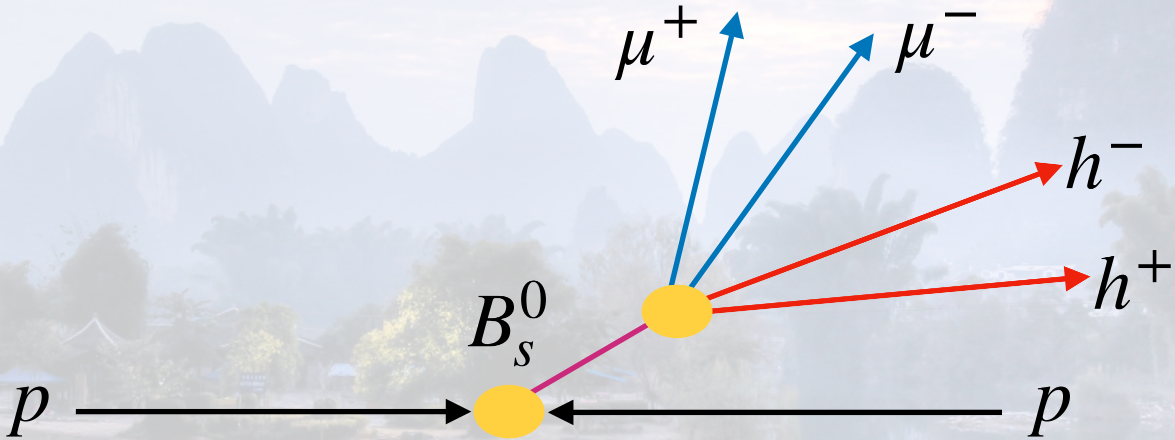
[HFLAV]

$$\phi_s^{\mathrm{SM}} = -0.0368^{+0.0010}_{-0.0008}\ \mathrm{rad}\ \text{[CKMFitter]}$$

$$\phi_s^{\mathrm{exp}} = -0.021 \pm 0.031\ \mathrm{rad}\ \text{[HFLAV]}$$

- World average dominated by LHCb
- Results consistent with SM-based global fits to data, but still room for NP

ϕ_s in $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$



$B_s^0 \to J/\psi(\to \mu^+\mu^-)K^+K^-$

- Relatively large BF, $\mathcal{O}(10^{-3})$
- The final state is a mixture of CP-even (L=0,2) and CP-odd (L=1+S-wave) components
- Allow to obtain $\Gamma_s = \frac{\Gamma_H + \Gamma_L}{2}$, $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ and $\Delta m_s = m_H - m_L$

$B_s^0 \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$

- BR $\mathcal{O}(10^{-4})$
- Crosscheck of $B_s^0 \to J/\psi K^+K^-$
- Dominated by CP-odd components which allows to measure Γ_H

H : Heavy mass eigenstate
L : Light mass eigenstate

Key ingredients

Definition of time-dependent CP asymmetry

$$A_{\mathrm{CP}} \equiv \frac{\Gamma(\overline{B}(t) - f) - \Gamma(B(t) - f)}{\Gamma(\overline{B}(t) - f) + \Gamma(B(t) - f)} \approx \eta_f \sin(\phi_s) \sin\Delta(m_s t)$$

Experimentally it becomes

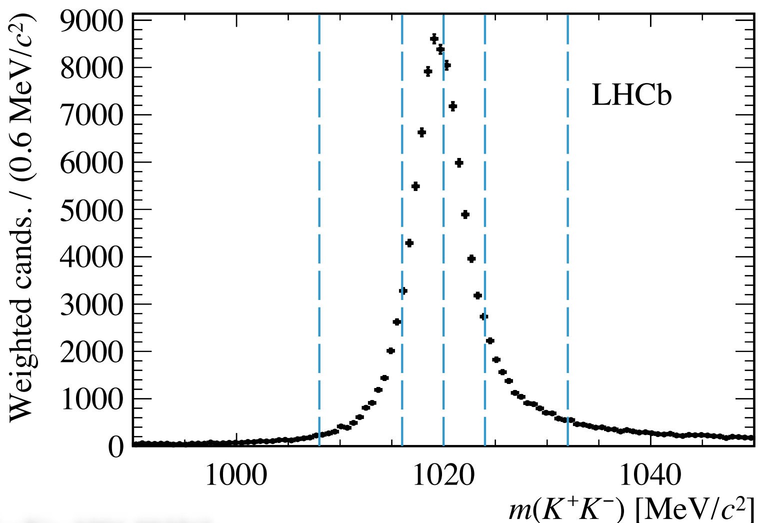
$$A_{\mathrm{CP}} = e^{\frac{1}{2}\Delta m_s \sigma_t^2}(1 - 2\omega)\eta_f \sin(\phi_s)\sin(\Delta m_s t)$$

Critical requirements

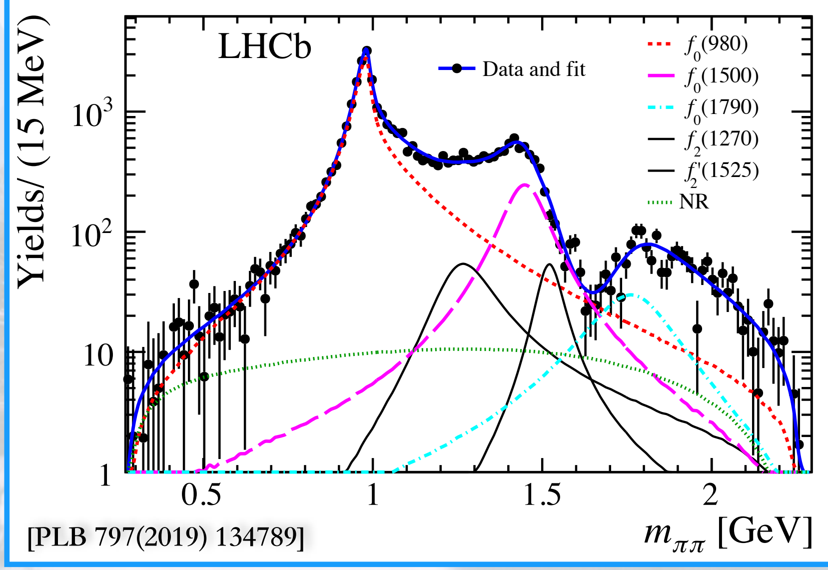
- Excellent decay-time resolution $\sigma_t \ll T$, B_s^0 oscillations fast $T \approx 350$ fs
- CP eigenvalue of the final state $\eta_f \Rightarrow$ angular analysis disentangles CP-odd and even mixture of the final states
- Tagging of meson flavor at production: probability of wrong tag ω
- Reliable modeling of decay-time efficiency $\epsilon(t)$ and angular efficiency $\epsilon(\Omega)$

New $B_s^0 \to J/\psi K^+K^-$ [arXiv:1906.08356] and $B_s^0 \to J/\psi\pi^+\pi^-$ [PLB 797(2019) 134789]

Run-II LHCb measurements with 2015 (0.3 fb-1) and 2016 (1.6 fb-1) datasets



[arXiv:1906.08356]



[PLB 797(2019) 134789]

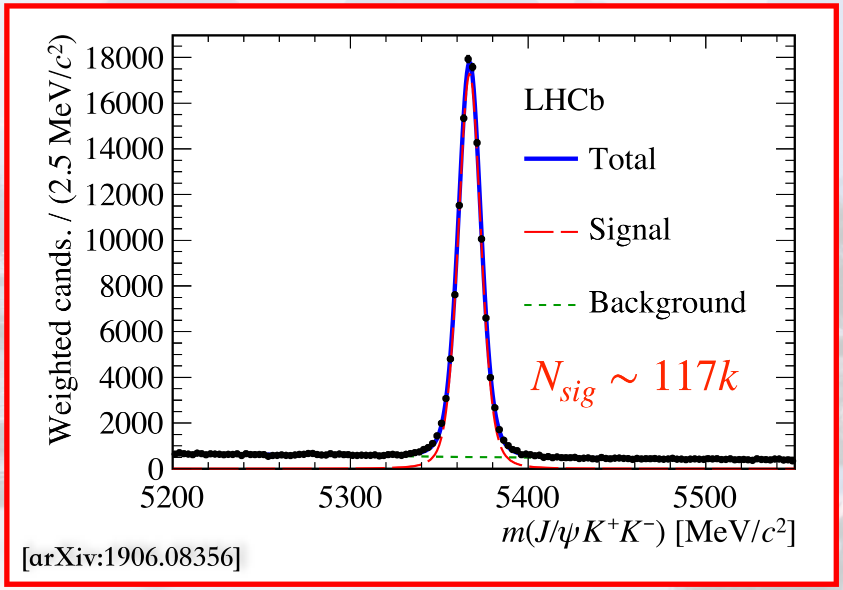
Analysis strategy

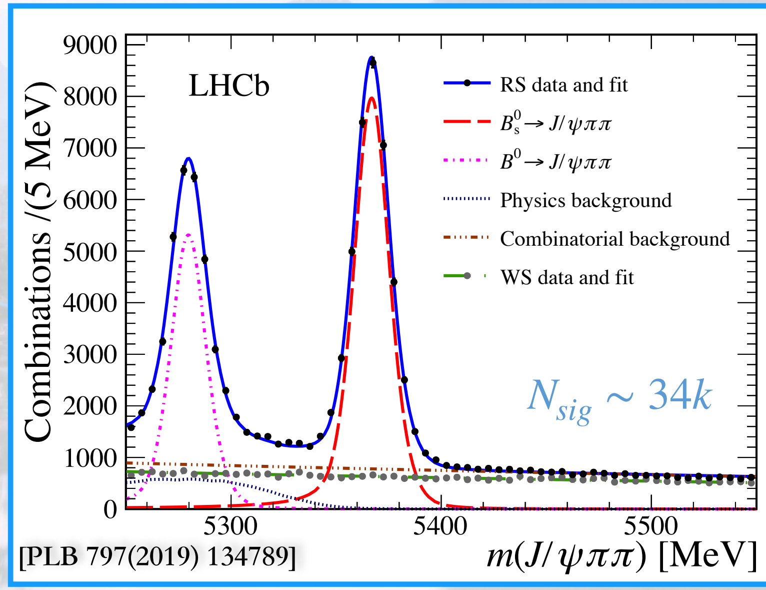
- Combinatorial background suppressed with a BDT using kinematic variables
- Background subtracted using *sPlot* with B_s^0 candidate masses
- Careful study of decay-time resolution and efficiencies, angular efficiencies and flavor tagging
- *sFit* to 3 helicity angles and B_s^0 candidates decay time+ ($m_{\pi\pi}$ for $B_s^0 \to J/\psi\pi^+\pi^-$)

Background subtraction

$B_s^0 \to J/\psi K^+K^-$
$B_s^0 \to J/\psi \pi^+\pi^-$

Boosted decision tree is trained to select signal candidates



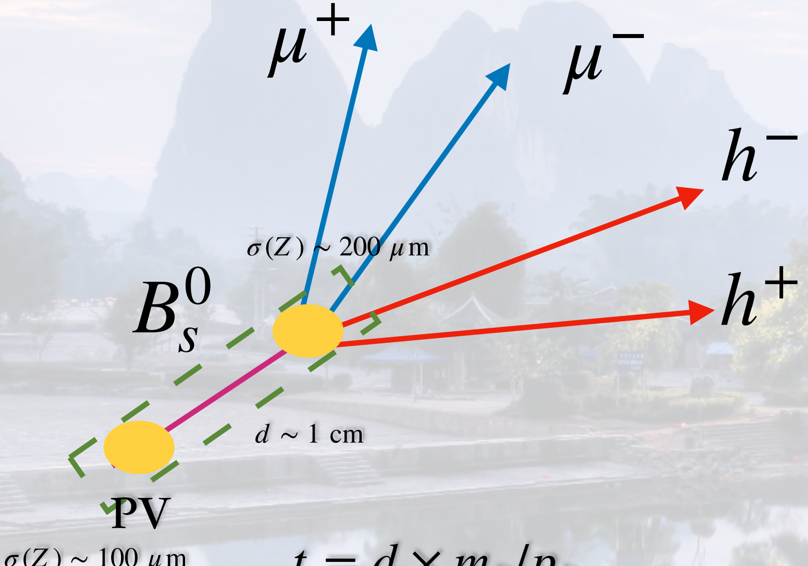


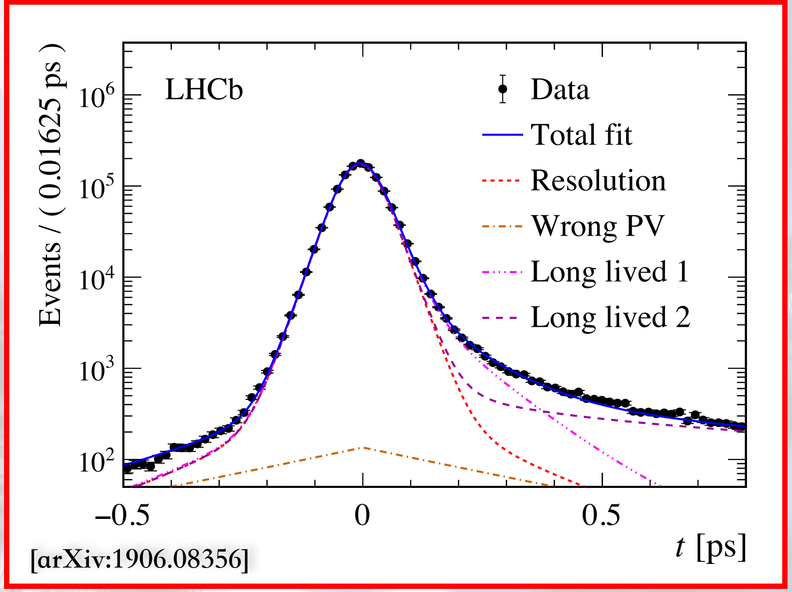
- $\Lambda_b^0 \to J/\psi pK$ subtracted with negative MC weights, $B^0 \to J/\psi K^+\pi^-$ negligible
- Mass fit: combinatorial background (exp,) and signal $B_s^0 \to J/\psi K^+K^-$

- $\Lambda_b^0 \to J/\psi pK$ and $B_s^0 \to J/\psi\eta'(\to \rho^0\gamma)$ using MC shaped
- Combinatorial background estimated using wrong sign (WS) $J/\psi\pi^\pm\pi^\pm$ data

Decay-time resolution

$B_s^0 \to J/\psi K^+ K^-$
$B_s^0 \to J/\psi \pi^+ \pi^-$





$t = d \times m_B / p_B$

- Pre-candidate decay-time error σ_t is calibrated using prompt J/ψ sample formed from J/ψ and two kaons (pions) from PV

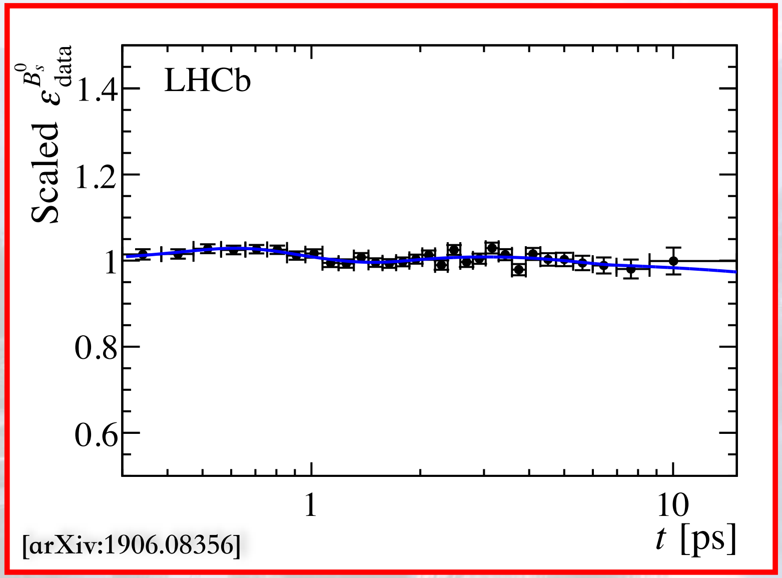
$\sigma_{\text{eff}}(B_s^0 \to J/\psi K^+ K^-) = 45.5$ fs

$\sigma_{\text{eff}}(B_s^0 \to J/\psi \pi^+ \pi^-) = 41.5$ fs

- Impact of decay-time resolution, $\Delta m_s \approx 17.7\ \text{ps}^{-1}$
  - If $\sigma_{\text{eff}} = 45$ fs, dilution factor $e^{\frac{1}{2}\Delta m_s \sigma_t^2} = 0.73$
  - If $\sigma_{\text{eff}} = 90$ fs, dilution factor $e^{\frac{1}{2}\Delta m_s \sigma_t^2} = 0.28$

Decay-time efficiency

$B_s^0 \to J/\psi K^+ K^-$

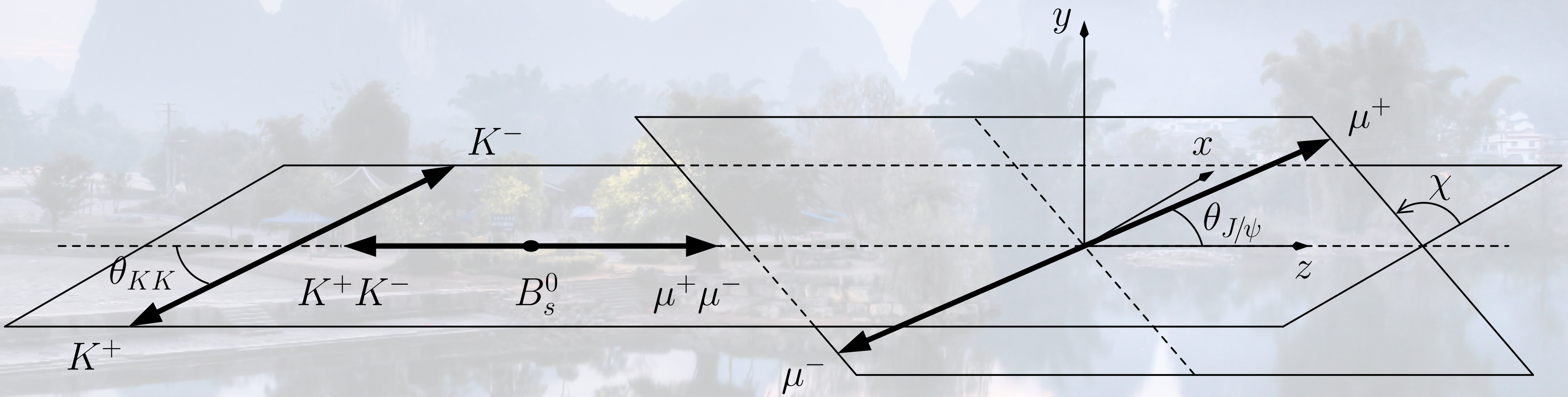


- Use $B^0 \to J/\psi K^{*0}(892)$ as control channel, fit simultaneously B^0 data, simulation and B_s^0 simulation

$$\epsilon_{\rm data}^{B_s^0}(t) = \epsilon_{\rm data}^{B^0}(t) \times \frac{\epsilon_{\rm MC}^{B_s^0}(t)}{\epsilon_{\rm MC}^{B^0}(t)}$$

- Method validated with $B^+ \to J/\psi K^+$
  - $\Gamma_u - \Gamma_d = -0.0478 \pm 0.0013\ \mathrm{ps}^{-1}$ (stat. only) vs. $(\Gamma_u - \Gamma_d)^{\rm PDG} = -0.0474 \pm 0.0023\ \mathrm{ps}^{-1}$

Angular and $m_{\pi\pi}$ efficiency

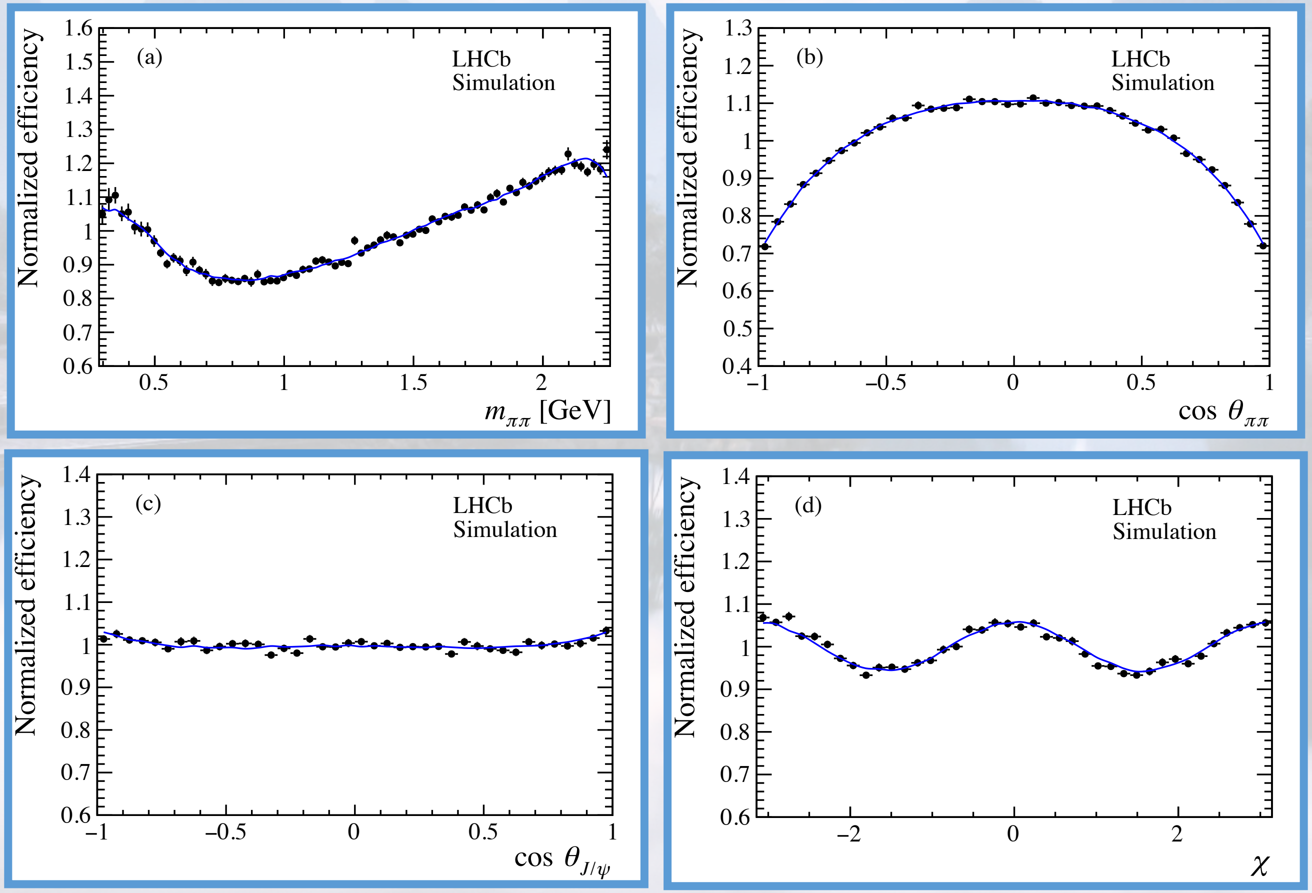


- Kinematic selection and detector acceptance can cause non uniform efficiency as function of decay angles and $m_{\pi\pi}$ ($B_s^0 \to J/\psi\pi^+\pi^-$)
- Efficiencies obtained from simulation and corrected to match the data
  - Method $B_s^0 \to J/\psi K^+K^-$ validated on $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^*$ data, good agreement are found

Angular and $m_{\pi\pi}$ efficiency

$B_s^0 \to J/\psi\pi^+\pi^-$

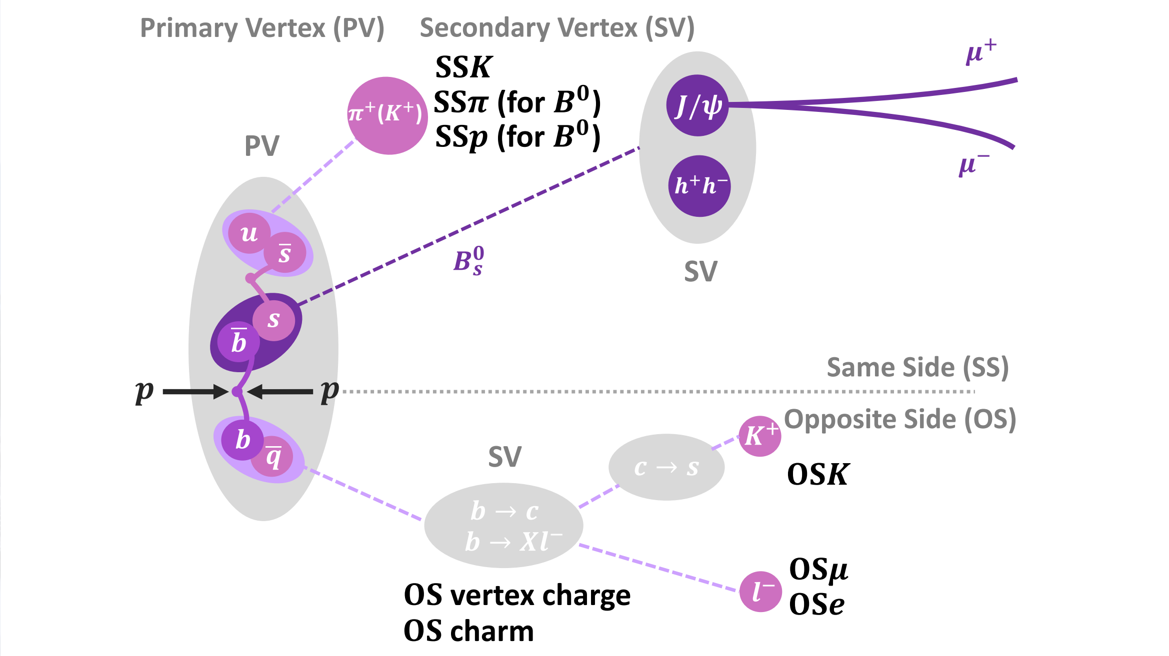
Angular and $m_{\pi\pi}$ efficiency obtained with $B_s^0 \to J/\psi\pi^+\pi^-$ simulation



[PLB 797(2019) 134789]

Flavour tagging

$B_s^0 \to J/\psi K^+ K^-$
$B_s^0 \to J/\psi \pi^+ \pi^-$



- Tagging power $\epsilon_{\text{tag}}(1-2\omega)^2$ is used to estimated the performance of flavor tagging
- More tagging power = better exploitation of data

$\epsilon_{\text{tag}}(1-2\omega)^2 = 4.73 \pm 0.34\ \%$

$\epsilon_{\text{tag}}(1-2\omega)^2 = 5.06 \pm 0.38\ \%$

$B_s^0 \to J/\psi K^+K^-$

Systematics for $B_s^0 \to J/\psi K^+K^-$

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	0.0005	0.0006	0.05	0.009
Mass: decay-time & angles dependence	0.004	0.0037	0.0007	0.0022	0.016	0.0004	0.0002	0.01	0.004
Multiple candidates	0.0011	0.0011	0.0003	0.0001	0.001	0.0001	0.0006	0.01	0.002
Fit bias	0.0010	-	-	0.0003	0.001	0.0006	0.0001	0.02	0.033
$C_{\rm SP}$ 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	0.0024	0.10	0.037

[arXiv:1906.08356]

- Main systematic uncertainties on ϕ_s is flavor tagging ~ 0.015 rad, which incorporated in statistical

Systematics for $B_s^0 \to J/\psi\pi^+\pi^-$

$B_s^0 \to J/\psi\pi^+\pi^-$

Source	$\Gamma_{\mathrm{H}} - \Gamma_{B^0}$ [fs^{-1}]	$\lvert\lambda\rvert$ [$\times 10^{-3}$]	ϕ_s [mrad]
Decay-time acceptance	2.0	0.0	0.3
τ_{B^0}	0.2	0.5	0.0
Efficiency ($m_{\pi\pi}$, Ω)	0.2	0.1	0.0
Decay-time resolution width	0.0	4.3	4.0
Decay-time resolution mean	0.3	1.2	0.3
Background	3.0	2.7	0.6
Flavour tagging	0.0	2.2	2.3
Δm_s	0.3	4.6	2.5
Γ_{L}	0.3	0.4	0.4
B_c^+	0.5	-	-
Resonance parameters	0.6	1.9	0.8
Resonance modelling	0.5	28.9	9.0
Production asymmetry	0.3	0.6	3.4
Total	3.8	29.9	11.0

[PLB 797(2019) 134789]

- $\Gamma_H - \Gamma_{B^0}$ mainly affected by Efficiency of $m_{\pi\pi}$ and Ω , ϕ_s and $|\lambda|$ by resonance modeling

Results and new LHCb combination

$B_s^0 \to J/\psi K^+K^-$
$B_s^0 \to J/\psi \pi^+\pi^-$

$B_s^0 \to J/\psi K^+K^-$ [arXiv:1906.08356]

$$\phi_s = -0.083 \pm 0.041 \pm 0.006 \text{ rad}$$
$$|\lambda| = 1.012 \pm 0.016 \pm 0.006$$
$$\Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.077 \pm 0.008 \pm 0.003 \text{ ps}^{-1}$$

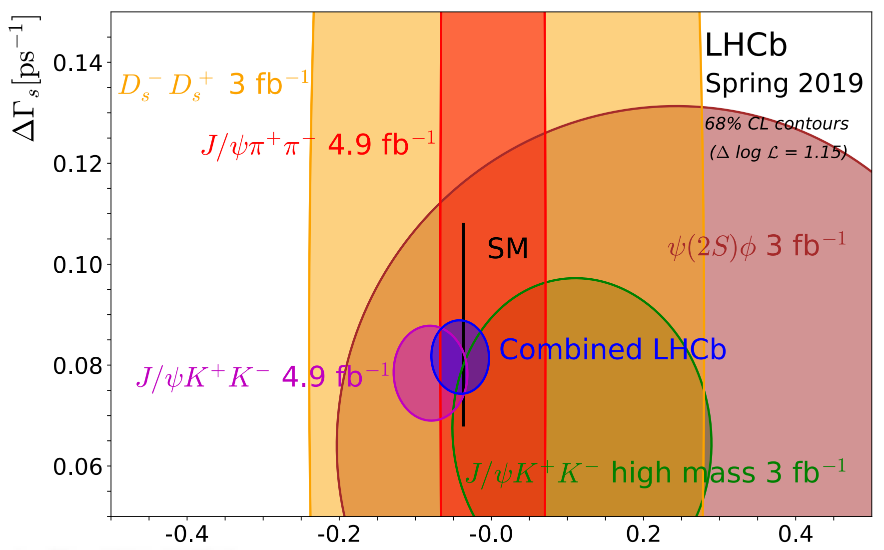
$B_s^0 \to J/\psi \pi^+\pi^-$ [PLB 797(2019) 134789]

$$\phi_s = -0.057 \pm 0.060 \pm 0.011 \text{ rad}$$
$$|\lambda| = 1.01^{+0.08}_{-0.06} \pm 0.03$$
$$\Gamma_H - \Gamma_{B^0} = -0.050 \pm 0.004 \pm 0.004 \text{ ps}^{-1}$$

Combination of all LHCb (Run I+II) results

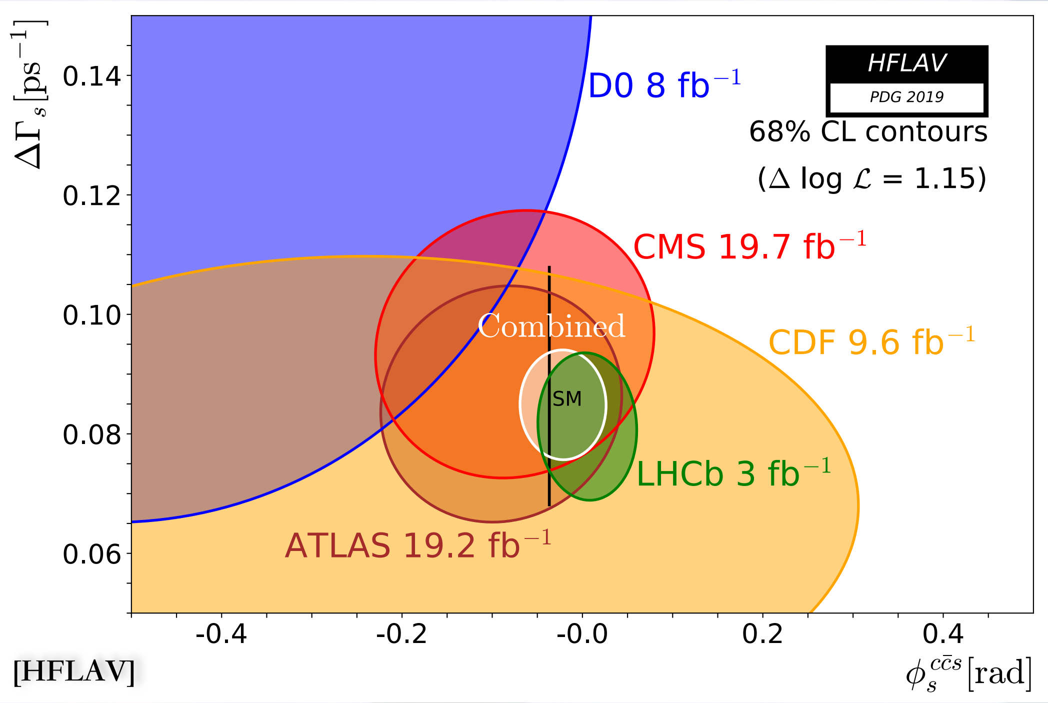
[arXiv:1906.08356]

$$\phi_s = -0.041 \pm 0.025 \text{ rad}$$
$$|\lambda| = 0.993 \pm 0.010$$
$$\Gamma_s = -0.6562 \pm 0.0021 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0816 \pm 0.0048 \text{ ps}^{-1}$$



[arXiv:1906.08356]

HFLAV combination

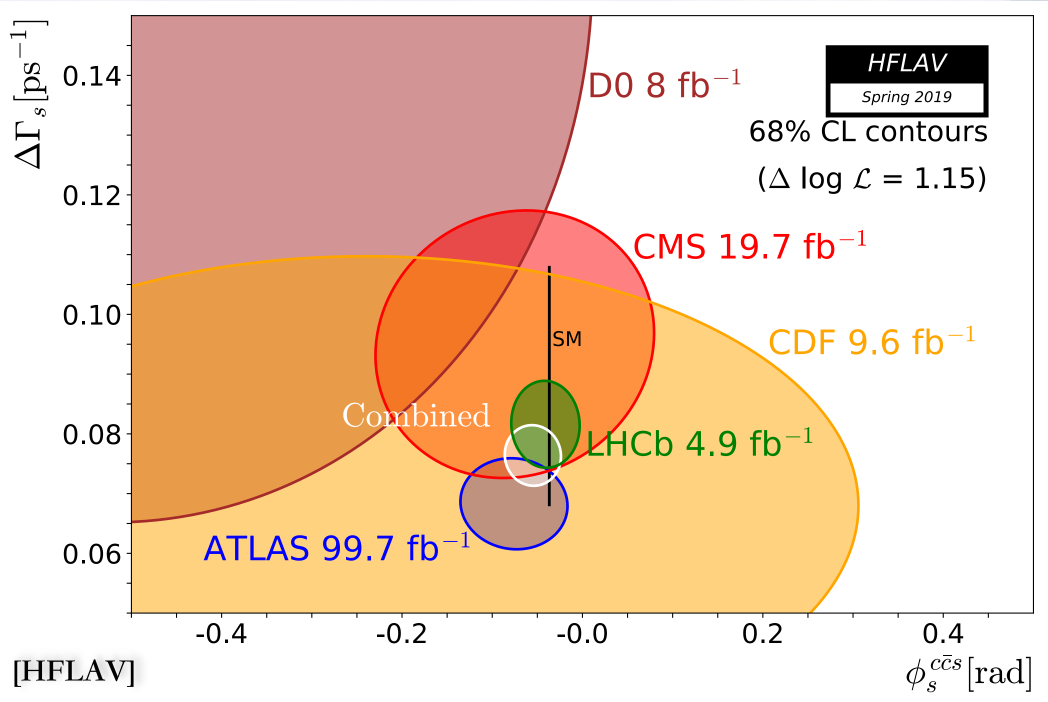


$$\phi_s^{\mathrm{exp}} = -0.021 \pm 0.031\ \mathrm{rad}$$
$$\Delta\Gamma_s^{\mathrm{exp}} = 0.0849 \pm 0.0061\ \mathrm{ps}^{-1}$$

Reminder:

$$\phi_s^{\mathrm{SM}} = -0.0368^{+0.0010}_{-0.0008}\ \mathrm{rad}$$ [CKMFitter]

HFLAV combination

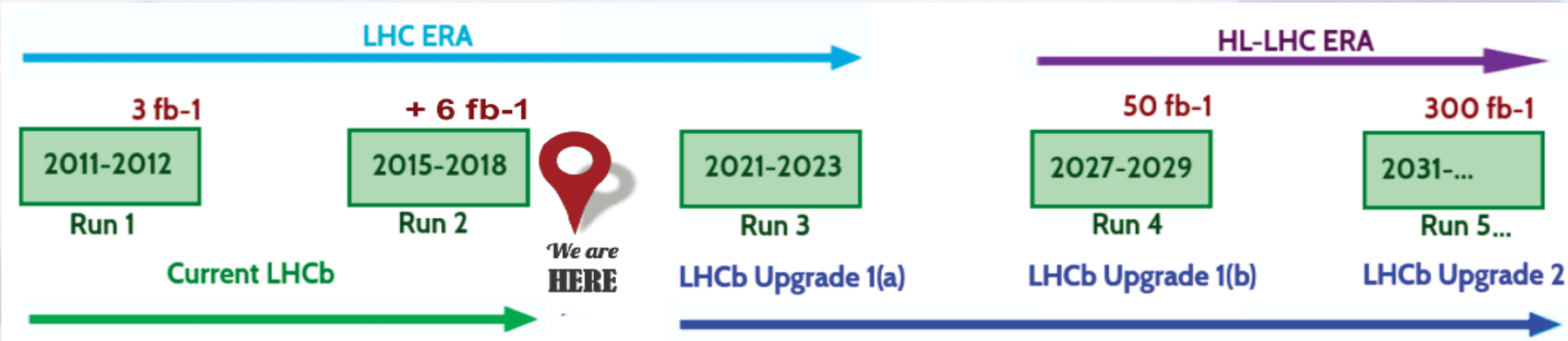


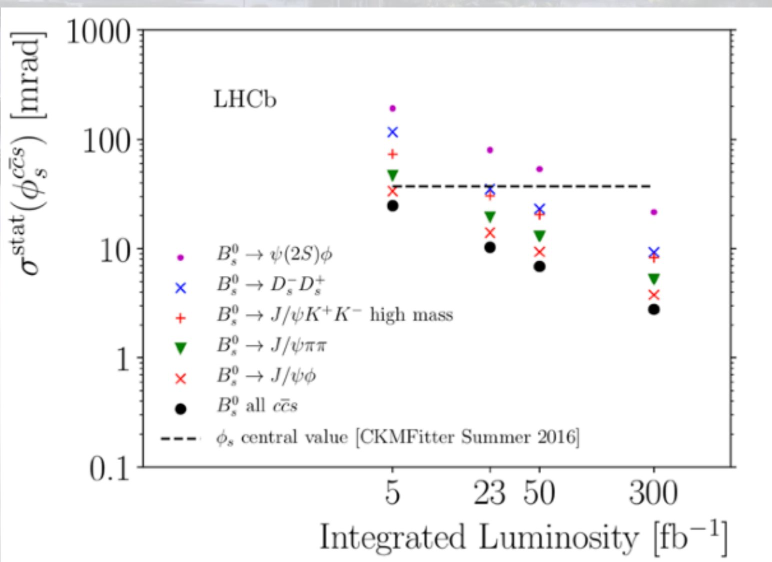
$$\phi_s^{\text{exp}} = -0.055 \pm 0.021 \text{ rad}$$
$$\Delta\Gamma_s^{\text{exp}} = 0.0764 \pm 0.0024 \text{ ps}^{-1}$$

Reminder:

$$\phi_s^{\text{SM}} = -0.0368^{+0.0010}_{-0.0008} \text{ rad}$$ [CKMFitter]

Prospects





[CERN-LHCC-2018-027]

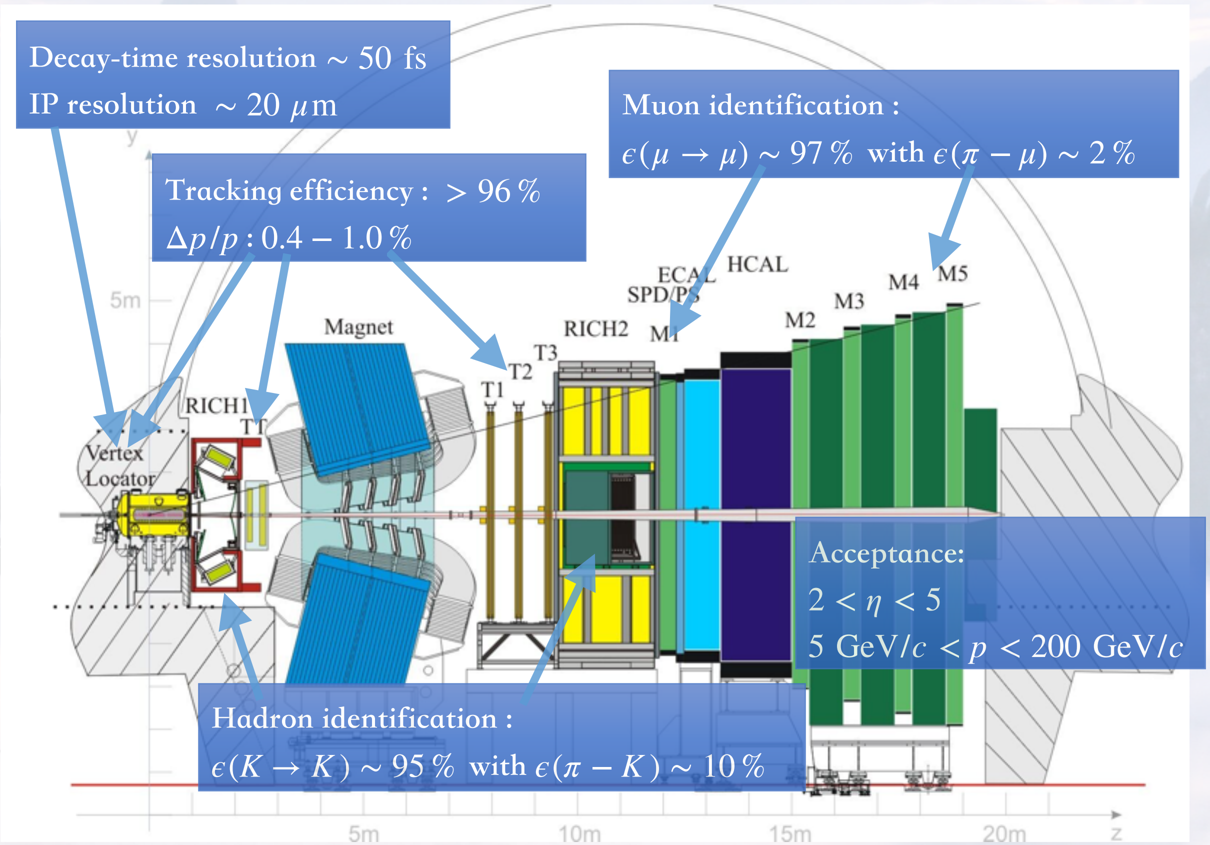
- Include gain in trigger for $B_s^0 \to D_s^+ D_s^-$ after Upgrade 1
- Exploring new modes: $J/\psi(\to ee), \eta'(\to \rho^0\gamma, \eta\pi\pi, \gamma\gamma))$
- Expect to have
  - $\sigma^{\rm stat} \sim 4$ mrad 300 /fb ($B_s^0 \to J/\psi\phi$)
  - $\sigma^{\rm stat} \sim 3$ mrad 300 /fb (total)
- ϕ_s would be statistically limited

Summary

- More precise measurement of ϕ_s from $b \to c\bar{c}s$ transitions using 2015-2016 data sets
- Overall picture is SM-like in ϕ_s measurements
  - Current results are mostly statistically dominated
- Exploring new modes would improved our knowledge of ϕ_s
- LHCb 300/fb data would decrease $\sigma^{\text{stat}} \sim 3$ mrad
- Analyses of 2017-2018 data sets are ongoing and significant precision improvement of ϕ_s measurement is expected
- Stay tuned for more results in the near future!

Backups

LHCb experiments



[IJMPA 30, 1530022 (2015), 2008 JINST 3 S08005]

LHCb data set

- Run I
  - 2011 1 fb^{-1}, 7 TeV
  - 2012 2 fb^{-1}, 8 TeV
- Run II
  - 2015 0.3 fb^{-1}, 13 TeV
  - 2016 1.6 fb^{-1}, 13 TeV
  - 2017 1.7 fb^{-1}, 13 TeV
  - 2018 2.1 fb^{-1}, 13 TeV

Decay-time resolution

- Pre-candidate decay-time error is calibrated using prompt J/ψ sample formed from J/ψ and two kaons (pions) from PV

$$\sigma_{\mathrm{eff}} = \sqrt{(-2/\Delta m_s^2)\ln D}, D = \sum_{i=1}^{3} f_i e^{-\sigma_i^2 \Delta m_s^2/2}$$

- Fit in bins of per-event decay-time error δ_t
- Method validated in MC comparing prompt and signal resolution