CP violation in beauty & charm

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(On behalf of LHCb, including ATLAS/CMS results)

5th Large Hadron Collider Physics Conference
Puebla, Mexico, May 20-25 2019

Outline

- **CP violation and CKM mechanism**
- **New results**
  - ➢ **B_s mixing phase: ϕ_s**
  - ➢ **Discovery of CP violation in charm: ΔA_{CP}**
- **Summary and outlook**

Parallel talks on 24th May

CP violation in beauty with LHCb, Melissa Maria Cruz Torres

CP violation in charm with LHCb, Martha Hilton

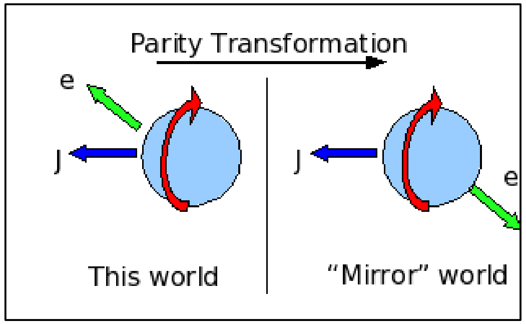
CP violation with ATLAS and CMS, name to be added

Why is CP interesting?

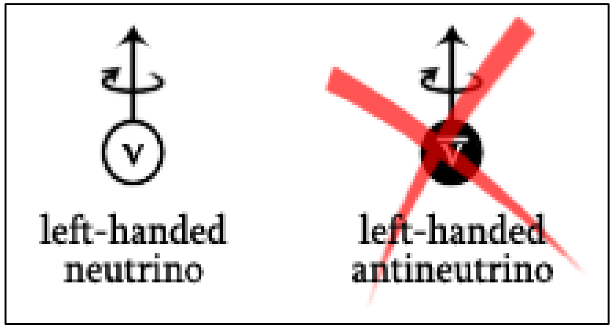
CP violation: violation of combined conservation laws under charge-conjugation (C) & parity (P) transformation

- Study of discrete symmetries revolutionized particle physics

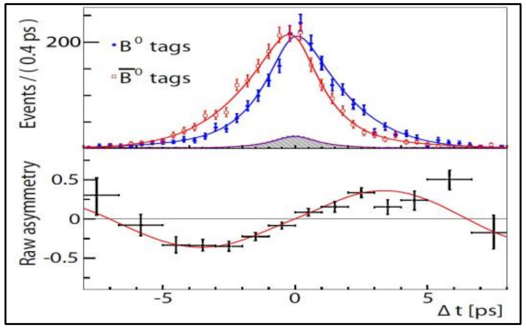
P violation



C violation



CP violation

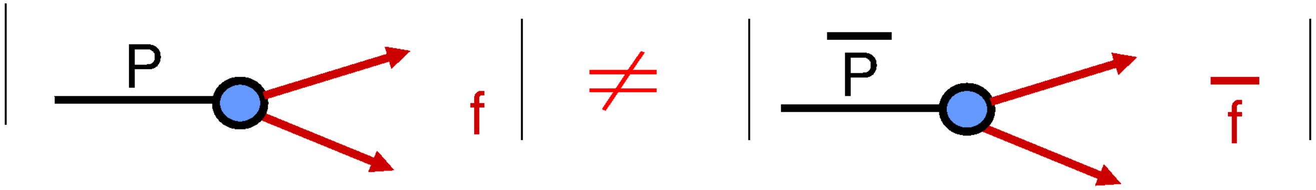


- Fundamental questions related to CP violation unanswered
  - Why is the universe matter-dominated?
  - Why is CPV not observed in strong interaction?
- CP violation is sensitive to new particles

Three types of CPV

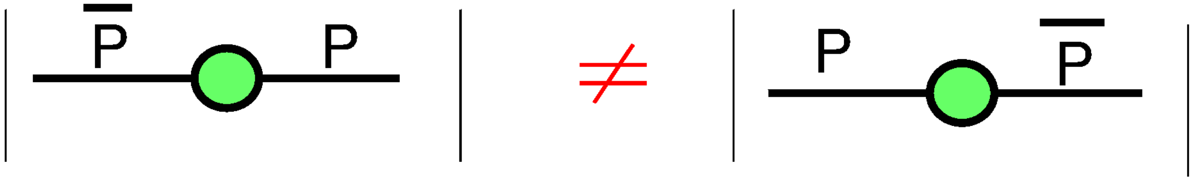
~~CP~~ in decay

(Interference of 2 or more complex amplitudes)



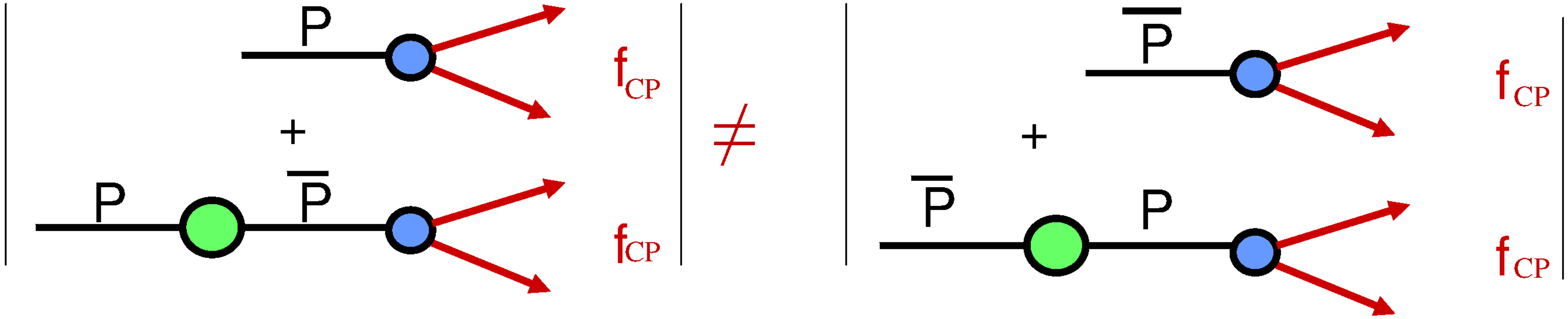
~~CP~~ in mixing

(“indirect ~~CP~~”)



~~CP~~ in interference between mixing and decay

(“Mixing induced ~~CP~~”)



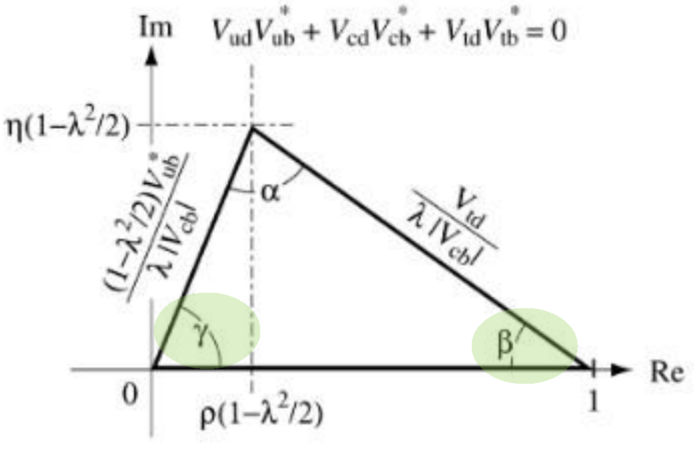
CPV & CKM mixing matrix

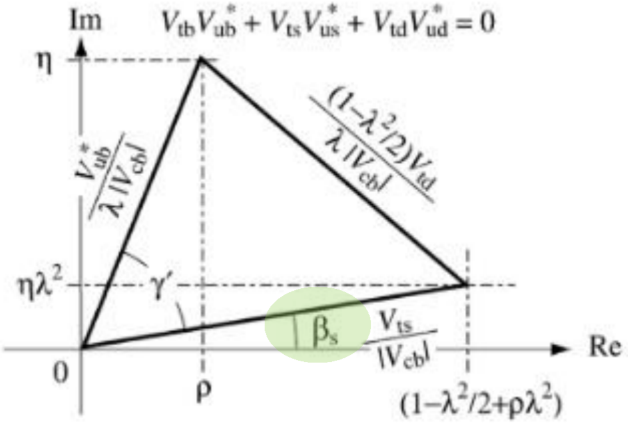
- **Origin of CPV in SM:** **nonzero CKM weak phase** $(\eta \neq 0)$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \underbrace{\boxed{A\lambda^3(\rho - i\eta)}}_{\gamma} \\ \underbrace{\boxed{-\lambda - iA^2\lambda^5\eta}}_{\text{CPV in charm}} & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ \underbrace{\boxed{A\lambda^3(1-\hat{\rho}-i\hat{\eta})}}_{\beta} & \underbrace{\boxed{-A\lambda^2 - iA\lambda^4\eta}}_{\beta_s} & 1 \end{pmatrix}$$

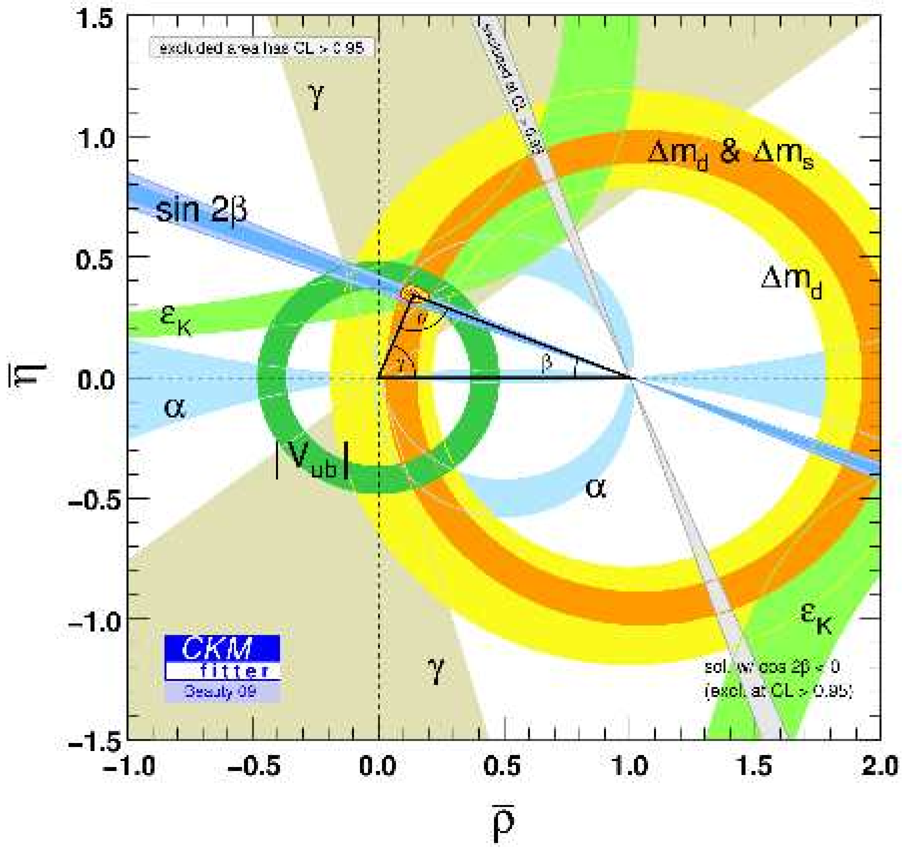
- **Unitarity triangles**
  - ✓ Angles (CP violating) and sides (CP conserving)



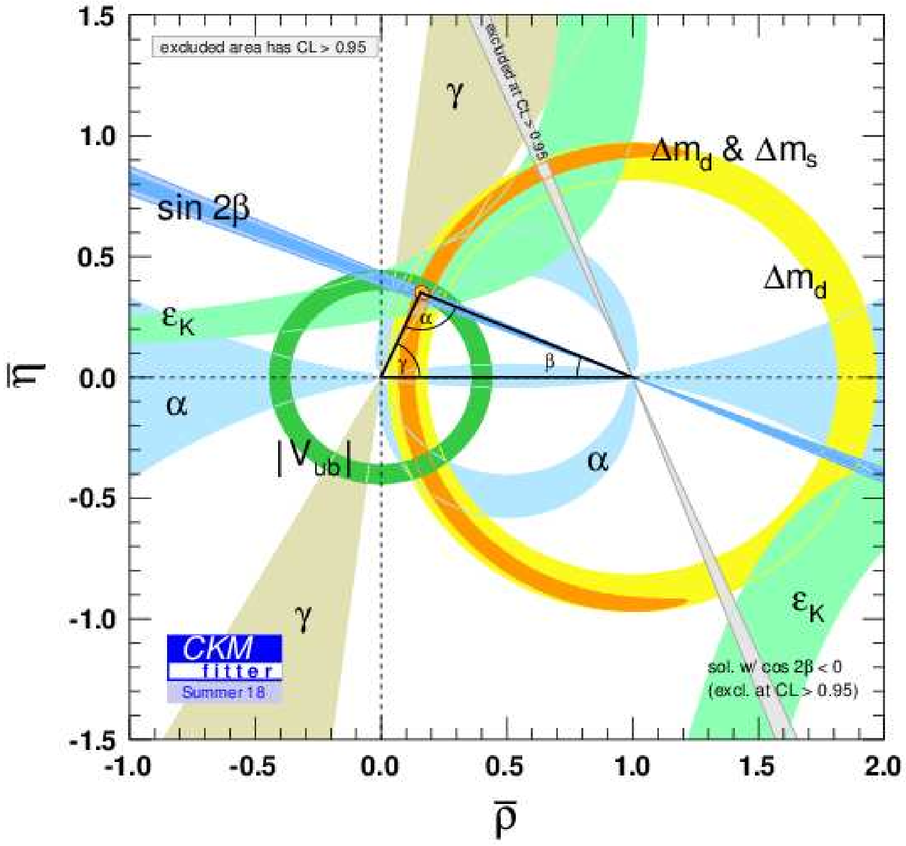


CKM fit in the LHC era

When LHC started



Ten years later



LHC: heavy flavour factory

Large production cross sections:

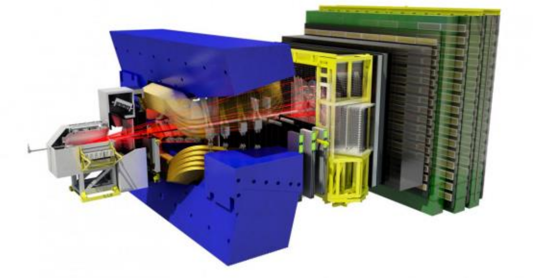
$\sigma(b\bar{b}X) \sim 0.2\% \times \sigma_{pp}^{inelas}$, $\sigma(c\bar{c}X) \sim 4\% \times \sigma_{pp}^{inelas}$

Many species of b- and c-hadrons:

$B^0, B_s^0, B^\pm, B_c^+, \Lambda_b^0, D^0, D^\pm, D_s^\pm, \Lambda_c^\pm, J/\psi, \Xi_{cc}^{++}, P_c,$ …

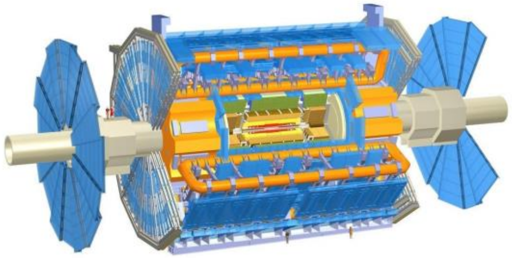
- **LHCb**: 3+6 fb^{-1}
  - ✓ Forward spectrometer $2 < \eta < 5$
  - ✓ Excellent vertexing, PID, tracking and flexible trigger
  - ✓ Luminosity levelling

[JINST 3 (2008) S08005]

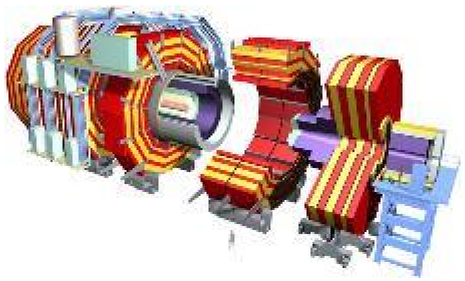


- **ATLAS/CMS**: ~180 fb^{-1}
  - ✓ B decays only triggered on muons
  - ✓ No hadron PID
  - ✓ ATLAS new IBL detector in run 2

[JINST 3 (2008) S08003]



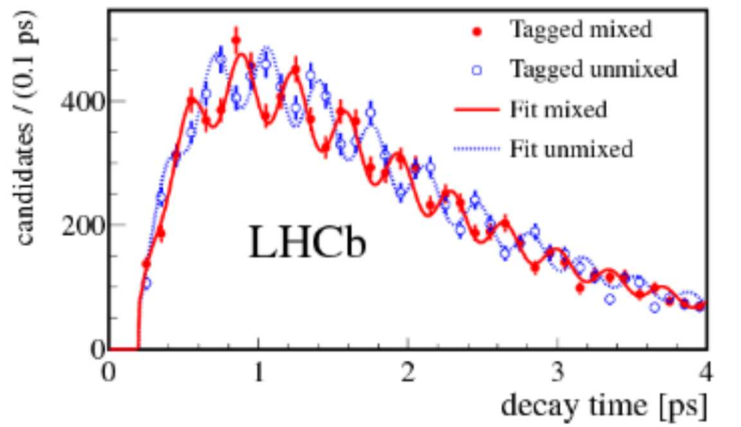
[JINST 3 (2008) S08004]



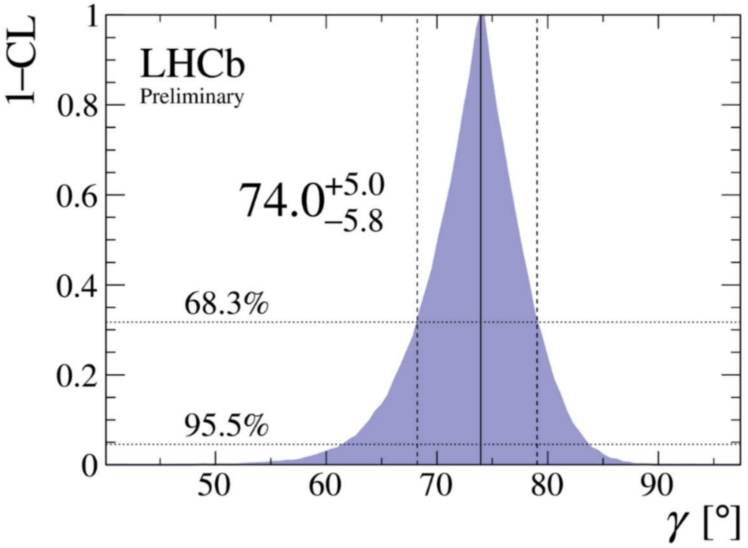
The major player: LHCb

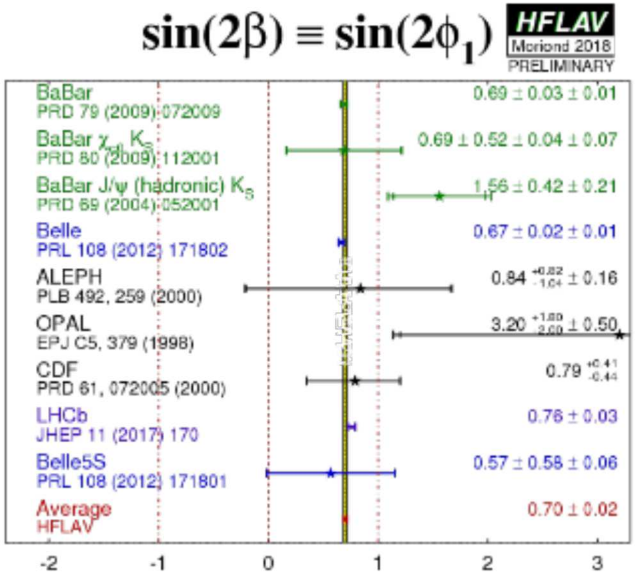
- $\Delta m_{s/d}$: LHCb dominating
- γ: LHCb overtaken B factories
- $\sin 2\beta$: similar precision at LHCb and B factories
- V_{ub}: LHCb starts to contribute

[New J.Phys. 15 (2015) 053201]



[LHCb-CONF-2018-002]





LHCb: $\gamma = (74.0^{+5.0}_{-5.8})^{\circ}$ **WA:** $\gamma = (73.5^{+4.2}_{-5.1})^{\circ}$

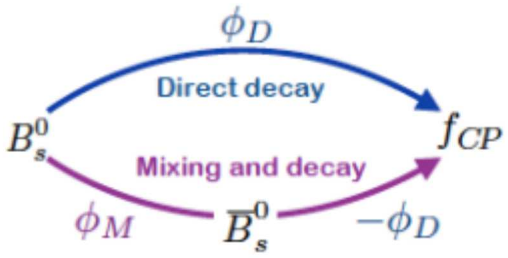
B_s mixing phase: ϕ_s

ϕ_s in $b \to c\bar{c}s$ decays

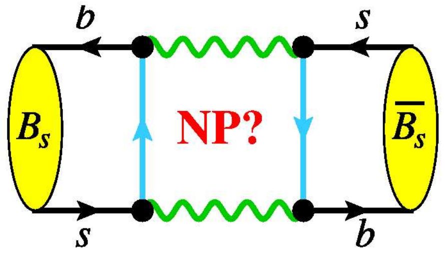
ϕ_s in $B_s \to J/\psi\phi$ is a core goal of LHCb, analogous to 2β in $B^0 \to J/\psi K^0$ at B factories

$$A_{\rm CP} \equiv \frac{\Gamma\left(\overline{B}^0_s \to f\right) - \Gamma\left(B^0_s \to f\right)}{\Gamma\left(\overline{B}^0_s \to f\right) + \Gamma\left(B^0_s \to f\right)} \approx \eta_f \boxed{\sin\phi_s} \sin(\Delta m_s t)$$

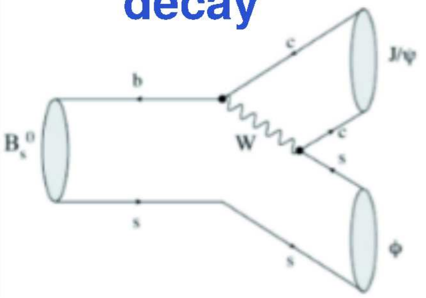
$\phi_s = \phi_M - 2\phi_D$



mixing



decay



- **ϕ_s precisely predicted to be very small in the SM**

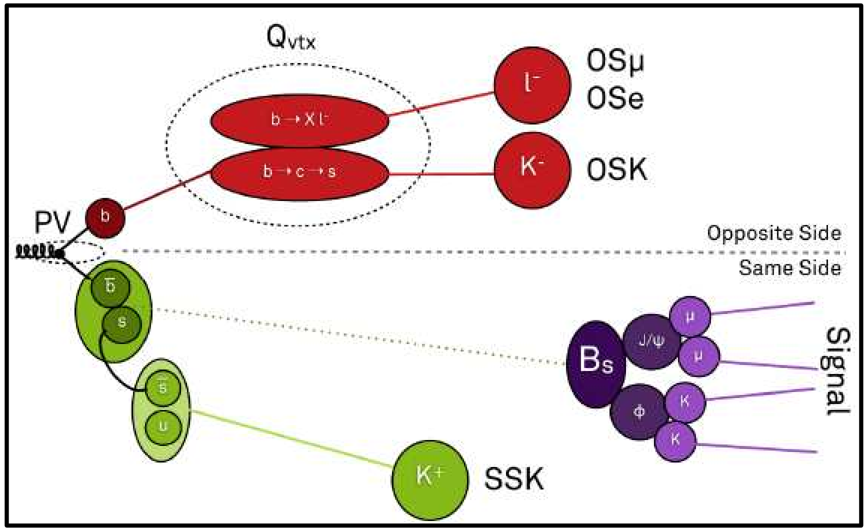
$$\phi_s^{\rm SM} \approx -2\beta_s = -36.8^{+1.0}_{-0.7}\ \text{mrad}$$ [CKMfitter]

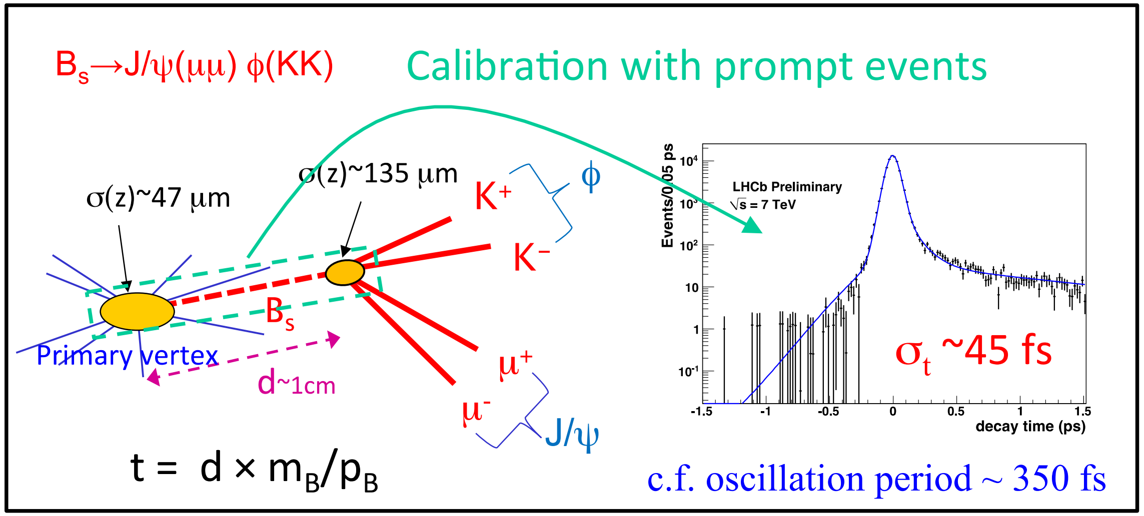
- **Could be modified by new particles in $B_s - \overline{B}_s$ mixing**
  - ✓ **Also interesting: $\Delta m_s = m_H - m_L, \Delta\Gamma_s = \Gamma_L - \Gamma_H$**

Key ingredients

- **Opposite side tagging:** use charge of decay products of other B
- **Same side tagging:** use charge of kaons associated with signal B_s
- **Tagging power:** $\epsilon(1-2\omega)^2$

[EPJC 42 (2012) 2022, JINST 11 (2016) P05010]





$t = d \times m_B/p_B$

c.f. oscillation period ~ 350 fs

- **Impact of decay time resolution**

σ_t (fs)	dilution
45	0.73
70	0.46
90	0.28

Previous status of ϕ_s (run 1)

LHCb

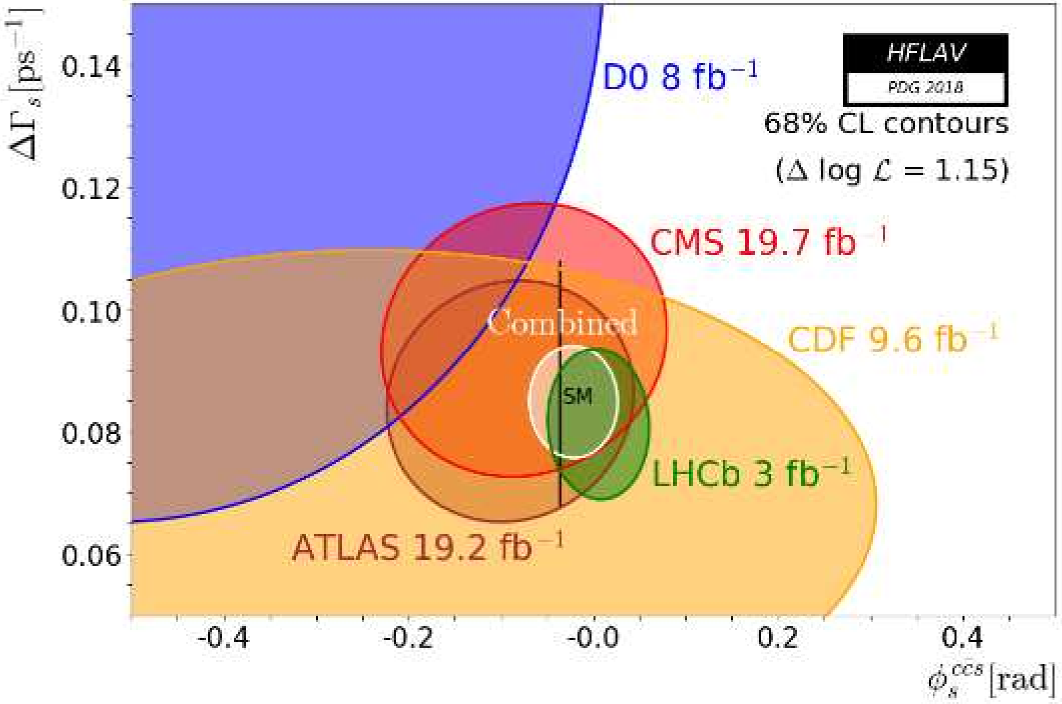
- $J/\psi\phi$ [PRL 114 (2015) 041801]
- $J/\psi\pi^+\pi^-$ [PLB 736 (2014) 186]
- $J/\psi K^+K^-$ above ϕ [JHEP 08 (2017) 037]
- $D_s^+D_s^-$ [PRL 114 (2015) 041801]
- $\psi(2S)\phi$ [PLB 762 (2016) 253]

ATLAS:

- $J/\psi\phi$ [JHEP 08 (2016) 147

CMS

- $J/\psi\phi$ [PLB 757 (2016) 97]

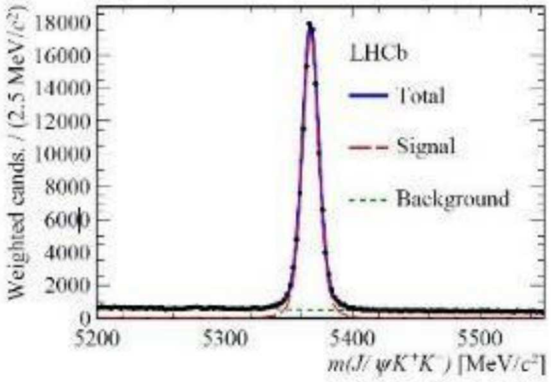


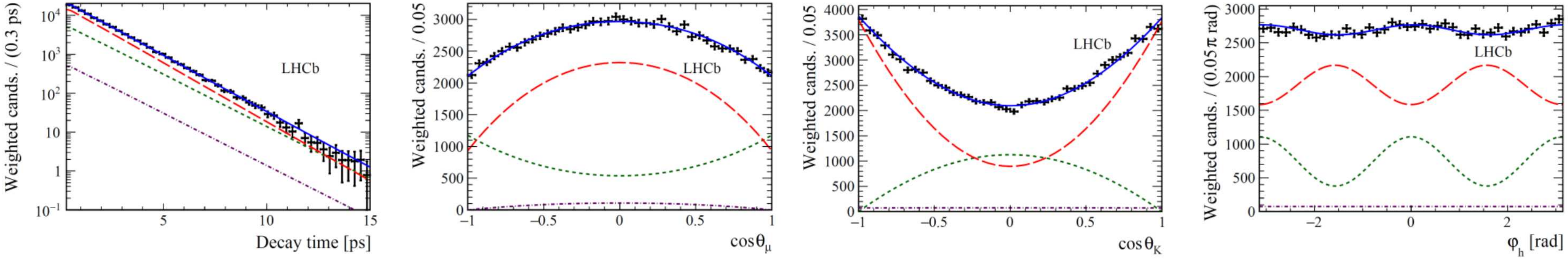
World average $\phi_s = -21 \pm 31$ mrad, dominated by LHCb, consistent with $\phi_s^{SM} = -36.9^{+1.0}_{-0.7}$ mrad

LHCb run 2: $B_s \to J/\psi\phi$

- 2015+2016 data (1.9 fb^{-1})
- 117k signals
- Decay time resolution $\sigma_t \sim 45$ fs
- Tagging power 4.7%,
  - 25% better than run 1
- Time-dependent angular analysis

[LHCb-PAPER-2019-013]



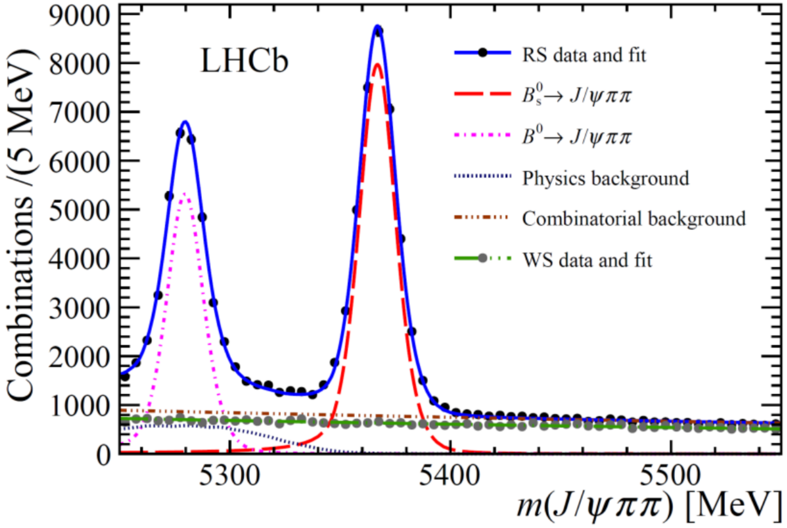


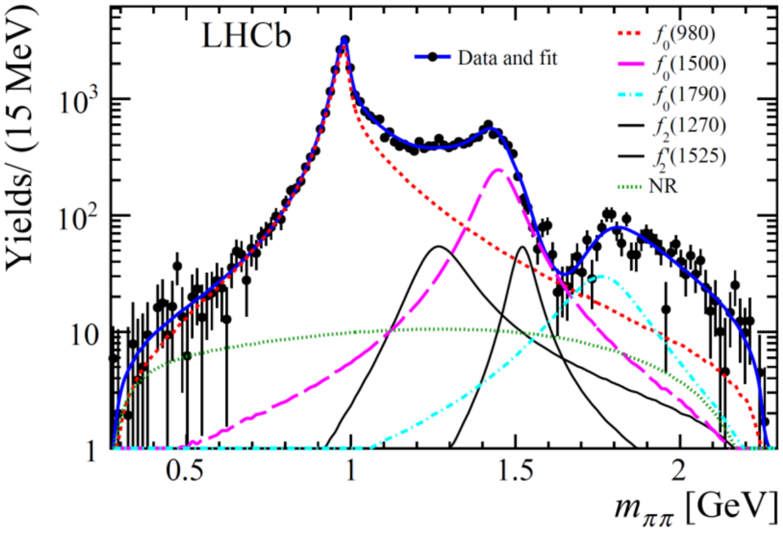
	2015+2016	Run 1 [PRL 114 (2015) 041801]
ϕ_s (mrad)	$-80 \pm 41 \pm 6$	$-58 \pm 49 \pm 6$
$\Delta\Gamma_s$ (ps^{-1})	$0.0772 \pm 0.0077 \pm 0.0026$	$0.0805 \pm 0.0091 \pm 0.0032$

Most precise single measurements, compatible with SM.

LHCb run 2: $B_s \to J/\psi\pi^+\pi^-$

[arXiv:1903.05530]





- 2015+2016 data (1.9 fb^{-1})
- 33.5k signals
- $\sigma_t \sim 41.5$ fs
- Tagging power ~5%
- 5D fit: time, 3 angles, $m_{\pi\pi}$
- $\Delta\Gamma_s$ from $B_s \to J/\psi\phi$

2015+2016

$\phi_s = -57 \pm 60 \pm 11$ mrad

Run 1 [PLB 742 (2015) 38]

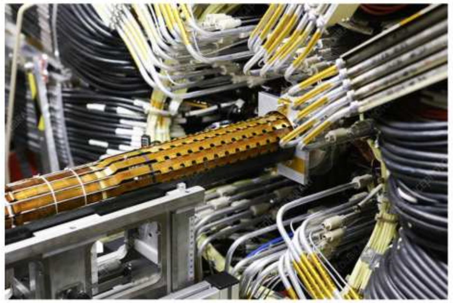
$\phi_s = +75 \pm 65 \pm 14$ mrad

Compatible with each other and SM

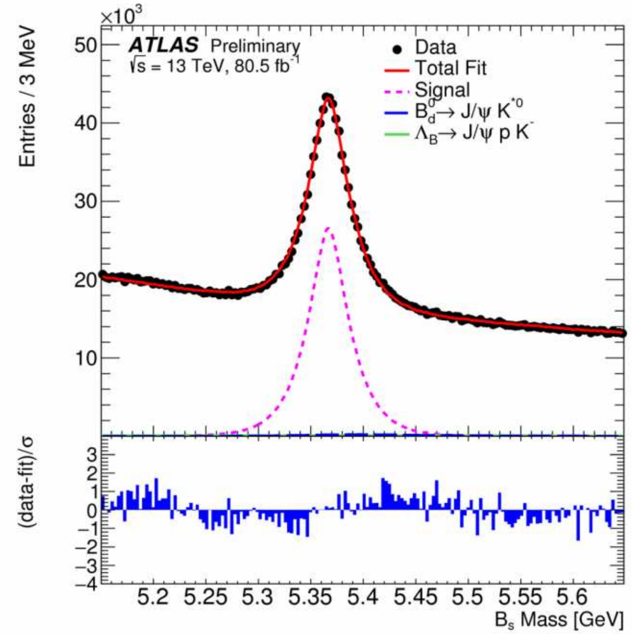
ATLAS run 2: $B_s \to J/\psi\phi$

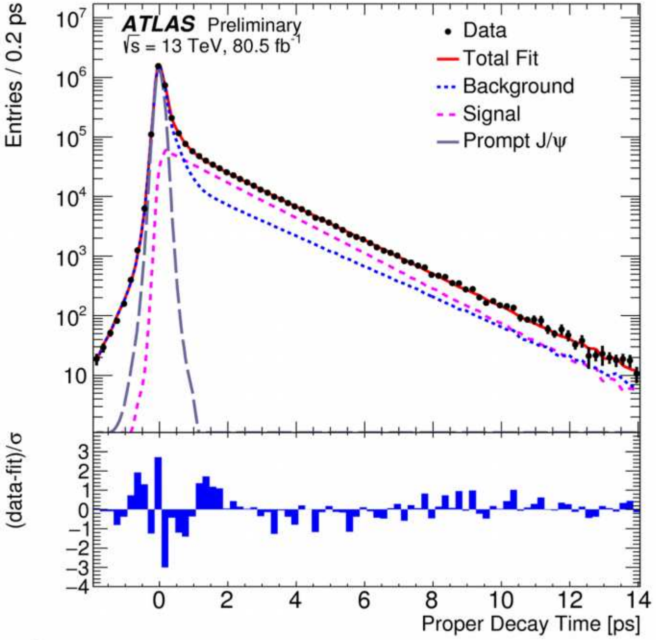
ATLAS-CONF-2019-009

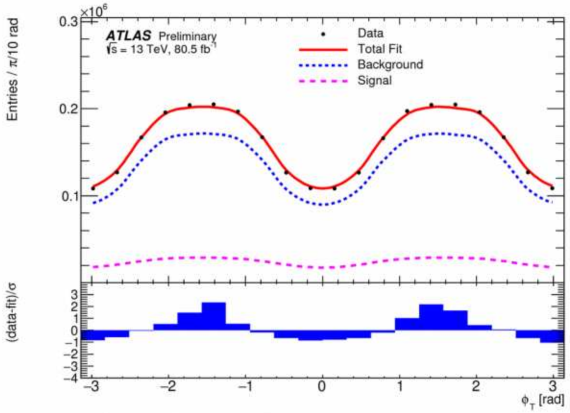
- Data from 2015-17
- Signal yield ~ 450k
- New Insertable B Layer (IBL) detector improves σ_t: 100 → 70 fs
- Tagging power ~ 1.6%

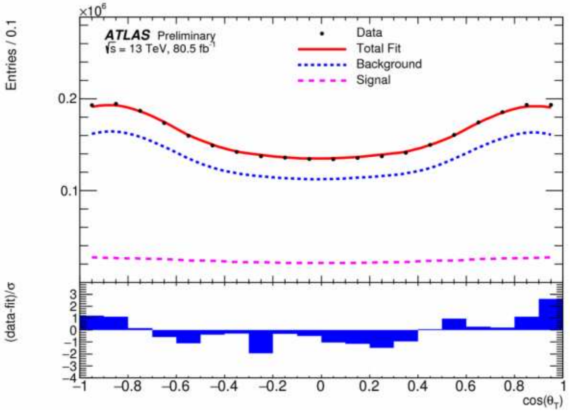


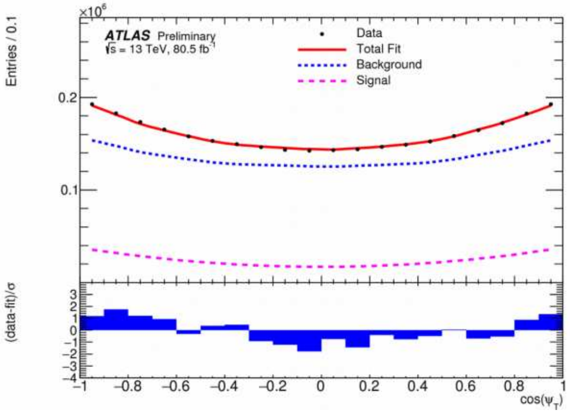
- Improved trigger











$\phi_s = -68 \pm 38 \pm 18$ **mrad,** $\Delta\Gamma_s = 0.067 \pm 0.005 \pm 0.002$ **ps^{-1}**

World average of ϕ_s and $\Delta\Gamma_s$

ATLAS (100 fb^{-1}, $J/\psi\phi$)

[ATLAS-CONF-2019-009]

$\phi_s = -76 \pm 34 \pm 19$ mrad

$\Delta\Gamma_s = 0.068 \pm 0.004 \pm 0.003$ ps^{-1}

LHCb (4.9 fb^{-1}, 5 $b \to c\bar{c}s$ modes)

[LHCb-PAPER-2019-013]

$\phi_s = -41 \pm 25 \pm 6$ mrad

$\Delta\Gamma_s = 0.0816 \pm 0.0048$ ps^{-1}

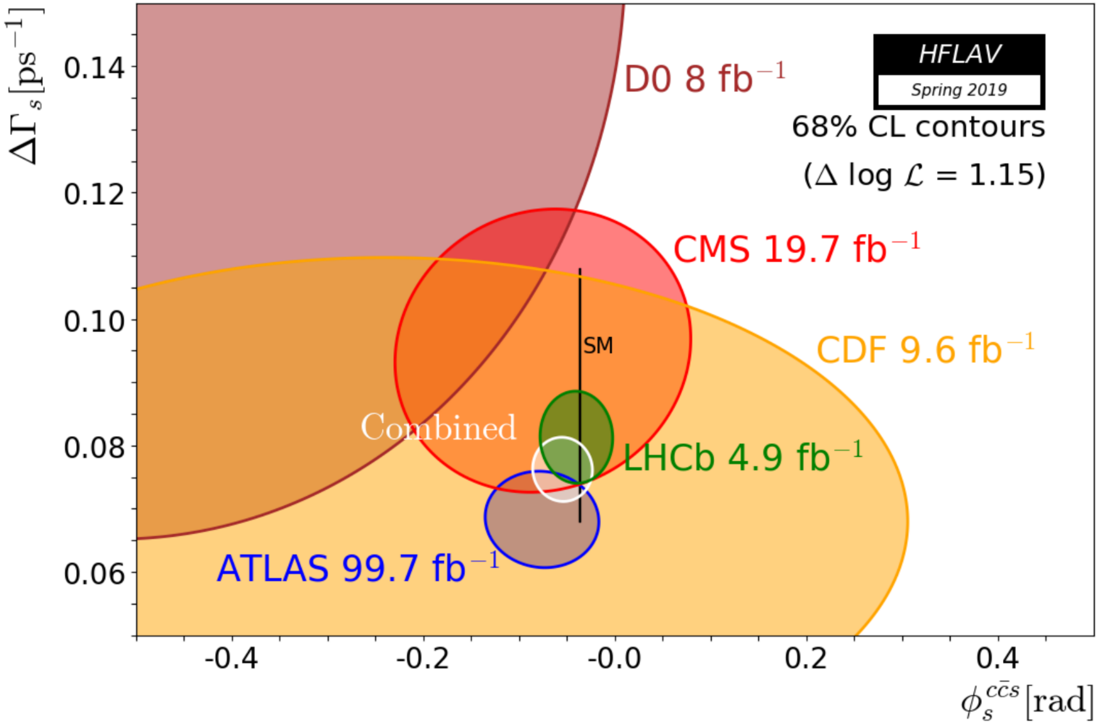
HFLAV average

$\phi_s^{c\bar{c}s} = -55 \pm 21$ mrad

$\Delta\Gamma_s = 0.0764^{+0.0034}_{-0.0033}$ ps^{-1}

Consistent with SM

$\phi_s^{SM} = -36.8^{+1.0}_{-0.7}$ mrad



LHCb: ϕ_s in $b \to s$ loop decays

Measuring ϕ_s in $b \to s$ processes probes new particles in loop decay diagrams

- $B_s \to \phi\phi$: $b \to s\bar{s}s$ penguin decay

Run 1+ 2015+2016 data

[LHCb-PAPER-2019-019]

$\phi_s = -0.073 \pm 0.115 \pm 0.027$ rad
Direct CPV $|\lambda| = 0.99 \pm 0.05 \pm 0.01$

- $B_s \to K^{*0}(K^+\pi^-)\overline{K}^{*0}(K^-\pi^+)$: $b \to s\bar{d}d$ penguin decay

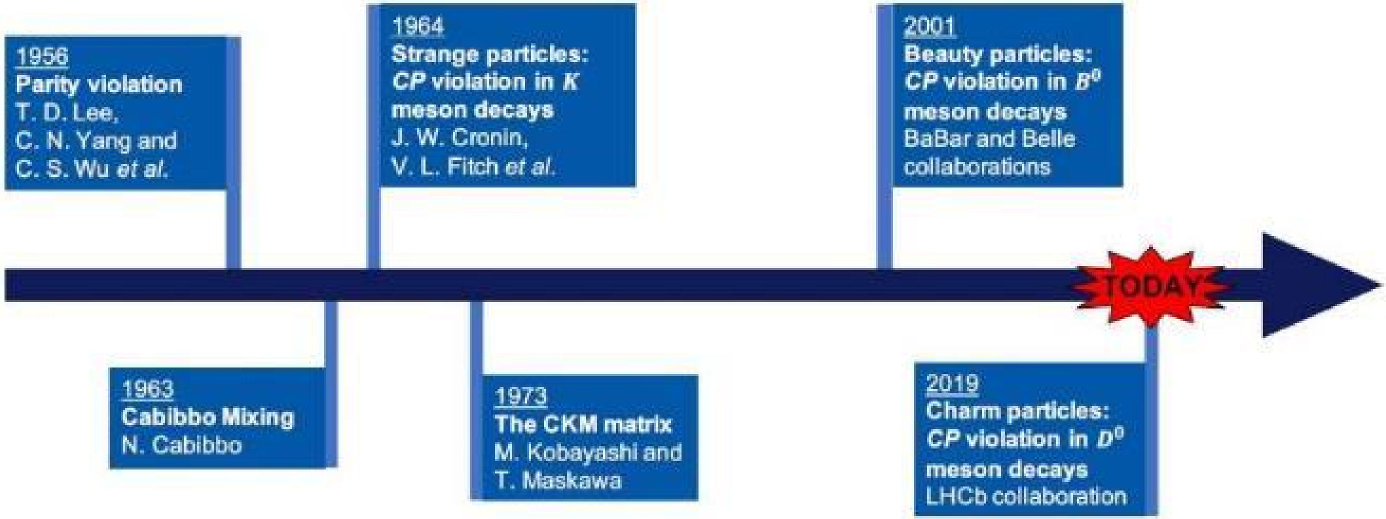
Run 1+ 2015+2016 data

[JHEP 03 (2018) 140]

$\phi_s = -0.06 \pm 0.13 \pm 0.03$ rad
Direct CPV $|\lambda| = 1.02 \pm 0.05 \pm 0.03$

In agreement with SM expectation $\phi_s^{b\to s} \approx 0, |\lambda| \approx 1$

Discovery of CP violation in charm: ΔA_{CP}



1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
CP* violation in *K
meson decays
J. W. Cronin,
V. L. Fitch *et al.*

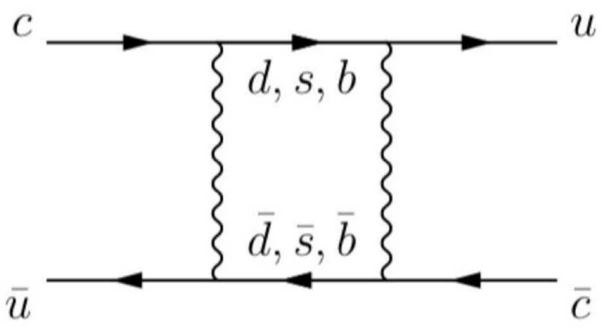
1973
The CKM matrix
M. Kobayashi and
T. Maskawa

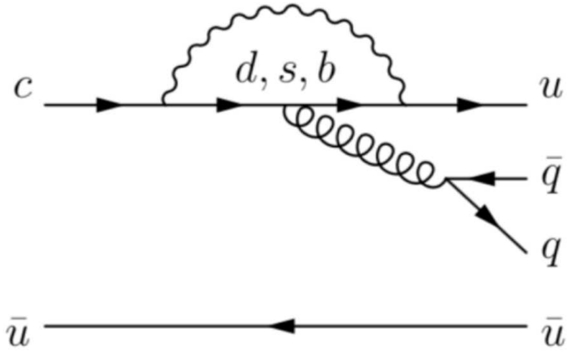
2001
Beauty particles:
***CP* violation in B^0**
meson decays
BaBar and Belle
collaborations

2019
Charm particles:
***CP* violation in D^0**
meson decays
LHCb collaboration

What is special about charm

- **Unique way to probe CPV in up-type FCNC, complementary to study of B and K mesons**





- **First 2 quark generations play dominant roles**

➢ **D^0 mixing small**

$$x \equiv \frac{\Delta \mathrm{M}}{2\Gamma} = \left(0.39^{+0.11}_{-0.12}\right)\%$$

$$y \equiv \frac{\Delta \Gamma}{2\Gamma} = \left(0.651^{+0.063}_{-0.069}\right)\%$$

[HFLAV]

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

➢ **CPV highly suppressed in SM,**

➢ **Challenge: long distance effect**

LHCb searches for indirect CPV

- Indirect CPV $\leq O\ (10^{-4})$ in the SM, not enough sensitivity yet
- Search for time-dependent CPV in $D^0 \to h^+h^-$ (run1 + 2015 +2016)

$$A_\Gamma(K^+K^-) = (1.3 \pm 3.5 \pm 0.7) \times 10^{-4}$$

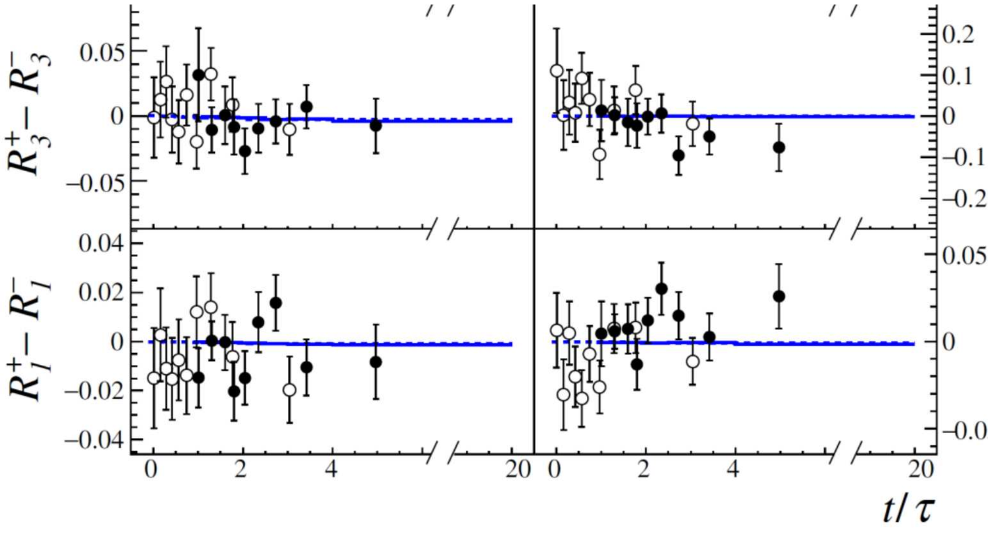
[LHCb-CONF-2019-001]

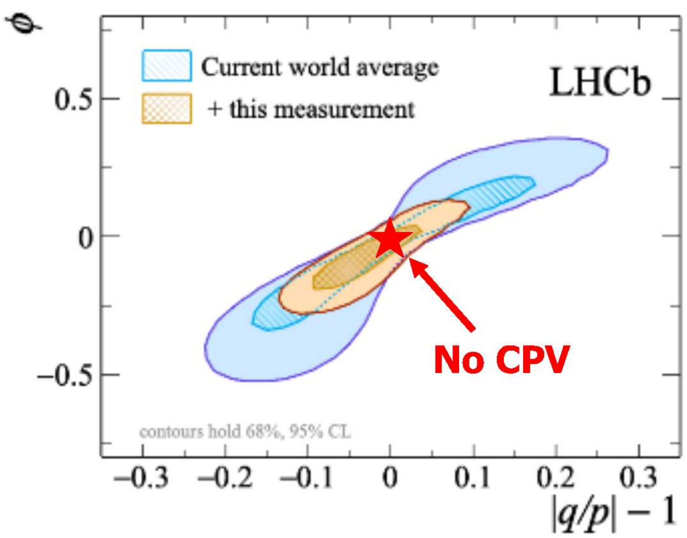
$$A_\Gamma(\pi^+\pi^-) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4}$$

- Search for indirect CPV in $D^0 \to K_S\pi^+\pi^-$ (run 1)

$$\Delta x = (-0.53 \pm 0.70 \pm 0.22) \times 10^{-3}$$

[arXiv:1903.03074]





LHCb searches for direct CPV

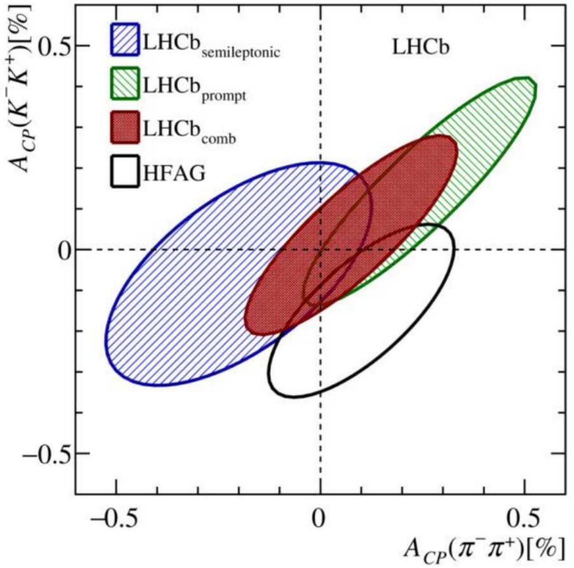
- **SM expectation of $\mathbf{A_{CP}^{dir}}$ small,** but “how small” is uncertain

$$\mathbf{A_{CP}^{dir}} \equiv \frac{\left|\mathbf{A}\left(\mathbf{D^0} \to \mathbf{f}\right)\right|^2 - \left|\mathbf{A}\left(\mathbf{\bar{D}^0} \to \mathbf{\bar{f}}\right)\right|^2}{|\mathbf{A}(\mathbf{D^0} \to \mathbf{f})|^2 + |\mathbf{A}\left(\mathbf{\bar{D}^0} \to \mathbf{\bar{f}}\right)|^2} \leq \; \boldsymbol{O}(\mathbf{10^{-3}})$$

- **No observation in extensive searches**

$$\begin{aligned} \mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) &= (\quad 1.3 \;\; \pm 1.9 \;\; (\text{stat}) \pm 0.5 \;\; (\text{syst})) \times 10^{-3} \\ \mathcal{A}_{CP}(D^+ \to K_S^0 K^+) &= (-0.09 \pm 0.65\,(\text{stat}) \pm 0.48\,(\text{syst})) \times 10^{-3} \\ \mathcal{A}_{CP}(D^+ \to \phi\pi^+) &= (\quad 0.05 \pm 0.42\,(\text{stat}) \pm 0.29\,(\text{syst})) \times 10^{-3} \end{aligned}$$

[arXiv:1903.01150] **(run 2, 3.8 fb^{-1})**



$$\mathbf{A_{CP}}(\boldsymbol{K^+K^-}) = (\mathbf{0.04} \pm \mathbf{0.12} \pm \mathbf{0.10})\%$$
$$\mathbf{A_{CP}}(\boldsymbol{\pi^+\pi^-}) = (\mathbf{0.07} \pm \mathbf{0.14} \pm \mathbf{0.11})\%$$

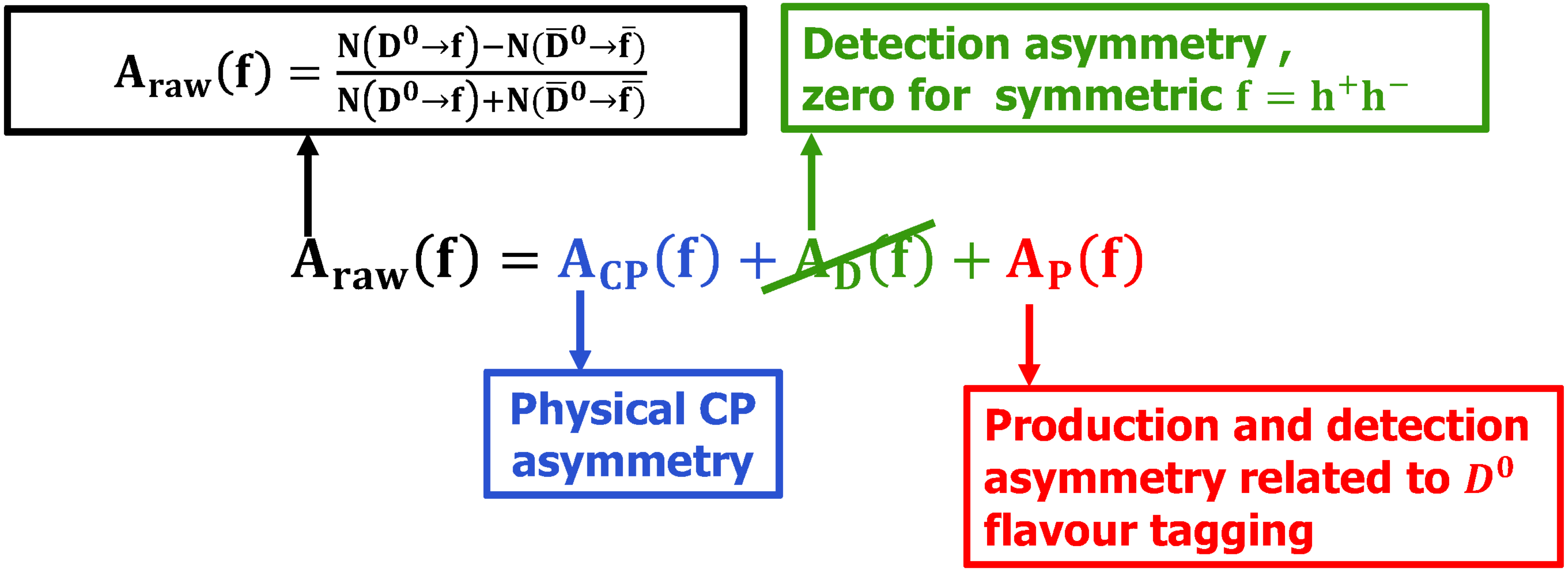
[PLB 767 (2017) 177] **(run 1)**

$$\mathbf{A_{CP}}\left(\boldsymbol{K_S^0 K_S^0}\right) = (\mathbf{2.3} \pm \mathbf{2.8} \pm \mathbf{0.9})\%$$

[JHEP 11 (2018) 048] **(run 1+2016+2016)**

- **Until the very recent update of $\boldsymbol{\Delta}\mathbf{A_{CP}}$**

$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$



$$A_{raw}(f) = \frac{N(D^0\to f)-N(\bar{D}^0\to \bar{f})}{N(D^0\to f)+N(\bar{D}^0\to \bar{f})}$$

Detection asymmetry , zero for symmetric $f = h^+h^-$

$$A_{raw}(f) = A_{CP}(f) + \cancel{A_D(f)} + A_P(f)$$

Physical CP asymmetry

Production and detection asymmetry related to D^0 flavour tagging

If D^0 kinematics are similar for the two modes (after proper weighting),

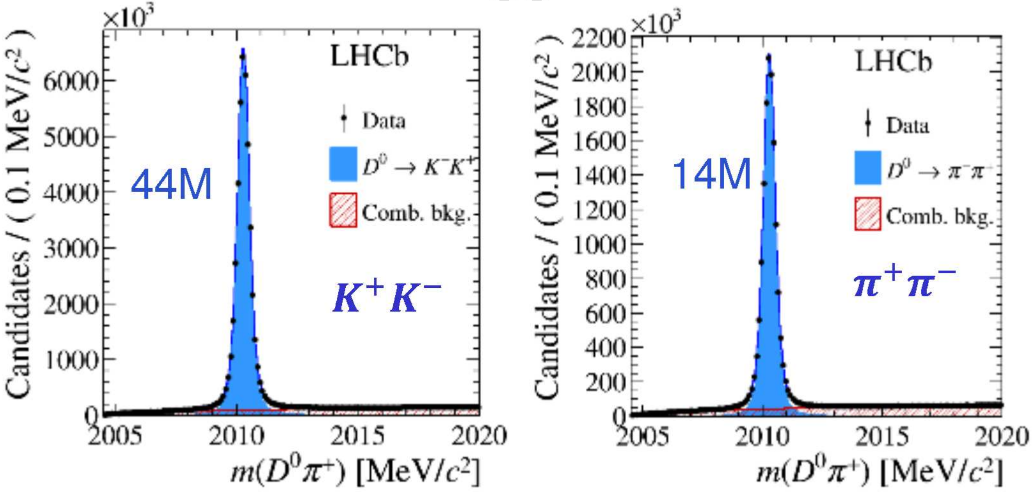
$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \approx A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-)$$

LHCb run 2 update on ΔA_{CP}

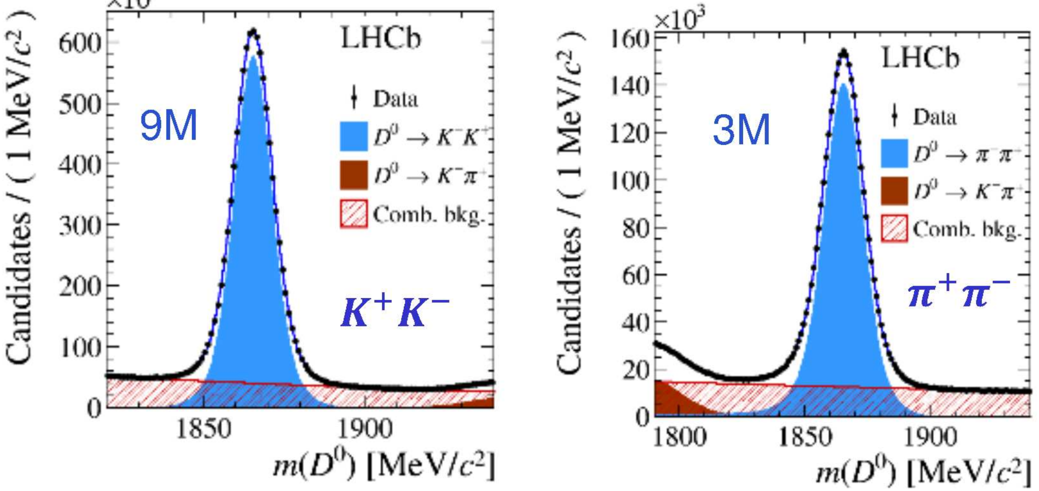
[arXiv:1903.08726]

- Update with 6 fb^{-1} from run 2
- Two tagging methods
  - π-tagged: $D^{*\pm} \rightarrow D^0\pi^\pm$
  - μ-tagged: $B \rightarrow D^0\mu^\pm X$
- Real time reconstruction
- Selection requirements on
  - Track quality, PID and p_T
  - D^0 vertex quality, p_T, IP
  - Fiducial cuts
- Kinematic reweighting
- Simultaneous fit of D^0 and $\overline{D}^0$ samples to obtain A_{raw}

π-tagged



μ-tagged



LHCb new ΔA_{CP} result

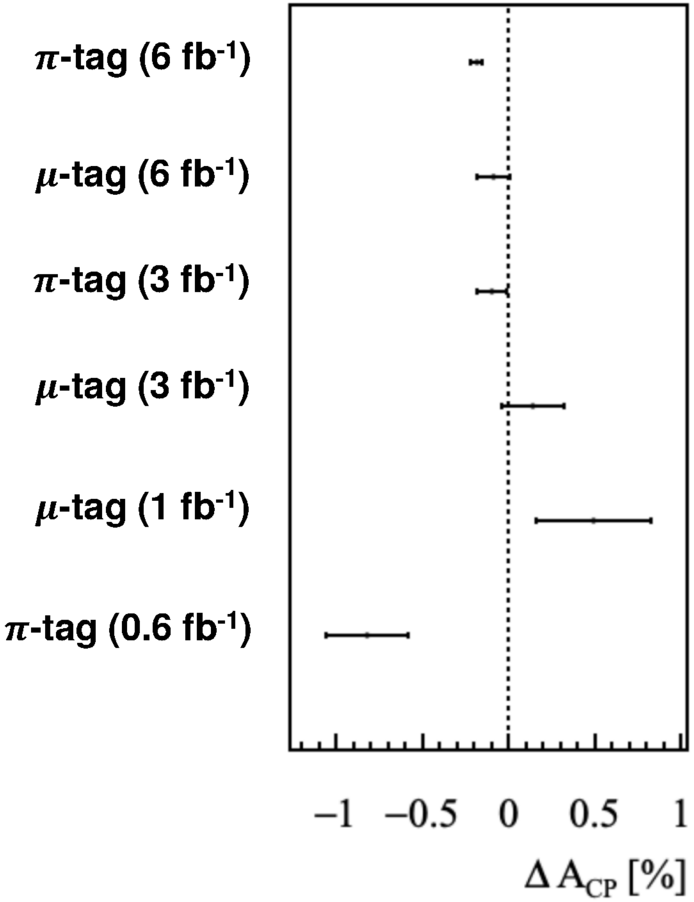
[arXiv:1903.08726]

Run 2 results

$$\Delta A_{CP}^{\pi-tag} = (-18.2 \pm 3.2 \pm 0.9) \times 10^{-4}$$

$$\Delta A_{CP}^{\mu-tag} = (-9 \pm 8 \pm 5) \times 10^{-4}$$

Compatible with previous LHCb results

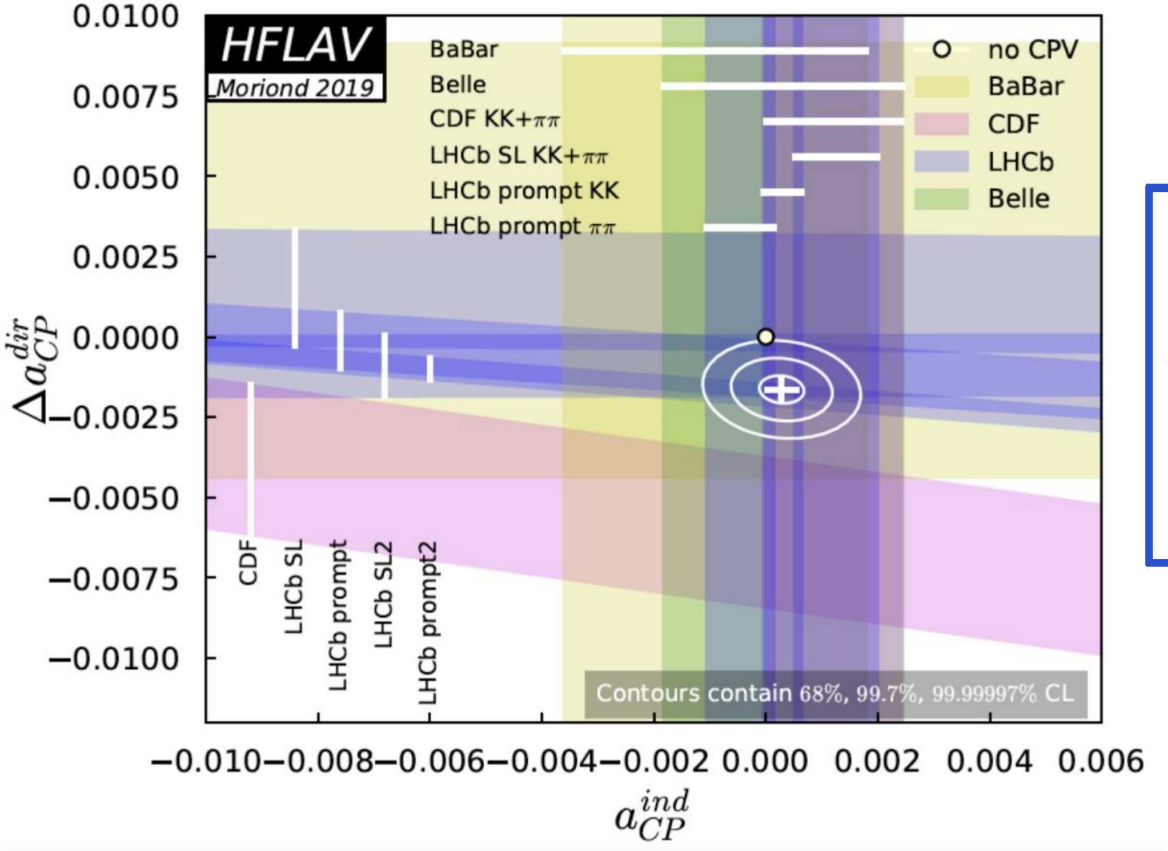


LHCb combination (9 fb^{-1})

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

First observation of CP violation in charm (5.3σ)!

HFLAV combination



$a_{\mathrm{CP}}^{ind} = (0.028 \pm 0.026)\%$

$\Delta a_{\mathrm{CP}}^{dir} = (-0.164 \pm 0.028)\%$

p-value of CP invariance hypothesis: 5×10^{-8} (5.4σ)

World average dominated by LHCb results

Summary and outlook

- **Both LHCb and ATLAS release new results of ϕ_s**

LHCb: $\phi_s = -40 \pm 25 \pm 6$ **mrad** [1]

ATLAS: $\phi_s = -76 \pm 34 \pm 19$ **mrad** [2]

HFLAV: $\phi_s^{WA} = -55 \pm 21$ **mrad**

Indirect: $\phi_s^{SM} = -36.8^{+1.0}_{-0.7}$ **mrad** [3]

- **Observation of CP violation in charm: a new milestone in flavour physics**

LHCb: $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$ [4]

Outlook

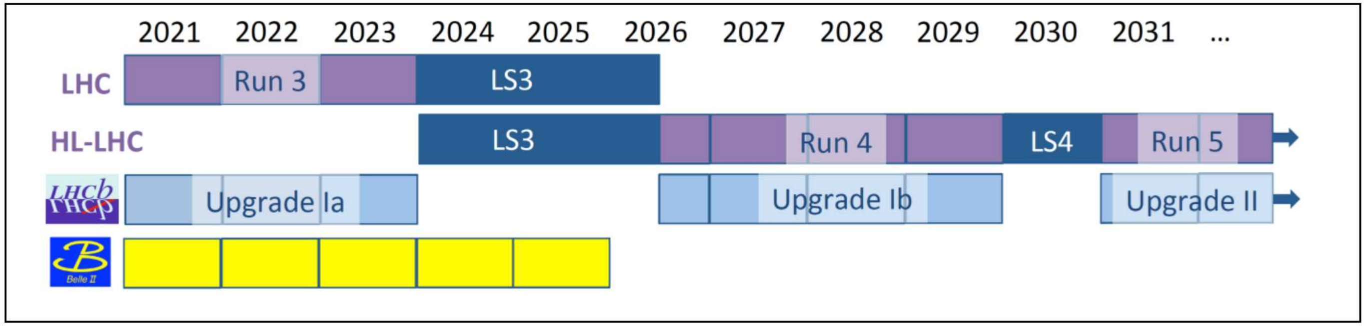
- **More CP violation results using full run 1+2 sample expected**
- **Exciting opportunities with flavour physics and CP violation in the HL-LHC era at LHCb, ATLAS and CMS**

[1: LHCb-PAPER-2019-013] [2: ATLAS-CONF-2019-009] [3: CKM fitter] [4: arXiv:1903.08726]

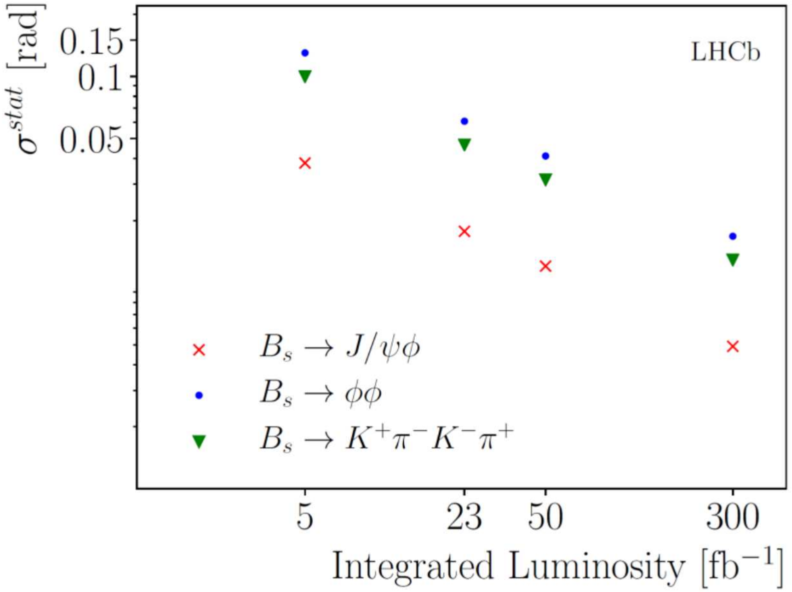
LHCb upgrade II

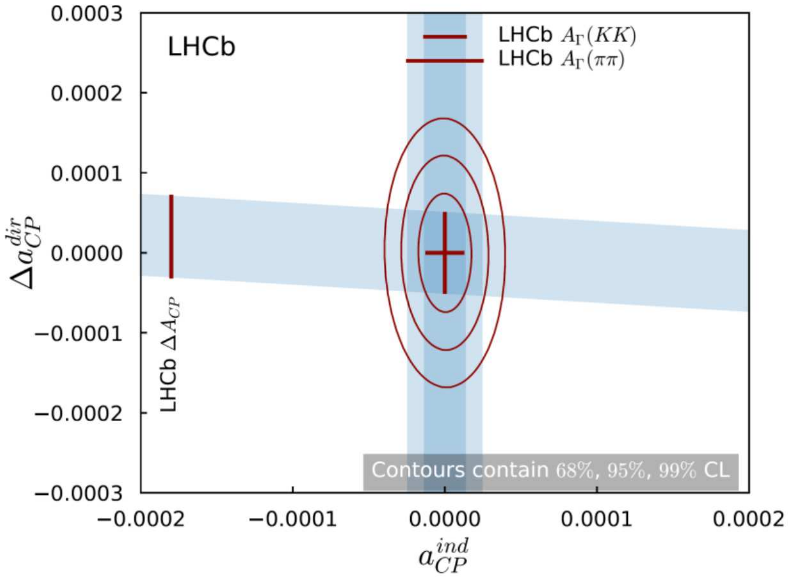
- **Two major upgrade at LS2 and LS4**

[arXiv:1808.08865]



- **Aim to take 300 fb^{-1}, improve key measurements by 10X**
  - $\sigma_{\phi_s} \sim 4$ **mrad**, $\sigma_{\gamma} \sim 0.4^{\circ}$, $\sigma_{A_{\Gamma}} \sim 10^{-5}$, $\sigma_{\Delta A_{CP}} \sim 3 \times 10^{-5}$

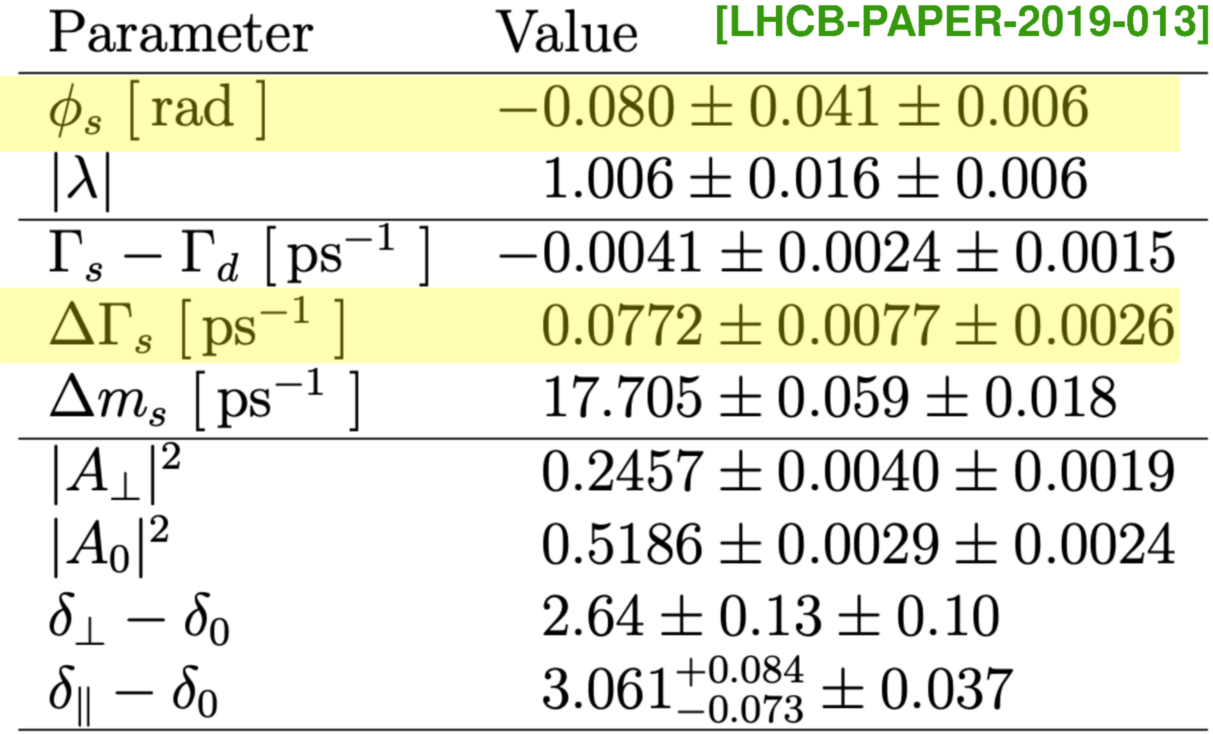




Backup slides

$B_s \to J/\psi\phi$ fit results

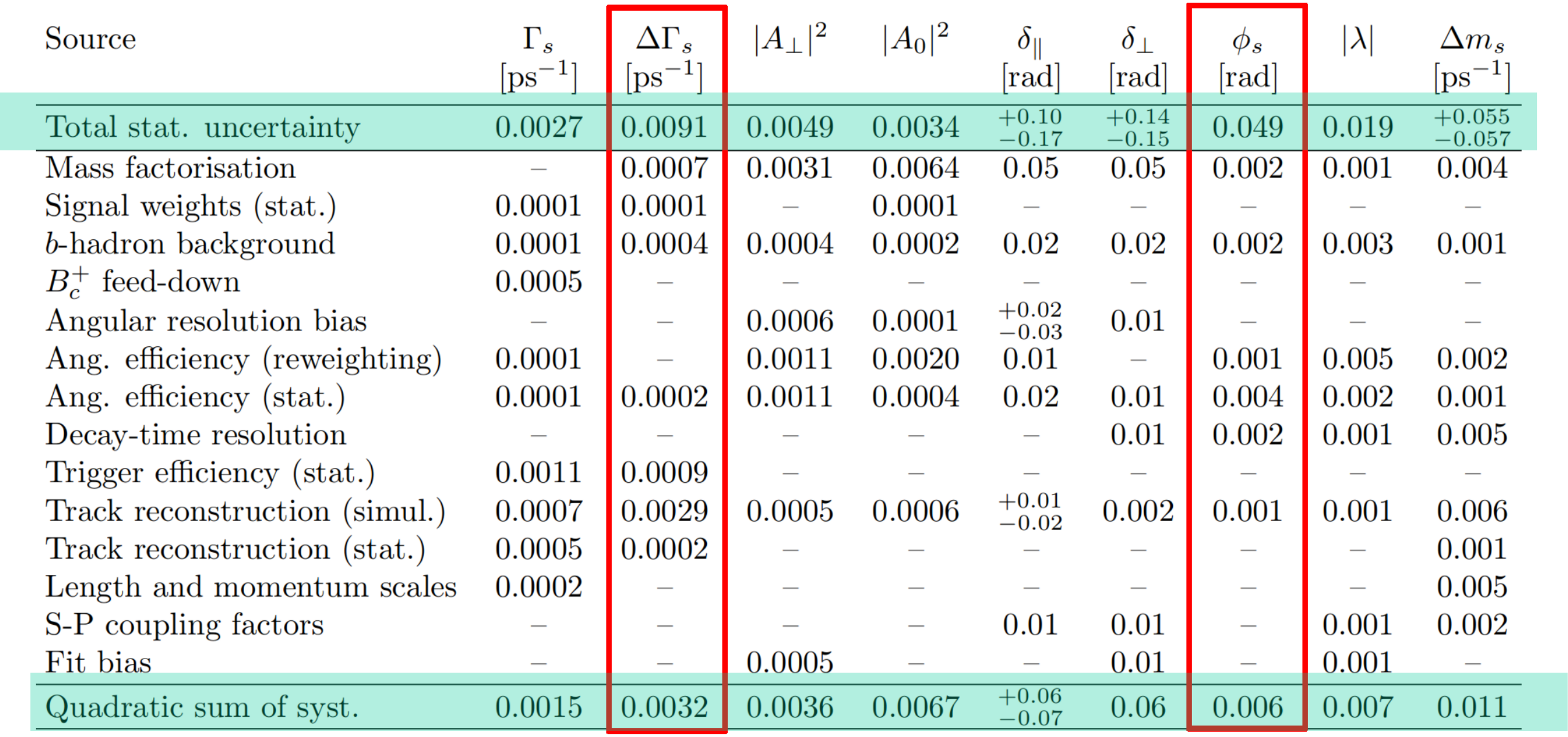
[LHCB-PAPER-2019-013]



Parameter	Value
ϕ_s [rad]	$-0.080 \pm 0.041 \pm 0.006$
$\lvert\lambda\rvert$	$1.006 \pm 0.016 \pm 0.006$
$\Gamma_s - \Gamma_d$ [ps^{-1}]	$-0.0041 \pm 0.0024 \pm 0.0015$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0772 \pm 0.0077 \pm 0.0026$
Δm_s [ps^{-1}]	$17.705 \pm 0.059 \pm 0.018$
$\lvert A_\perp\rvert^2$	$0.2457 \pm 0.0040 \pm 0.0019$
$\lvert A_0\rvert^2$	$0.5186 \pm 0.0029 \pm 0.0024$
$\delta_\perp - \delta_0$	$2.64 \pm 0.13 \pm 0.10$
$\delta_\parallel - \delta_0$	$3.061^{+0.084}_{-0.073} \pm 0.037$

ϕ_s systematic uncertainties

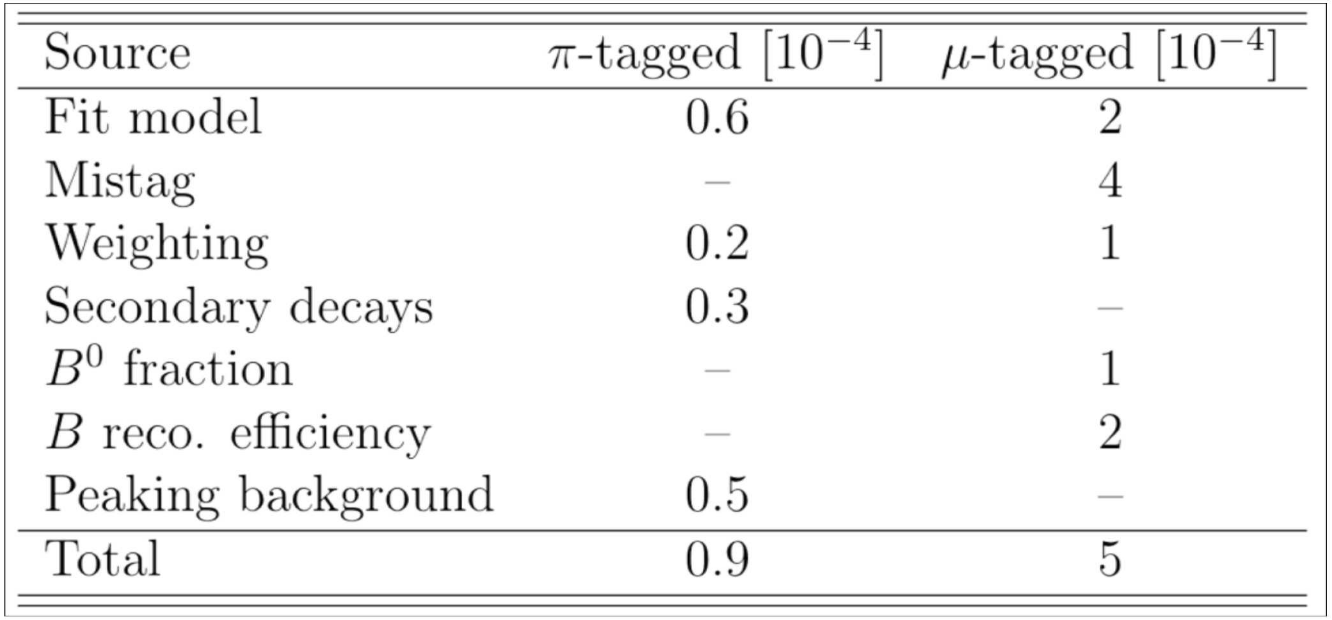
- **Statistical uncertainties dominate** [LHCB-PAPER-2019-013]
- **Major sources of systematics for ϕ_s**
  - Size of simulation samples
  - Signal and background modelling
  - Decay time resolution model



Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\lvert A_\perp\rvert^2$	$\lvert A_0\rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\lvert\lambda\rvert$	Δm_s [ps^{-1}]
Total stat. uncertainty	0.0027	0.0091	0.0049	0.0034	$^{+0.10}_{-0.17}$	$^{+0.14}_{-0.15}$	0.049	0.019	$^{+0.055}_{-0.057}$
Mass factorisation	–	0.0007	0.0031	0.0064	0.05	0.05	0.002	0.001	0.004
Signal weights (stat.)	0.0001	0.0001	–	0.0001	–	–	–	–	–
b-hadron background	0.0001	0.0004	0.0004	0.0002	0.02	0.02	0.002	0.003	0.001
B_c^+ feed-down	0.0005	–	–	–	–	–	–	–	–
Angular resolution bias	–	–	0.0006	0.0001	$^{+0.02}_{-0.03}$	0.01	–	–	–
Ang. efficiency (reweighting)	0.0001	–	0.0011	0.0020	0.01	–	0.001	0.005	0.002
Ang. efficiency (stat.)	0.0001	0.0002	0.0011	0.0004	0.02	0.01	0.004	0.002	0.001
Decay-time resolution	–	–	–	–	–	0.01	0.002	0.001	0.005
Trigger efficiency (stat.)	0.0011	0.0009	–	–	–	–	–	–	–
Track reconstruction (simul.)	0.0007	0.0029	0.0005	0.0006	$^{+0.01}_{-0.02}$	0.002	0.001	0.001	0.006
Track reconstruction (stat.)	0.0005	0.0002	–	–	–	–	–	–	0.001
Length and momentum scales	0.0002	–	–	–	–	–	–	–	0.005
S-P coupling factors	–	–	–	–	0.01	0.01	–	0.001	0.002
Fit bias	–	–	0.0005	–	–	0.01	–	0.001	–
Quadratic sum of syst.	0.0015	0.0032	0.0036	0.0067	$^{+0.06}_{-0.07}$	0.06	0.006	0.007	0.011

ΔA_{CP} Systematics

[LHCb-PAPER-2019-006]



Source	π-tagged $[10^{-4}]$	μ-tagged $[10^{-4}]$
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B^0 fraction	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

Interpreting the ΔA_{CP} result

$$\Delta \mathrm{A_{CP}} \approx \Delta \mathrm{a_{CP}^{dir}}\left(1+\frac{\overline{<t>}}{\tau(D^0)}y_{CP}\right)+\frac{\Delta\mathrm{<t>}}{\tau(\mathrm{D^0})}\mathrm{a_{CP}^{ind}}$$

- **Using LHCb averages**
  - $\mathrm{a_{CP}^{ind}} \approx -\mathrm{A_\Gamma} = (+0.29 \pm 0.28\,) \times 10^{-3}$ [PRL 118 (2017) 261803]
  - $\mathrm{y_{CP}} = (5.7 \pm 1.5\,) \times 10^{-3}$ [PRL 122 (2019) 011802]
- **For the data sample**

$\Delta\langle t\rangle/\tau(D^0) = 0.115 \pm 0.002,\ \overline{\langle t\rangle}/\tau(D^0) = 1.71 \pm 0.10$

$$\boxed{\Delta a_{CP}^{dir} = (-15.6 \pm 2.9\,) \times 10^{-4}}$$

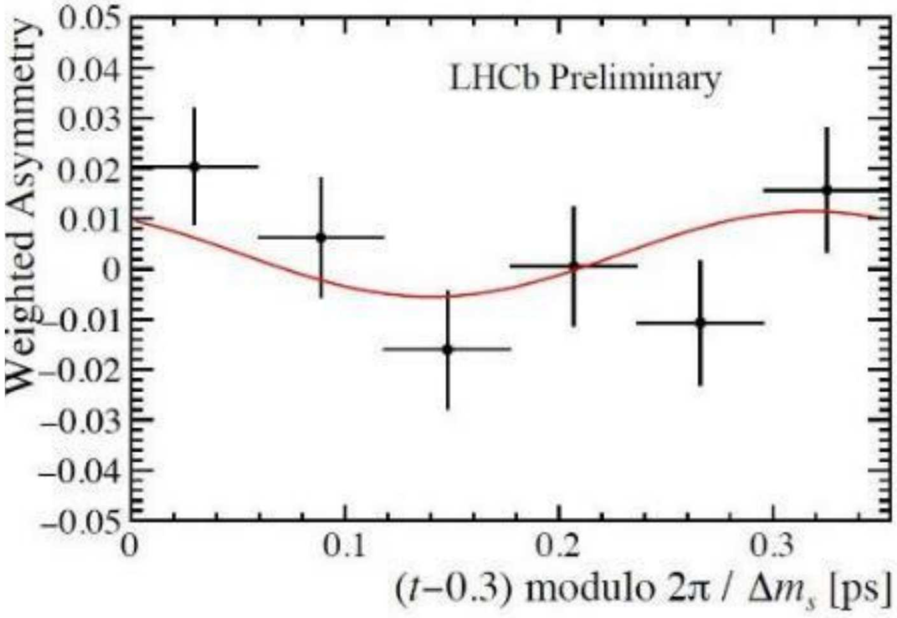
[LHCb-PAPER-2019-006]

ΔA_{CP} mostly sensitive to direct CP violation

CP asymmetry visualization

[LHCb-paper-2019-013]

$$A_{\rm CP} \equiv \frac{\Gamma\left(\overline{B}{}^0_s \to f\right) - \Gamma\left(B^0_s \to f\right)}{\Gamma\left(\overline{B}{}^0_s \to f\right) + \Gamma\left(B^0_s \to f\right)} \sim \eta_f \sin\phi_s \sin(\Delta m_s t)$$



Weak pattern of oscillation seen (2.4σ significance)