STATUS AND PROSPECTS WITH CP VIOLATION IN BEAUTY AT LHCB

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On behalf of the LHCb Collaboration

Upgrade-2 workshop
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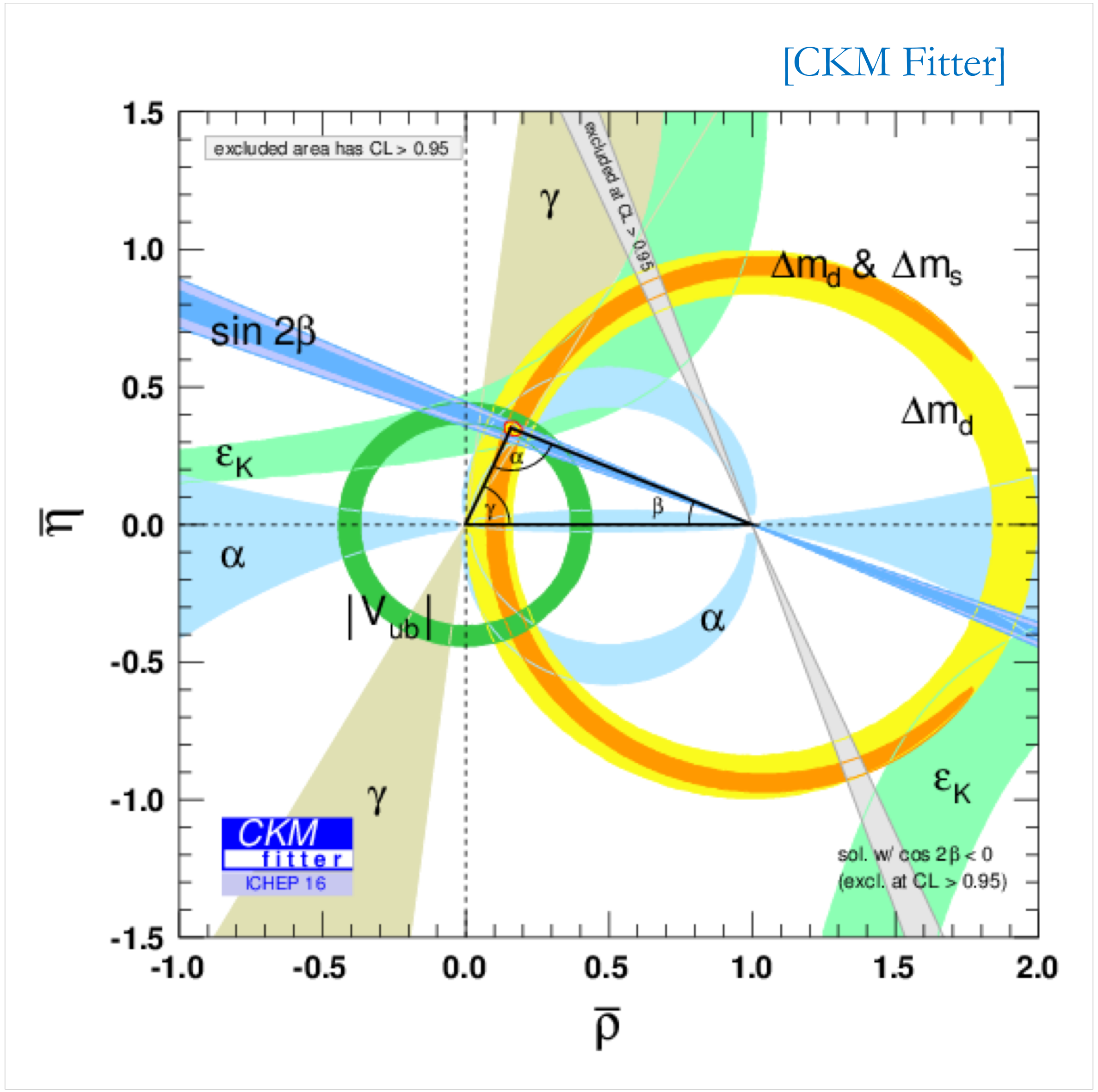


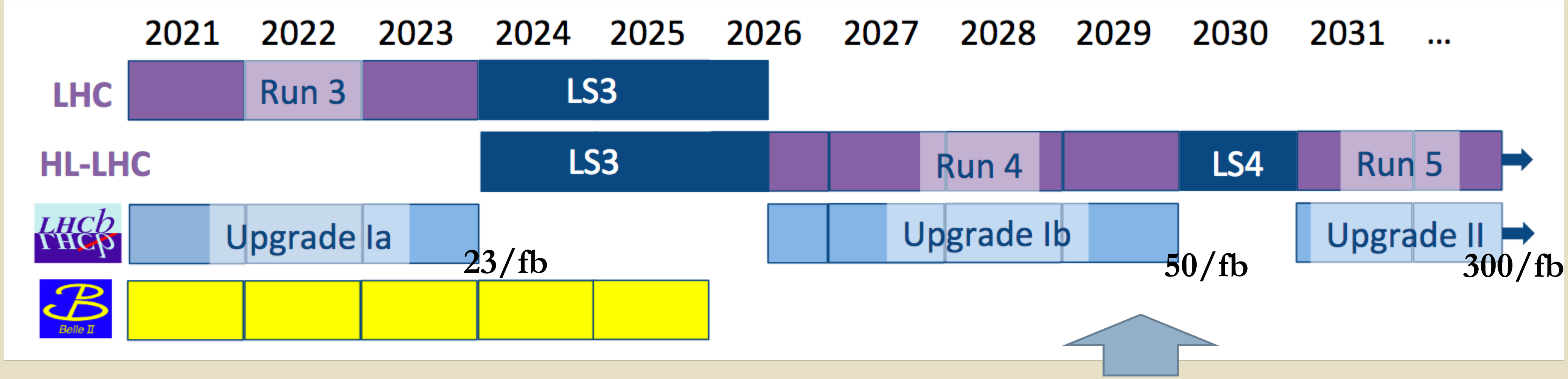
The CKM fit: a lot of room for NP

- It is safe to say that the era of HL-LHC (together with Belle II) will produce a much more precise picture of the physics of flavour
- **O(20%) NP contributions to most loop-level processes (FCNC) are still allowed**
  - See e.g. arXiv:1309.2293 [hep-ph]
- Interesting comparison of tree-level vs higher-order observables. In the latter, unknown particles could contribute.
- The SM works so remarkably well that we have to make **more and more precise measurements**

The experimental scenario

In this talk I will:

- Summarise current status of art of γ, φ_s and β
- Give some perspectives for the evolution of these measurements for the LHCb Upgrade II
- Refer to the milestones indicated below



LHCb may be the only large-scale flavour physics experiment operating in the HL-LHC era.

End Run 3 → End Run 5: **ATLAS/CMS**: 300/fb → 3000/fb, **LHCb:** 23/fb → 300/fb

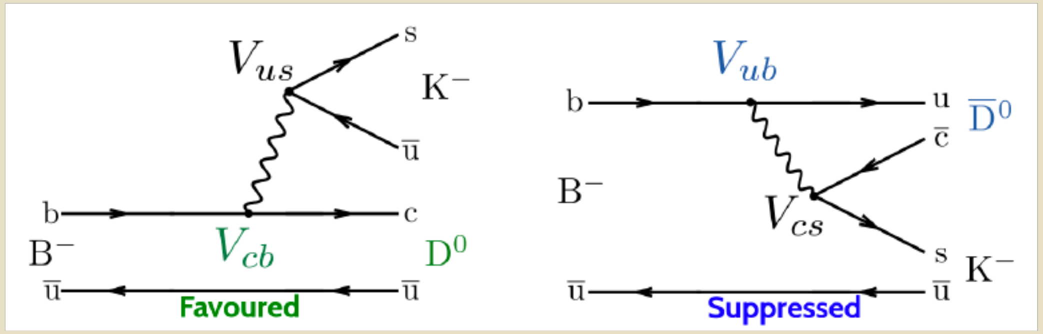
Status of γ

$\gamma = -\arg(V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*})$

- γ is still the **least well-known** angle of the Unitarity Triangle
- Measurements of γ from B decays mediated only by **tree-level** transitions provide a "standard candle" for the SM (assuming no new physics in tree-level decays [Phys. Rev.D 92, 033002 (2015)])
  $\Rightarrow$ **Theoretically clean** $[\delta\gamma/\gamma] \lesssim \mathcal{O}(10^{-7})$ [JHEP 1401 (2014) 051]
- This can be compared with γ values from B decays involving **loop-level** transitions, such as $B^0_{d,s} \to hh'$ decays ($h = K, \pi$), to get **signs of NP**.

→If the assumption is dropped, Upgrade 2 will allow to search for NP.

- Can be measured in the interference between $b \to c$ (favoured) and $b \to u$ (suppressed) transitions, e.g.:



Ratio of magnitudes

$$\frac{A_{sup}}{A_{fav}} = r_B^{Dh} e^{i(\delta_B^{Dh} \pm \gamma)}$$

Strong phase difference

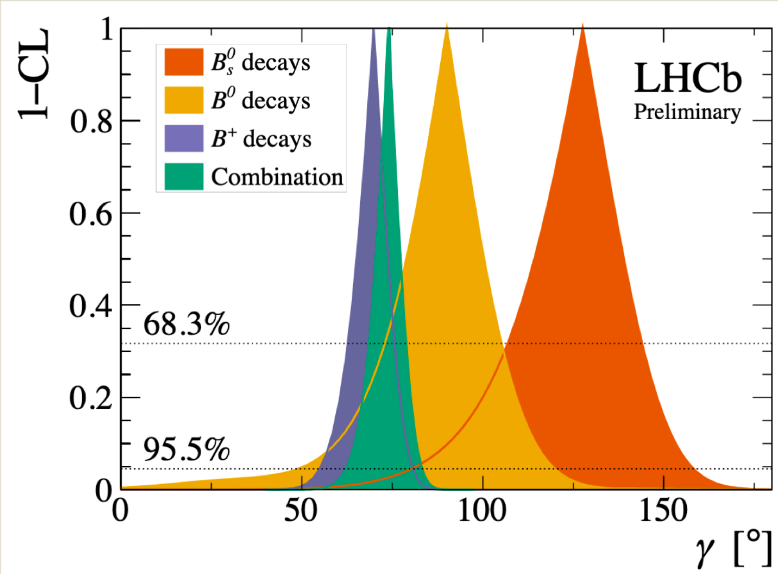
Small signal yields (BR 10^-7), small interference effects (10%). Combining a plethora of independent decay modes is the key to achieve the ultimate precision.

State of art of γ

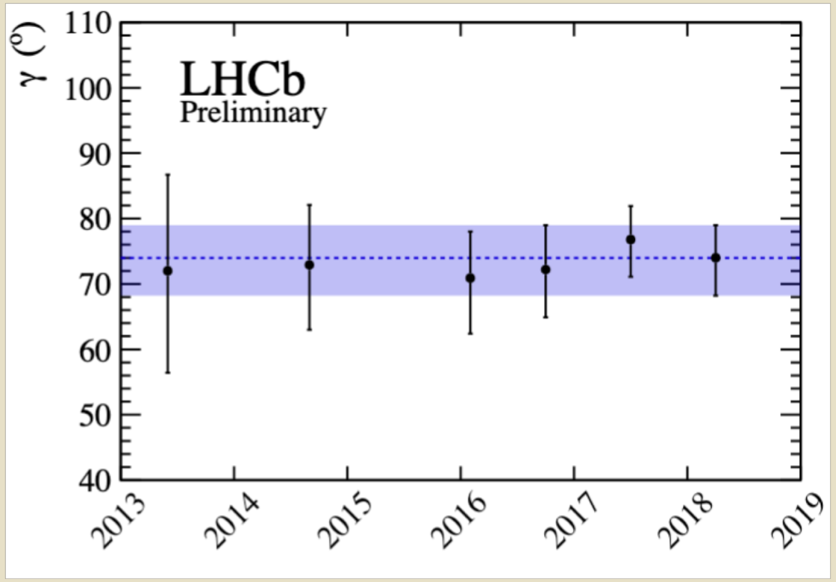
- Strategy similar to previous combinations: frequentist treatment.
- This combination includes new and updated measurements.

[LHCb-CONF-018-002]

B decay	D decay	Method	Ref.	Dataset[†]	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2	New
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1	As before
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	[25]	Run 1	Updated results
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1	New



[LHCb-CONF-018-002]



[LHCb-CONF-018-002]

LHCb combination
$\gamma = (74.0^{+5.0}_{-5.8})^\circ$

In agreement with world averages
Supersedes the previous LHCb measurement.
Most precise determination of γ from a single experiment to date.

Some thoughts on Upgrade 2

- Since the bulk of the sensitivity to γ comes from the difference in rates of the $B - \bar{B}$ processes, a **precise control of asymmetries in charged-particle identification and detection is crucial**
  → these systematic uncertainties are considered to scale with integrated luminosity

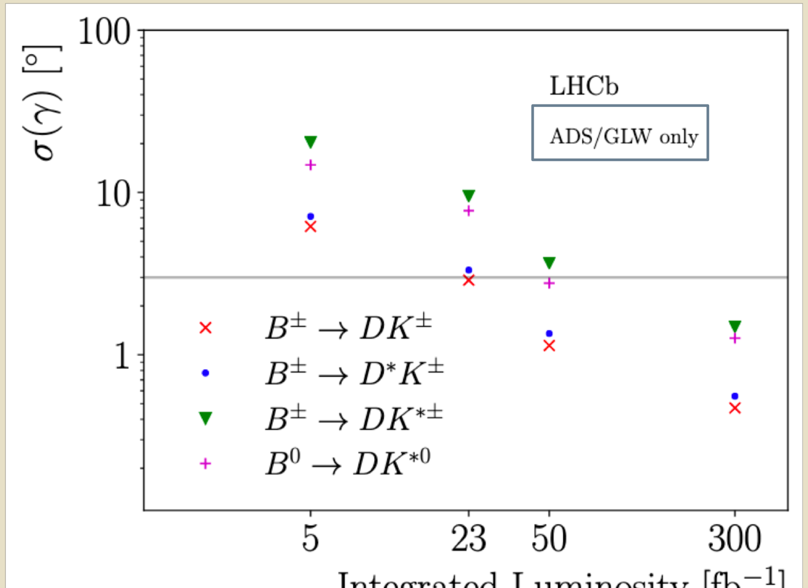
- Upgrade of the calorimeter will greatly expand LHCb's capabilities for modes with neutrals in the final state.

- Upgrade 2 will also make it interesting to measure γ using baryonic decays
  → **TORCH** system particularly helpful in allowing for low-momentum separation of protons and kaons

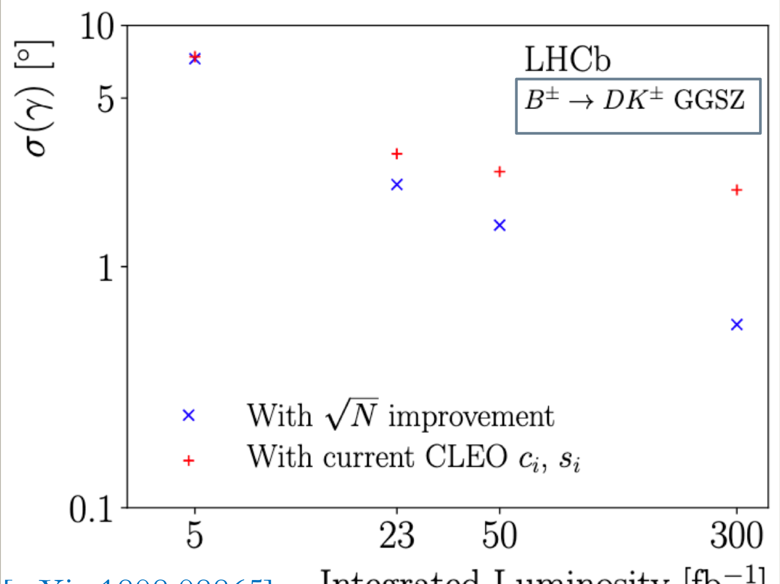
- Addition of **magnet-side stations** may lead to important signal-yield improvements, particularly for high-multiplicity final states.

- Constrain $\beta_{(s)}$ without penguin contaminations → $\sim 2°$ sensitivity on $\gamma - 2\beta_s$ from $B_s^0 \to D_s K$

Prospects for γ



[arXiv:1808.08865]



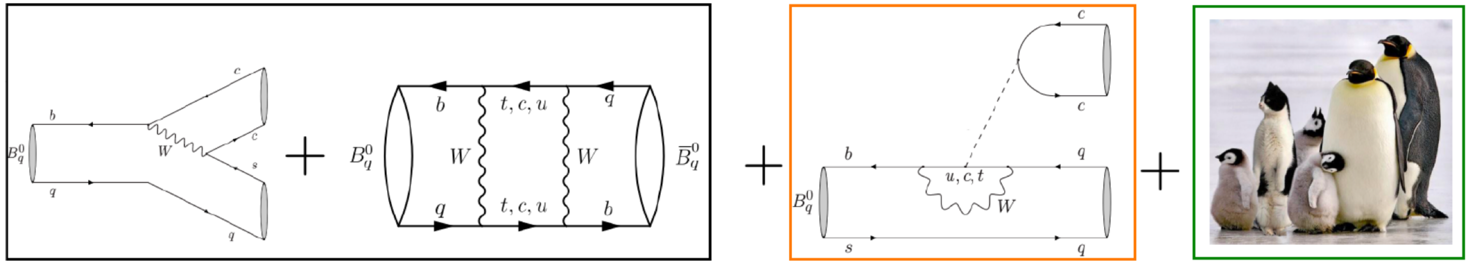
[arXiv:1808.08865]

- D is reconstructed in a two charged-track final state
- All ADS/GLW asymm. currently statistically limited
- Dominant syst., due to knowledge of background contributions, expected to scale with statistics

- D is reconstructed in a three-body self-conjugated final state
- Powerful input to the overall determination of γ
- Need good description of strong phase difference δ_D
  - Current inputs taken from CLEO-c (current syst ~ 2°)
  - Future BESIII and LHCb charm inputs are vital

- Belle-II targets a precision of 1.5° at the end of data-taking (2025)
- Comparison of measurements made in single decay modes interesting after Upgrade II (1° sensitivity) →NP in tree level different for different final states

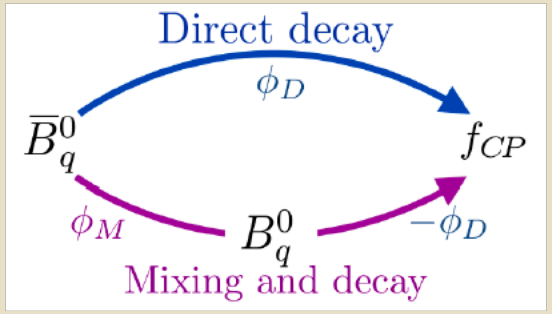
CP violation in B mixing and decay, φ_s

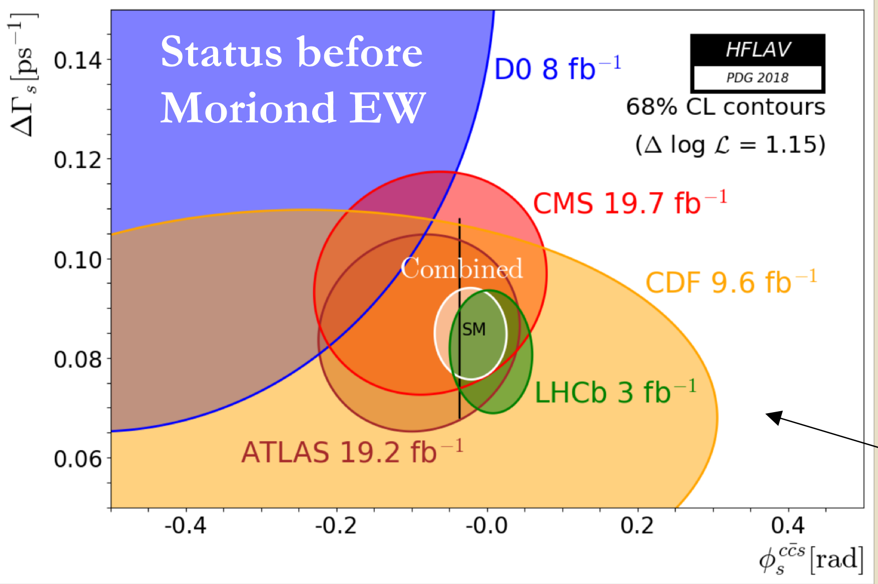


Dominant SM "tree" contribution

Higher order "penguin" contributions from non-perturbative hadronic effects

NP could be difficult to distinguish from penguins...





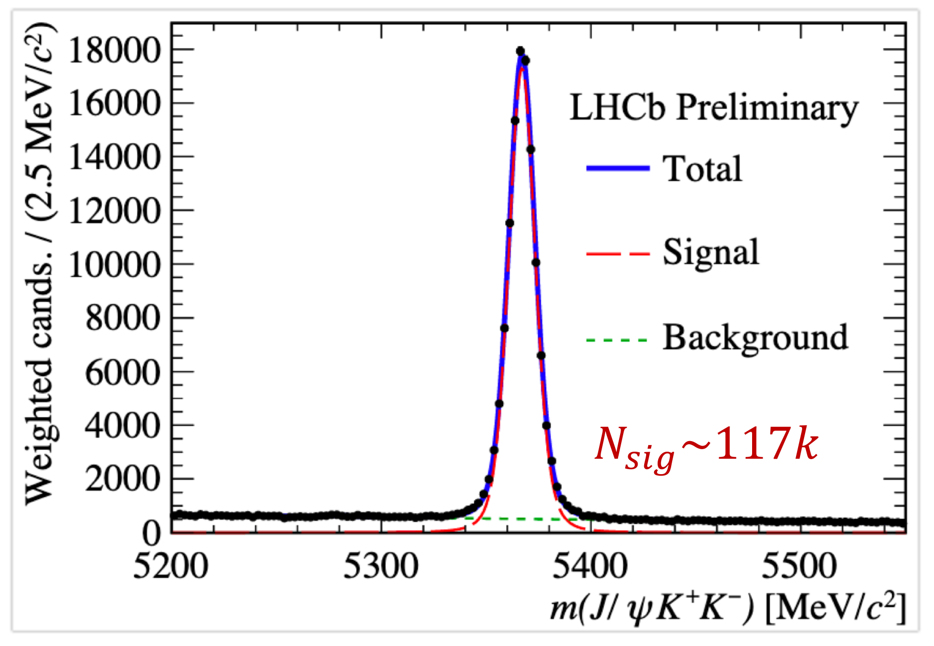
CP-violating phase arising from interference between mixing and decay.

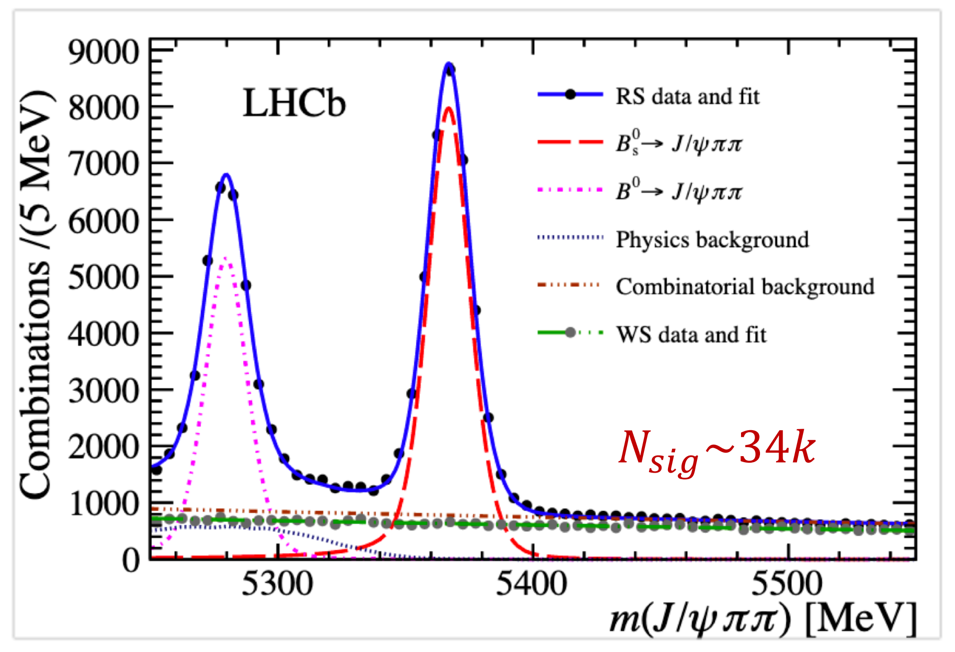
- Precisely predicted by the SM: $\boldsymbol{\varphi_s^{SM} = 36.86^{+0.96}_{-0.68}}$ **mrad** [CKMFitter]
- Golden channel exploited by LHCb, ATLAS, CMS: $B_s^0 \to J/\psi\phi$
- LHCb also measured many other channels

- World average (dominated by LHCb) consistent with predictions;
- Exp. uncertainty (31 mrad) almost a factor of 30 larger than uncert. of indirect determination when penguin pollution is ignored.

First harvest of LHCb Run 2 data

- New results obtained analysing 2015 (0.3 fb^{-1}) and 2016 (1.6 fb^{-1}) data presented at Moriond EW '19
- $B_s^0 \to J/\psi KK$ [LHCb-PAPER-2019-013] and $B_s^0 \to J/\psi \pi\pi$ [arXiv:1903.05530]
- Both measure φ_s and λ + $\Delta\Gamma_s$ and $\Gamma_s - \Gamma_d$ (excellent test of HQE) and $\Gamma_H - \Gamma_d$ (final state mostly CP-odd)
- Simultaneous fit to the decay time and three helicity angles in 6 bins in $m(K^+K^-)$ and $m(\pi^+\pi^-)$





Overview of the results

Combination of all LHCb (Run1 and 2) results

$$\varphi_s = -0.040 \pm 0.025 \text{ rad}$$
$$|\lambda| = 0.991 \pm 0.010$$
$$\Gamma_s = 0.6563 \pm 0.0021 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0812 \pm 0.0048 \text{ ps}^{-1}$$

φ_s 0.1σ away from SM

consistent with Standard Model

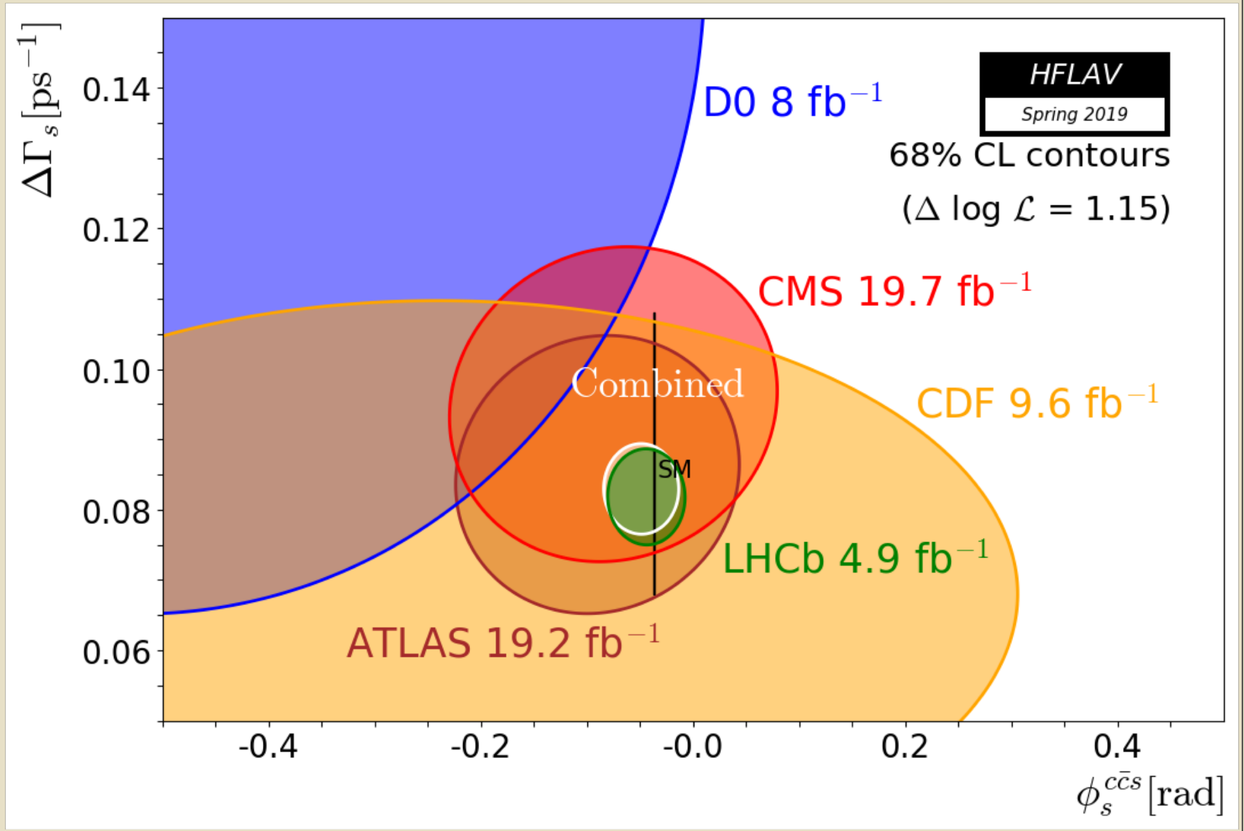
φ_s 1.6σ away from 0

consistent with no CPV in interference

$|\lambda|$ consistent with 1

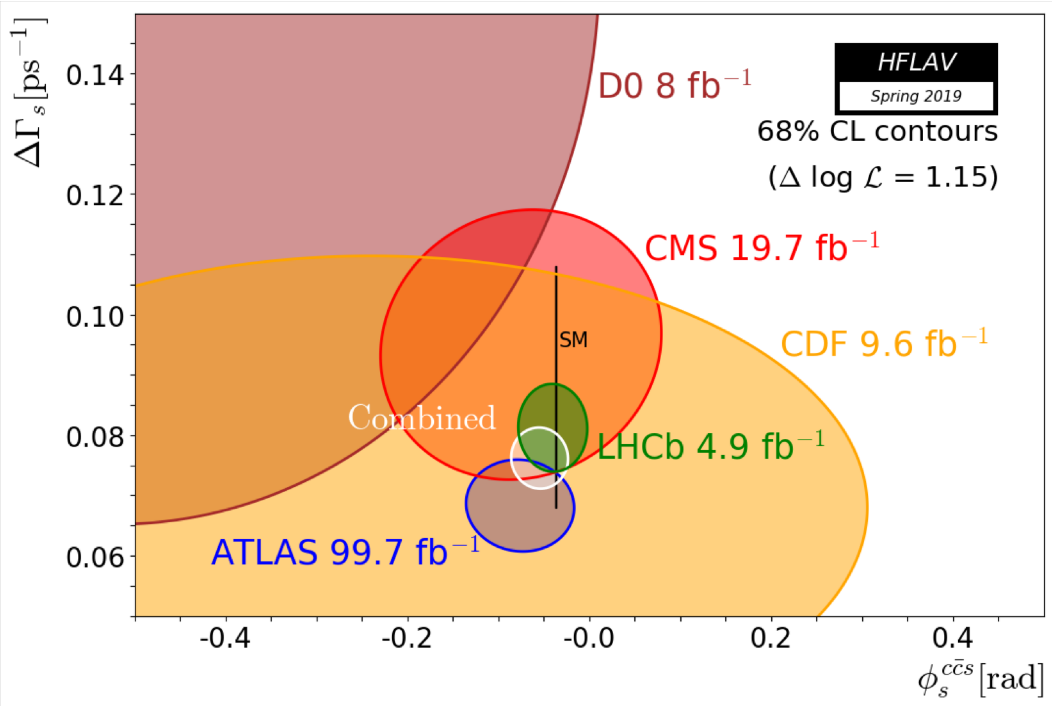
consistent with no direct CPV

$\Gamma_s - \Gamma_d$ consistent with HQE prediction



News from ATLAS

[ATLAS-CONF-2019-009]



Very preliminary HFLAV combination

$$\varphi_s = -0.054 \pm 0.021 \text{ rad}$$
$$\Delta\Gamma_s = 0.0762 \pm 0.0034 \text{ ps}^{-1}$$

- New since Run2: Insertable pixel B-Layer (IBL) + topological L1 trigger
  - $\boldsymbol{\sigma_{eff}} = \mathbf{69\ fs}$ (wrt 100 fs in Run 1)
- Integrated lumi of 80.5 fb^{-1} (2015-2017) → Full Run 2 is 139 fb^{-1}
- $\varepsilon_{tag} D^2$=1.65% (Run 1 was 1.49%)

Run 2

$$\varphi_s = -0.068 \pm 0.038 \pm 0.018 \text{ rad}$$
$$\Gamma_s = 0.669 \pm 0.001 \pm 0.001 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.067 \pm 0.005 \pm 0.002 \text{ ps}^{-1}$$

Single measurement stat. precision comparable to LHCb (which is 2015-2016) →$\varphi_{s,ATLAS}^{stat}(RUN1) = 0.078$ for 19/fb

Combining ATLAS Run 1 + Run 2:

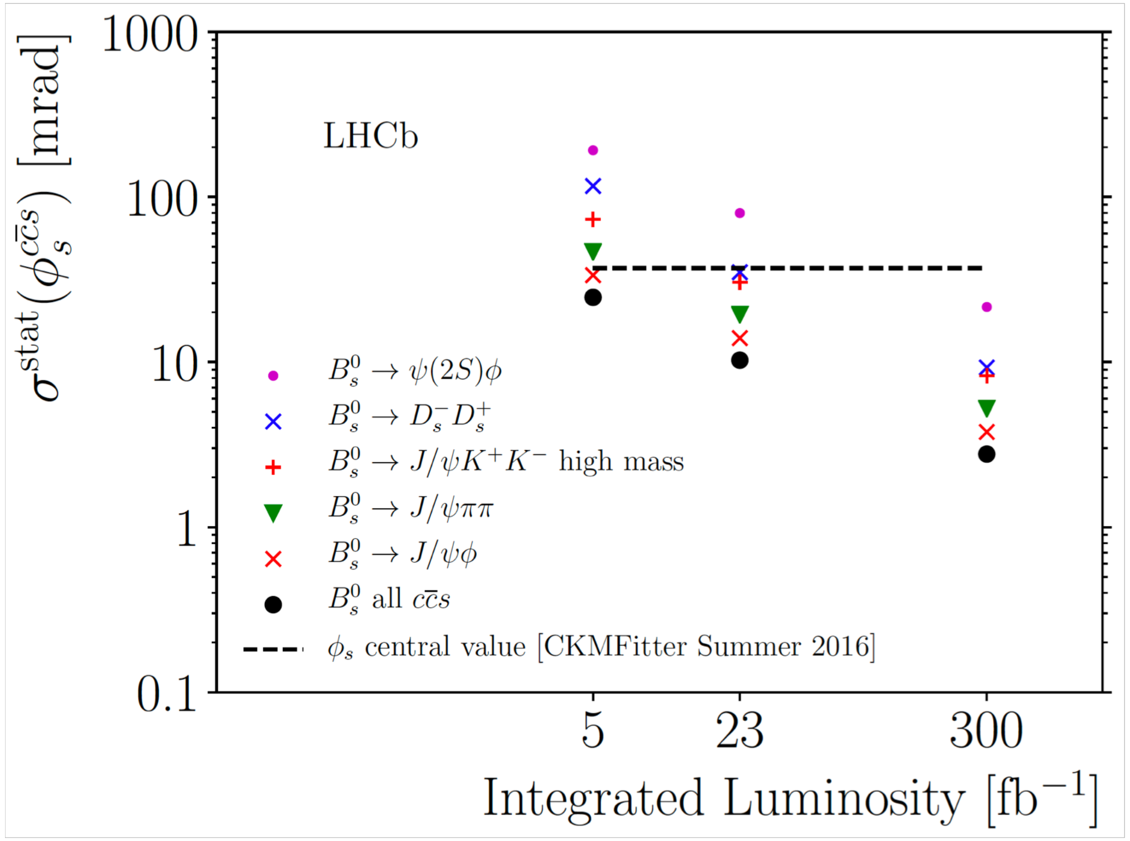
$$\varphi_s = -0.076 \pm 0.034 \pm 0.019 \text{ rad}$$
$$\Gamma_s = 0.669 \pm 0.001 \pm 0.001 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.068 \pm 0.004 \pm 0.003 \text{ ps}^{-1}$$

Some considerations on the combination

- **Combination among the experiments is getting more and more interesting**
  - The largest correlation for the φ_s LHCb result is with λ (~15%), that ATLAS is not fitting for.
  - Interesting to see CMS results
- Strenght of LHCb: **versatility** and possibility to measure φ_s also with many other channels, in particular $B_s^0 \to J/\psi\pi\pi$
  - In Run 2 and beyond: time-dependent flavour-tagged analyses become possible for other channels (e.g., with 300/fb, we could have 4% x 300k = ~12k tagged $B_s^0 \to J/\psi\eta$, with $\eta \to \gamma\gamma$, candidates)
- Entering in a regime where **penguin pollution** constraints are similar to the precision of the combination
- The value of $\boldsymbol{\Gamma_s}$ **shows tension** between LHCb and ATLAS:
  - HFLAV (not including Run 2): $\Gamma_s^{HFLAV} = 0.6629 \pm 0.0018\ \text{ps}^{-1}$
  - LHCb Run 2: $\Gamma_s^{LHCb} = 0.6538 \pm 0.0033\ \text{ps}^{-1}$ → $-2.4\ \sigma$ from WA
  - ATLAS Run 2: $\Gamma_s^{ATLAS} = 0.669 \pm 0.0014\ \text{ps}^{-1}$ → $+2.7\ \sigma$ from WA
  - Wrt $\Gamma_s / \Gamma_d(HQE)$=1.0006 ± 0.0025, LHCb is @1.4 σ, ATLAS @3.1 σ

→ Difference between ATLAS and LHCb of ~ 5 σ

Need to be very cautious when assigning systematics for the lifetimes.



[arXiv:1808.08865]

Prospects for the future

- Include gain in trigger for $B_s^0 \to D_s^- D_s^+$ after Upgr 1
- Same performances as in Run 2 (tagging power 4%)
- Planning new modes: $J/\psi \to ee, \eta' \to \rho^0\gamma$ or , $\eta' \to \eta\pi\pi$ or $\gamma\gamma$
  - To improve the precision
  - But also to allow independent tests of the SM

300/fb: $\sigma^{STAT}(\varphi_s)$ ~ 4 mrad from $B_s^0 \to J/\psi\phi$ only

- Fundamental that FT keep the same performance
- **φ_s expected to be statistically limited**

Control of penguin pollution

- U-spin or SU(3) flavour symmetry to constrain size of penguin with b→c$\bar{c}$d
- Penguin pollution and/or CP violation could be different for each polarisation state, f ∈ (0, ⊥, ∥, S)

  → no sign yet of dependence in $B_s^0 \to J/\psi$ KK (also in Run 2) so penguins are small

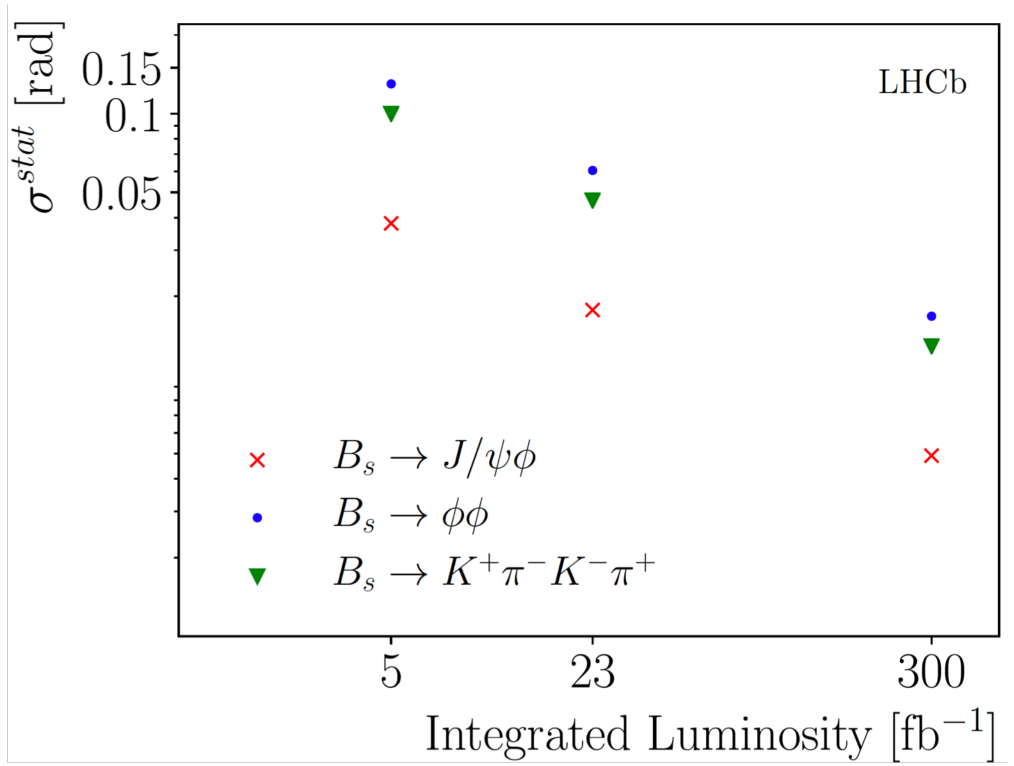
- **SU(3)$_F$: $B_s^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi\rho^0$ are b→c$\bar{c}$d transitions** (related by s-d spectator exchange).
  $B^0 \to J/\psi\rho^0$ contains E + PA diagrams that are not present in $B_s^0 \to J/\psi K^{*0}$

$$\Delta\phi_{s,0}^{J/\psi\,\phi} = 0.000^{+0.009}_{-0.011}\,(\text{stat})\;{}^{+0.004}_{-0.009}\,(\text{syst})\,\text{rad}$$
$$\Delta\phi_{s,\parallel}^{J/\psi\,\phi} = 0.001^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\,\text{rad}$$
$$\Delta\phi_{s,\perp}^{J/\psi\,\phi} = 0.003^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\,\text{rad}$$

[JHEP 11 (2015) 082]

Precision of ~10 mrad
To be compared with the current precision of HFLAV of **21 mrad**

Fundamental to update these analyses, expected sensitivity **at 300/fb is 1.5 mrad** (statistically limited) [arXiv:1808.08865]
+ $B_s^0 \to J/\psi\omega$ and $B^0 \to J/\psi\varphi$ (E + PA diagrams only)



[arXiv:1808.08865]

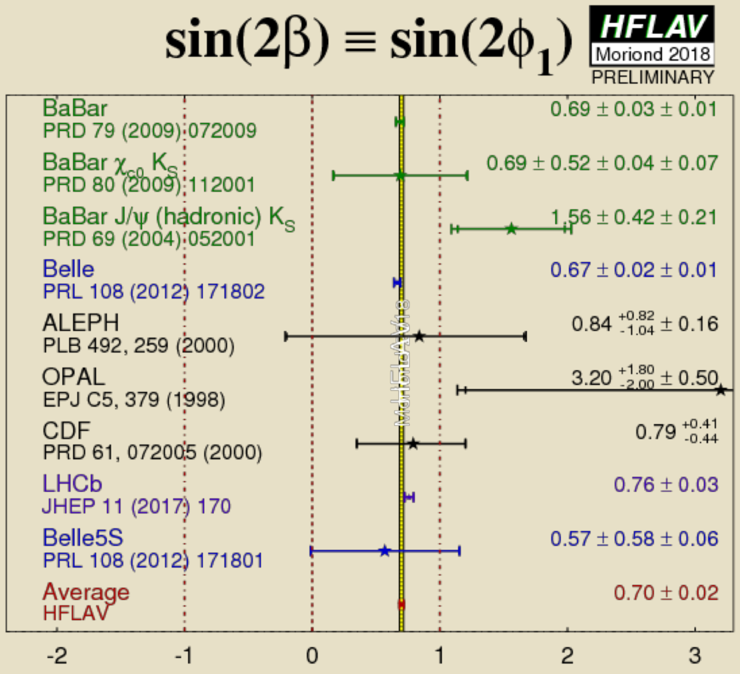
φ_s from penguin decays

- Include gain in trigger after Upgrade 1

300/fb: $\sigma^{STAT}(\varphi_s)$ ~ 11 mrad from $B_s^0 \to \phi\phi$
300/fb: $\sigma^{STAT}(\varphi_s)$ ~ 9 mrad from $B_s^0 \to K\pi K\pi$

- $B_s^0 \to \phi\phi$ will remain stat. limited
- Limiting syst for $B_s^0 \to K\pi K\pi$ <30 mrad from MC (important to exploit rapid MC production) and modelling resonances.

State of art of $\sin(2\beta)$



Golden channel $B^0 \to J/\psi K_s^0$, averages including all charmonium:

LHCb:

- $\boldsymbol{S = 0.760 \pm 0.034}$ [JHEP 11(2017) 170]

Belle:

- $\boldsymbol{S = 0.667 \pm 0.026}$ [PRL 108(2012) 171802]

Babar:

- $\boldsymbol{S = 0.691 \pm 0.031}$ [PRD 79(2009) 072009]

$$\boxed{S \equiv -\eta_{CP}\sin(2\beta) = 0.699 \pm 0.017}$$

[HFLAV 2018]

$$\boxed{S^{SM} \equiv \sin(2\beta) = 0.748^{+0.030}_{-0.032}}$$

[CKMfitter]

- LHCb has a similar precision to the B-factories
- Small tension of B-factories results with SM predictions to be clarified

Prospects for $\sin(2\beta)$

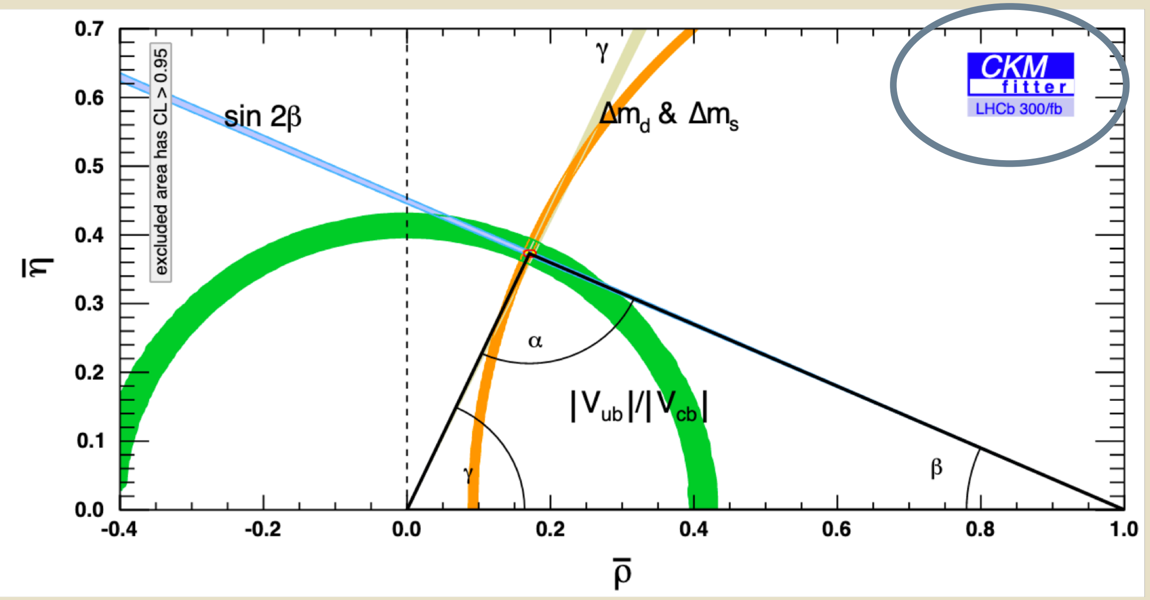
- ◦ @50/fb: $\sigma_{stat} = 0.006$ with $B^0 \to J/\psi K_s^0$
- ◦ @300/fb: $\sigma_{stat} = 0.003$ with $B^0 \to J/\psi K_s^0$

Belle II @50/ab: $\sigma_{stat} = 0.005$ with $B^0 \to J/\psi K_s^0$

Systematics:

- Mostly depends on size of control samples → scale with statistics
- Important to understand how to take into account $K^0 - \overline{K}^0$ CP violation and nuclear cross-section asymmetry.

Leading sources of systematic uncertainty are different between Belle II and LHCb



[arXiv:1808.08865]

Penguins controlled using $B^0 \to J/\psi\pi^0$ and $B_s^0 \to J/\psi K_s^0$

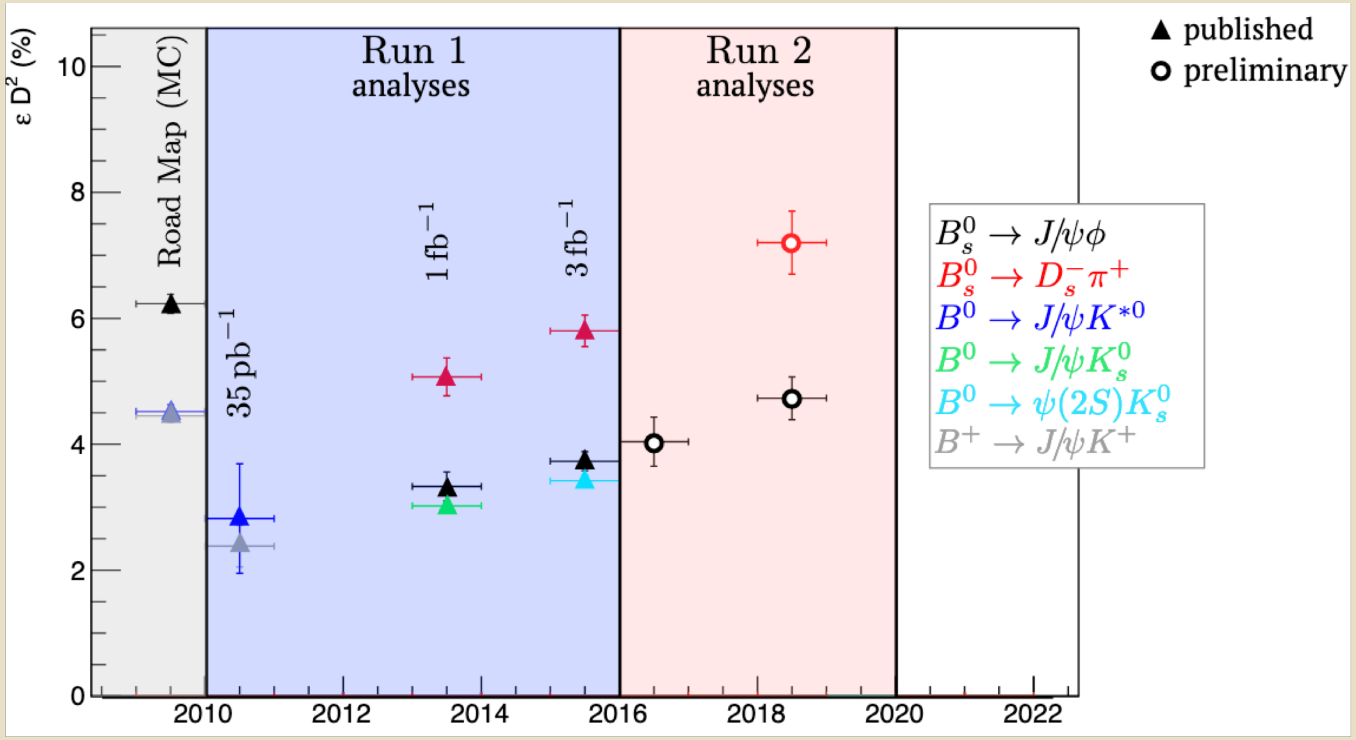
- $B_s^0 \to J/\psi K_s^0$ studied by LHCb [Phys. Rev. Lett. 115 (2015) 031601]
- Belle II expects a good precision for $B^0 \to J/\psi\pi^0$
- Improving ECAL will allow also LHCb to contribute
- Upgrade II will also allow to study other SU(3) related modes

Flavour tagging in the future

Almost everything will be new in Run3 (similar situation as in 2010)

- **Upgrade challenge**: increase in track multiplicity and pile-up (~6 for Upgrade-I and ~55 for Upgrade-II) that have negative effect on ω and ε_{tag}.
- FT performance directly linked to the ability to associate PV ⟺ track. To improve/maintain tagging performance need:
  - **Hardware**: timing information (upgrade-II workshops)
  - **Software**: deep neural networks to learn correlations between all tracks and the signal B meson (inclusive taggers), need to reduce significantly persisted info.

Plot from S. Akar



- **Better exploitation of data = more tagging power!**
  - Run2 LHCb : ~30% relative improvement of tagging power
  - Belle 2 will do much better with their data for B^0
  - CMS/ATLAS do worse **but with more data**

Conclusions and remarks

- Interest in precision flavour measurements is stronger than ever → If no direct evidence of NP pops out of the LHC, flavour physics can play a key role;
- All results in this sector in good agreement with SM → need to go to even higher precision;
- Good prospects for the precision measurements in the Upgrade phase;
- Didn't talk about CP violation in Baryons which is also a rich program for Upgrade 2.

- For LHCb upgrades we should improve/maintain the flavour-tagging performance, use high-yield control channels to control efficiencies and understand precisely vertex/time resolution.

"And if someone dares to yawn during your presentation, this pointer easily transforms from a laser to a taser!"

BACKUP

Results using 2015-2016 data

$B_s^0 \to J/\psi KK$

$$\varphi_s = -0.080 \pm 0.041 \pm 0.006 \text{ rad}$$
$$|\lambda| = 1.006 \pm 0.016 \pm 0.006$$
$$\Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0772 \pm 0.0077 \pm 0.0026 \text{ ps}^{-1}$$

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

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

$$\Gamma_s = 0.6538 \pm 0.0024 \pm 0.0015 \pm 0.0017 \text{ (input } \Gamma_\mathrm{d}\text{) ps}^{-1}$$

Combining the above + Run 1: $B_s^0 \to J/\psi KK$, $B_s^0 \to J/\psi \pi\pi$, $B_s^0 \to J/\psi KK$ high mass, $B_s^0 \to D_s D_s$, $B_s^0 \to \psi(2S)\varphi$

$$\varphi_s = -0.040 \pm 0.025 \text{ rad}$$
$$|\lambda| = 0.991 \pm 0.010$$
$$\Gamma_s = 0.6563 \pm 0.0021 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0812 \pm 0.0048 \text{ ps}^{-1}$$

Systematics for $B_s^0 \to J/\psi KK$

φ_s mainly affected by Time res. & Ang. Acc., $\Delta\Gamma_s$ ($|\lambda|$)by Mass factorisation (& Ang. Acc.), $\Gamma_s - \Gamma_d$ by Time eff.

Source	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	ϕ_s [rad]	$\lvert\lambda\rvert$	$\delta_\perp - \delta_0$ [rad]	$\delta_\parallel - \delta_0$ [rad]	$\Gamma_s - \Gamma_d$ [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [ps^{-1}]
Mass width parametrisation	0.0006	0.0005	-	-	0.05	0.009	-	0.0002	0.001
Mass factorisation	0.0002	0.0004	0.004	$\boxed{0.0037}$	0.01	0.004	0.0007	$\boxed{0.0022}$	0.016
Multiple candidates	0.0006	0.0001	0.0011	0.0011	0.01	0.002	0.0003	0.0001	0.001
Fit bias	0.0001	0.0006	0.001	-	0.02	0.033	-	0.0003	0.001
C_{SP} factors	-	0.0001	0.001	0.0010	0.01	0.005	-	0.0001	0.002
Quadratic OS tagging	-	-	-	-	-	-	-	-	-
Time res.: statistical	-	-	-	-	-	-	-	-	-
Time res.: prompt	-	-	-	-	-	0.001	-	-	0.001
Time res.: mean offset	-	-	$\boxed{0.0032}$	0.0010	0.08	0.001	0.0002	0.0003	0.005
Time res.: Wrong PV	-	-	-	-	-	0.001	-	-	0.001
Ang. acc.: statistical	0.0003	0.0004	0.0011	0.0018	-	0.004	-	-	0.001
Ang. acc.: correction	0.0020	0.0011	0.0022	0.0043	0.01	0.008	0.0001	0.0002	0.001
Ang. acc.: low-quality tracks	0.0002	0.0001	0.0005	0.0014	-	0.002	0.0002	0.0001	-
Ang. acc.: t & σ_t dependence	0.0008	0.0012	0.0012	0.0007	0.03	0.006	0.0002	0.0010	0.003
Dec.-time eff.: statistical	0.0002	0.0003	-	-	-	-	$\boxed{0.0012}$	0.0008	-
Dec.-time eff.: $\Delta\Gamma_s = 0$ sim.	0.0001	0.0002	-	-	-	-	0.0003	0.0005	-
Dec.-time eff.: knot pos.	-	-	-	-	-	-	-	-	-
Dec.-time eff.: p.d.f. weighting	-	-	-	-	-	-	0.0001	0.0001	-
Dec.-time eff.: kin. weighting	-	-	-	-	-	-	0.0002	-	-
Length scale	-	-	-	-	-	-	-	-	0.004
Quadratic sum of syst.	0.0024	0.0019	0.0061	0.0064	0.10	0.037	0.0015	0.0026	0.018

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

$\Gamma_H - \Gamma_d$ mainly affected by Background, φ_s and $|\lambda|$ by Resonance modelling

Source	$\Gamma_H - \Gamma_{B^0}$ [fs^{-1}]	$\lvert\lambda\rvert$ [$\times 10^{-3}$]	ϕ_s [mrad]
t acceptance	2.0	0.0	0.3
τ_{B^0}	0.2	0.5	0.0
Efficiency $(m_{\pi\pi}, \Omega)$	0.2	0.1	0.0
t resolution width	0.0	4.3	4.0
t resolution mean	0.3	1.2	0.3
Background	$\boxed{3.0}$	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	$\boxed{28.9}$	$\boxed{9.0}$
Production asymmetry	0.3	0.6	3.4
Total	3.8	29.9	11.0

1Using reweighted WS samples in the fit
2) Vary the background yields by $\pm 1\sigma$

1) Vary Barrier factor
2) Replace NR by $f_0(500)$
3) Solution II
4) Add $\rho(770)$

ATLAS systematics

Table 5: Summary of systematic uncertainties assigned to the physical parameters of interest.

	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	$\lvert A_\parallel(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_\perp$ [rad]	$\delta_\parallel$ [rad]	$\delta_\perp - \delta_S$ [rad]
Tagging	1.7×10^{-2}	0.4×10^{-3}	0.3×10^{-3}	0.2×10^{-3}	0.2×10^{-3}	2.3×10^{-3}	1.9×10^{-2}	2.2×10^{-2}	2.2×10^{-3}
Acceptance	0.7×10^{-3}	$<10^{-4}$	$<10^{-4}$	0.8×10^{-3}	0.7×10^{-3}	2.4×10^{-3}	3.3×10^{-2}	1.4×10^{-2}	2.6×10^{-3}
ID alignment	0.7×10^{-3}	0.1×10^{-3}	0.5×10^{-3}	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	1.0×10^{-2}	7.2×10^{-3}	$<10^{-4}$
S–wave phase	0.2×10^{-3}	$<10^{-4}$	$<10^{-4}$	0.3×10^{-3}	$<10^{-4}$	0.3×10^{-3}	1.1×10^{-2}	2.1×10^{-2}	8.3×10^{-3}
Background angles model:									
Choice of fit function	1.8×10^{-3}	0.8×10^{-3}	$<10^{-4}$	1.4×10^{-3}	0.7×10^{-3}	0.2×10^{-3}	8.5×10^{-2}	1.9×10^{-1}	1.8×10^{-3}
Choice of p_T bins	1.3×10^{-3}	0.5×10^{-3}	$<10^{-4}$	0.4×10^{-3}	0.5×10^{-3}	1.2×10^{-3}	1.5×10^{-3}	7.2×10^{-3}	1.0×10^{-3}
Choice of mass interval	0.4×10^{-3}	0.1×10^{-3}	0.1×10^{-3}	0.3×10^{-3}	0.3×10^{-3}	1.3×10^{-3}	4.4×10^{-3}	7.4×10^{-3}	2.3×10^{-3}
Dedicated backgrounds:									
B_d^0	2.3×10^{-3}	1.1×10^{-3}	$<10^{-4}$	0.2×10^{-3}	3.1×10^{-3}	1.4×10^{-3}	1.0×10^{-2}	2.3×10^{-2}	2.1×10^{-3}
Λ_b	1.6×10^{-3}	0.4×10^{-3}	0.2×10^{-3}	0.5×10^{-3}	1.2×10^{-3}	1.8×10^{-3}	1.4×10^{-2}	2.9×10^{-2}	0.8×10^{-3}
Fit model:									
Time res. sig frac	1.4×10^{-3}	1.1×10^{-3}	$<10^{-4}$	0.5×10^{-3}	0.6×10^{-3}	0.6×10^{-3}	1.2×10^{-2}	3.0×10^{-2}	0.4×10^{-3}
Time res. p_T bins	3.3×10^{-3}	1.4×10^{-3}	0.1×10^{-2}	$<10^{-4}$	$<10^{-4}$	0.5×10^{-3}	6.2×10^{-3}	5.2×10^{-3}	1.1×10^{-3}
Total	1.8×10^{-2}	0.2×10^{-2}	0.1×10^{-2}	0.2×10^{-2}	0.4×10^{-2}	0.4×10^{-2}	9.7×10^{-2}	2.0×10^{-1}	0.1×10^{-1}