CP violation in b-meson decays @ LHCb

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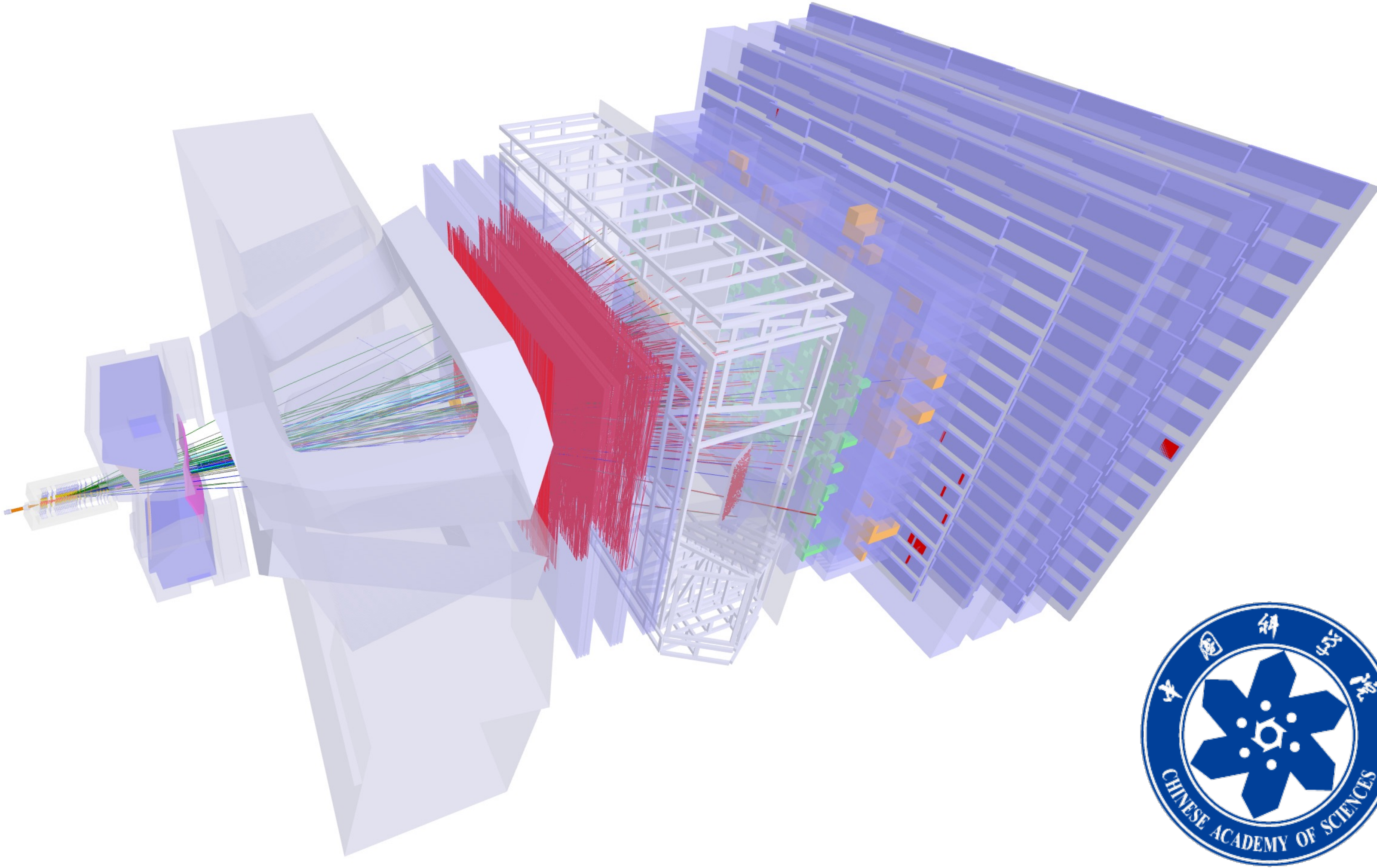


CP violation @ LHCb

- CP violation:
  - One of the Sakharov conditions for the generation of a matter-antimatter asymmetry in the early Universe
  - Arises from the complex phase in the CKM mixing matrix.

$$V_{\text{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- The main purpose of LHCb is to study CP violation in b-mesons

LHCb LoI, 1995

Conclusions

1) LHC provides a unique opportunity to study CP violation in B-meson decays with very high statistics and LHC-B can fully exploit this with well controlled systematics.

2) Dedicated B experiment with a forward spectrometer, LHC-B, can provide a flexible, robust and efficient trigger.

3) Open geometry allows easy access to the detector for adjusting the spectrometer to the machine condition.

4) With the particle identification capability, excellent mass and decay time resolutions and many B_d and B_s produced, LHC-B can study CP violation channels measuring α, β and γ as well as B_s oscillations to very large value of $x_s > 50$ with small systematics.

5) The spectrometer can study other physics such as charm and tau decays as well as a wide variety of forward physics at the same time.

6) Low required luminosity of 1.5×10^{32} allows LHC-B to provide physics results from the beginning of the LHC run.

7) LHC-B can be installed in one of the existing LEP experimental areas with no major modification.

CP violation in b-sector

- Of the 6 orthogonality relations the CKM matrix satisfies

$$\sum_j V_{ij} V_{jk}^* = \delta_{ik}$$

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

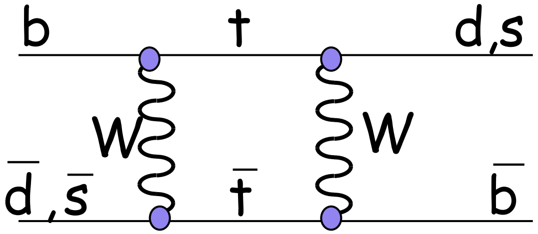
- the “bd” term is central in many B-meson decays:

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = \delta_{bd} = 0$$

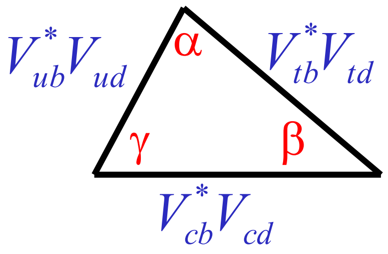
b→u transitions

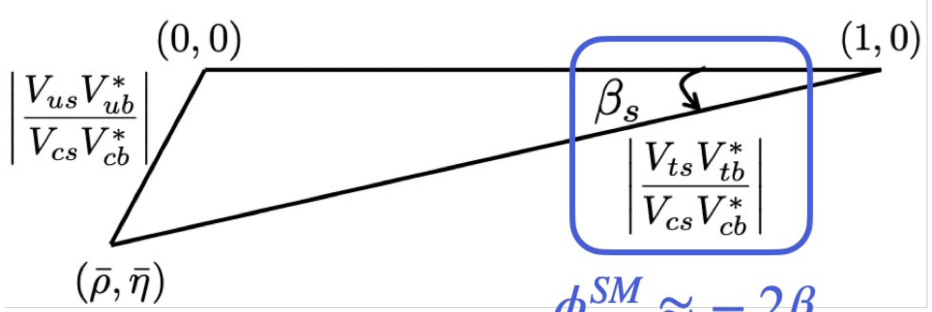
b→c transitions

B^0 mixing

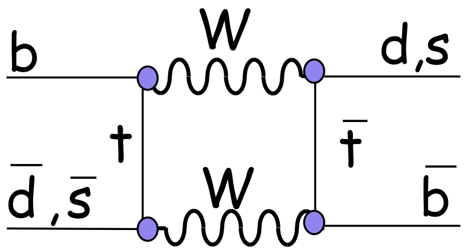


“The” unitarity triangle (“bd”)





$$\phi_s^{SM} \approx -2\beta_s$$



CKM parameter measurements with B decays

- The CKM matrix in terms of the Wolfenstein parameters

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

$|V_{ub}|e^{-i\gamma}$

$|V_{cb}|$

- B^0 $|V_{td}|e^{-i\beta}$ and B_s $|V_{ts}|e^{-i\beta_s}$ mixing phases sensitivity

The standard techniques for the angles

β : B^0 mixing (phase β) (+ single $b \to c$ decay)

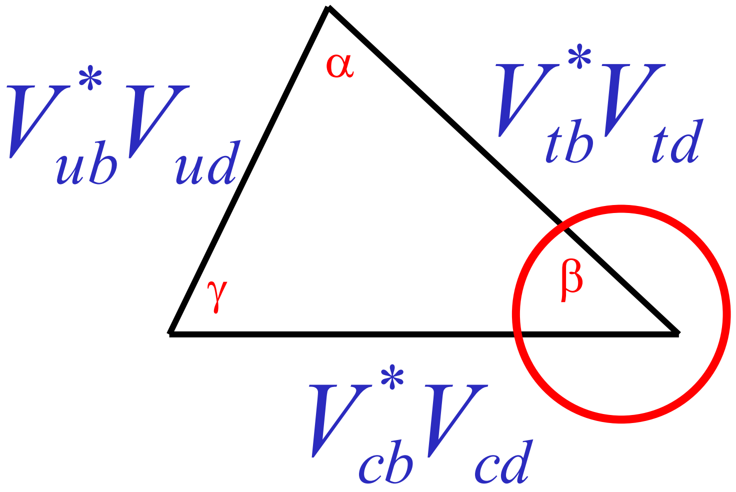
α : B^0 mixing (phase β) + single $b \to u$ decay (phase γ)

γ : $b \to u$ (phase γ) (interference with $b \to c$)

β_s : B_s^0 mixing (phase β_s) (+ single $b \to c$ decay)

$\boldsymbol{sin\,2\beta}$

Measurement of CP violation in $B^0 \to \psi(\to \ell^+\ell^-)K^0_S(\to \pi^+\pi^-)$ decays, PHYS. REV. LETT. 132 (2024) 021801

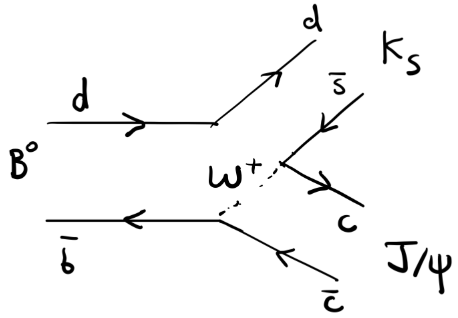


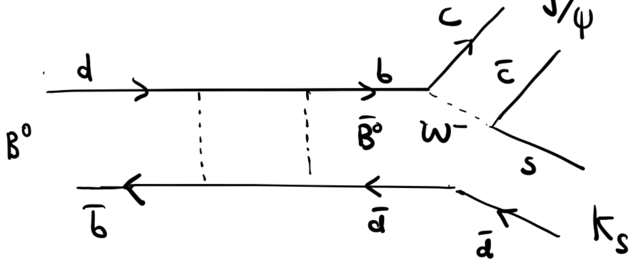
$sin\, 2\beta$

- Golden measurement channel $B_d \to J/\psi K_S$
- tree dominated $b \to \bar{c}cs$ transition
- Interference between decays with and without mixing leads to CP asymmetry

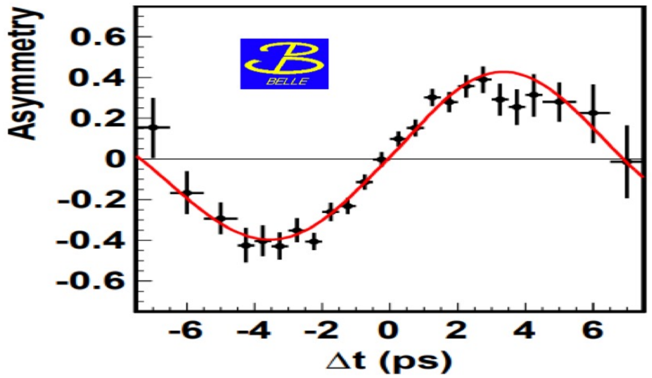
$$A_{CP}(t) = -\eta_f \sin 2\beta \sin(\Delta m_d t)$$

- Measurement primary goal of the b-factories

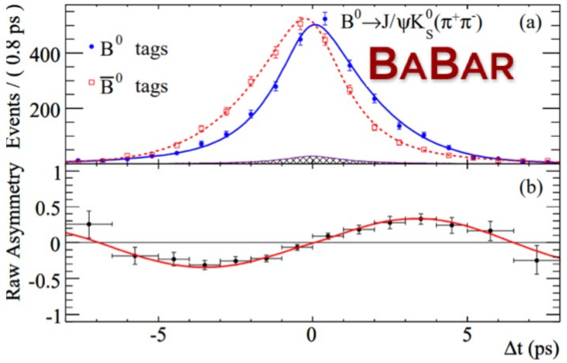




$\sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012$



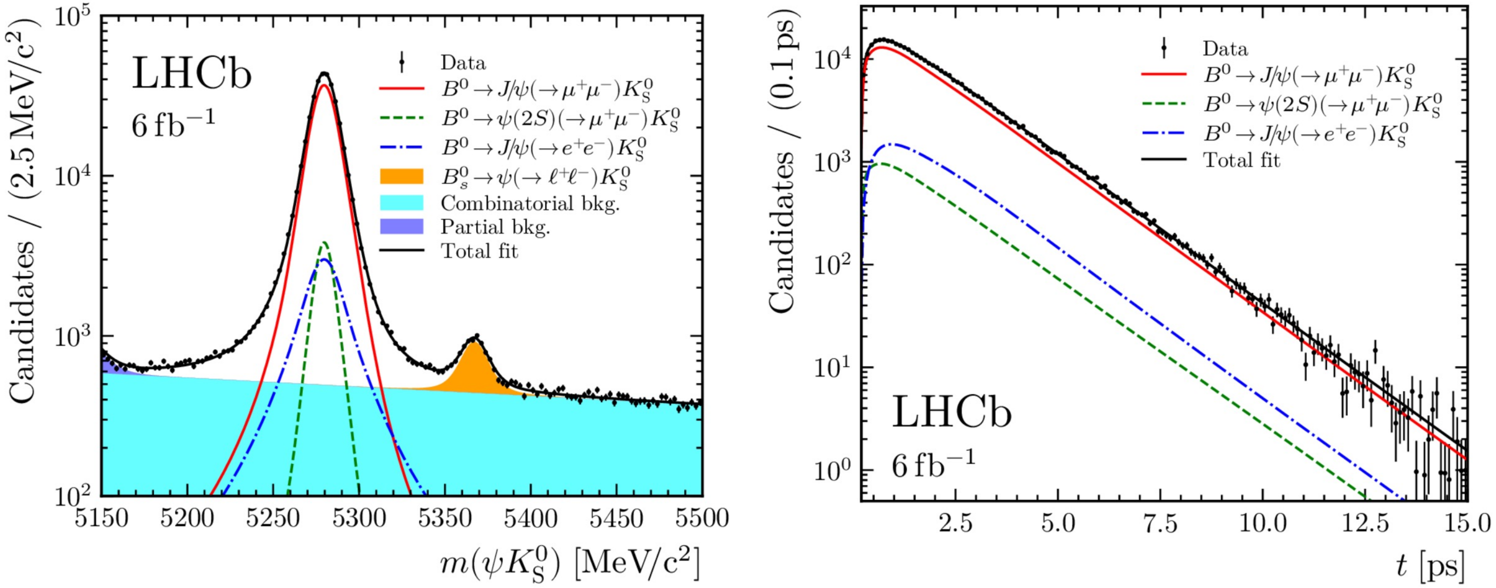
$\sin 2\beta = 0.687 \pm 0.028 \pm 0.012$



PRD 79 (2009) 072009 PRL 108 (2012) 171802

$sin\,2\beta$

- LHCb Run 2 (6 fb^{-1}) results using $B_d \to J/\psi K_S$ (both muons and electrons) and $B_d \to \psi(2S)K_S$
- Flavor-tagged time-dependent analysis to determine sin 2β

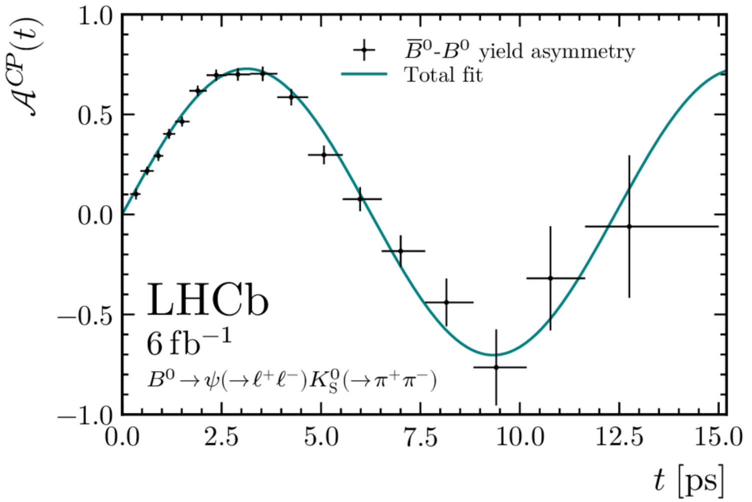


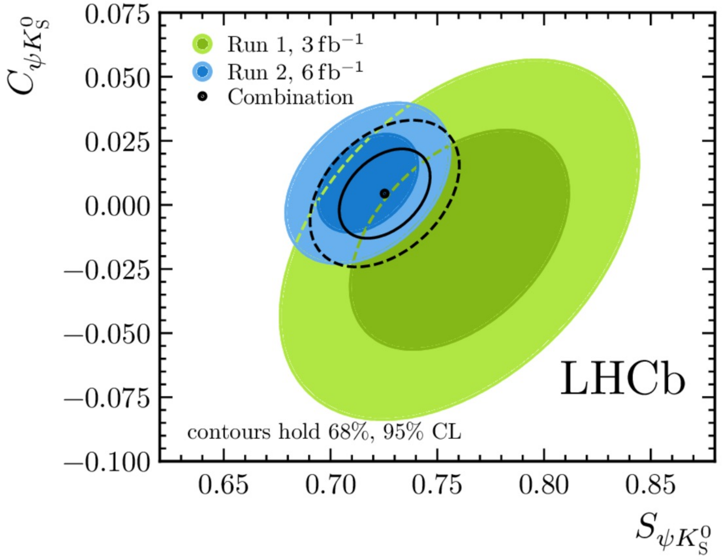
$$N_{J/\psi(\to\mu\mu)K^0_S} = 306\,322 \pm 619$$

$$N_{J/\psi(\to ee)K^0_S} = 42\,870 \pm 269$$

$$N_{\psi(2S)(\to\mu\mu)K^0_S} = 23\,570 \pm 164$$

$\sin 2\beta$





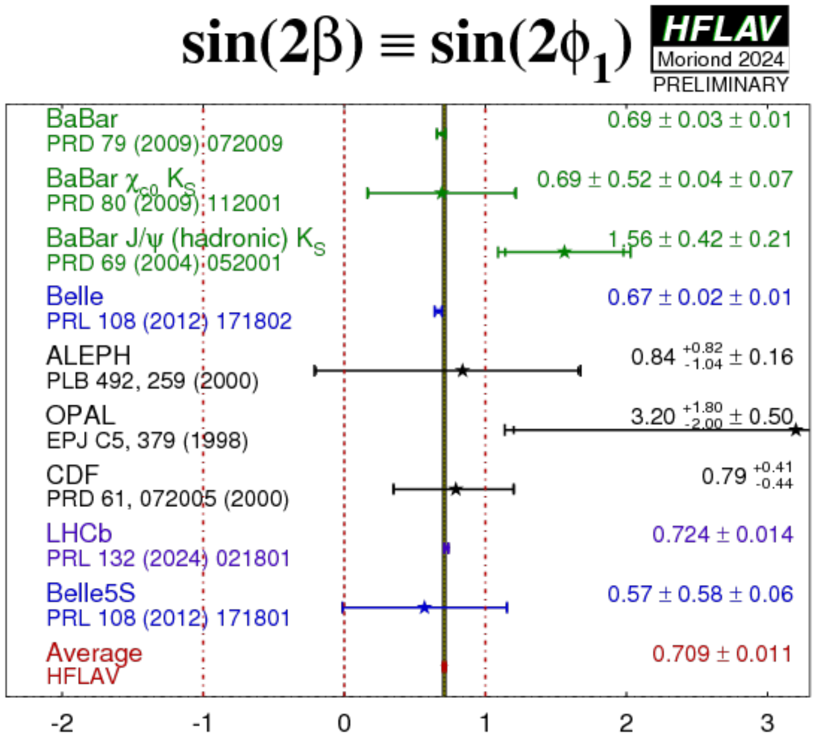
$$S^{\text{Run 2}}_{J/\psi(\to\mu^+\mu^-)K^0_S} = 0.714 \pm 0.015\,(\text{stat}) \pm 0.007\,(\text{syst})$$
$$C^{\text{Run 2}}_{J/\psi(\to\mu^+\mu^-)K^0_S} = 0.013 \pm 0.014\,(\text{stat}) \pm 0.003\,(\text{syst})$$
$$S^{\text{Run 2}}_{\psi(2S)K^0_S} = 0.647 \pm 0.053\,(\text{stat}) \pm 0.018\,(\text{syst})$$
$$C^{\text{Run 2}}_{\psi(2S)K^0_S} = -0.083 \pm 0.048\,(\text{stat}) \pm 0.005\,(\text{syst})$$
$$S^{\text{Run 2}}_{J/\psi(\to e^+e^-)K^0_S} = 0.752 \pm 0.037\,(\text{stat}) \pm 0.084\,(\text{syst})$$
$$C^{\text{Run 2}}_{J/\psi(\to e^+e^-)K^0_S} = 0.046 \pm 0.034\,(\text{stat}) \pm 0.008\,(\text{syst})$$

Run 1+2 combination all modes

$$S^{\text{Run 1+2}}_{\psi K^0_S} = 0.723 \pm 0.014\,(\text{stat+syst})$$
$$C^{\text{Run 1+2}}_{\psi K^0_S} = 0.007 \pm 0.012\,(\text{stat+syst})$$

$\sin 2\beta$

- LHCb Run 2 result most precise to date
- Still dominated by statistical uncertainty

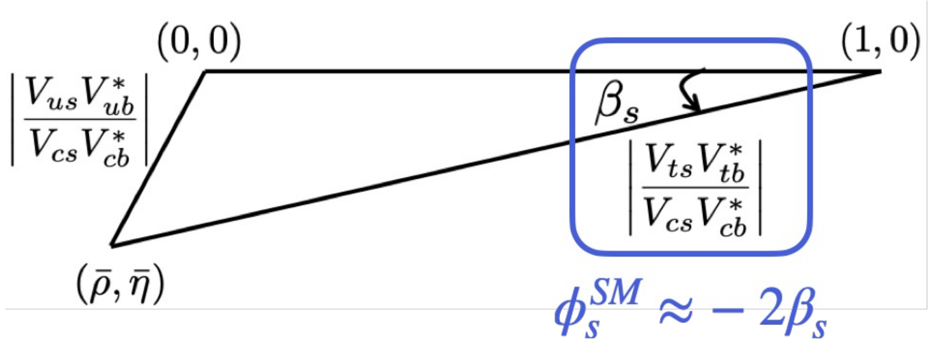


Source	$\sigma(S)$	$\sigma(C)$
Fitter validation	0.0004	0.0006
Decay-time bias model	0.0007	0.0013
FT $\Delta\epsilon_{\rm tag}$ portability	0.0014	0.0017
FT calibration portability	0.0053	0.0001
$\Delta\Gamma_d$ uncertainty	0.0055	0.0017

ϕ_s, $\phi_s^{s\bar{s}s}$

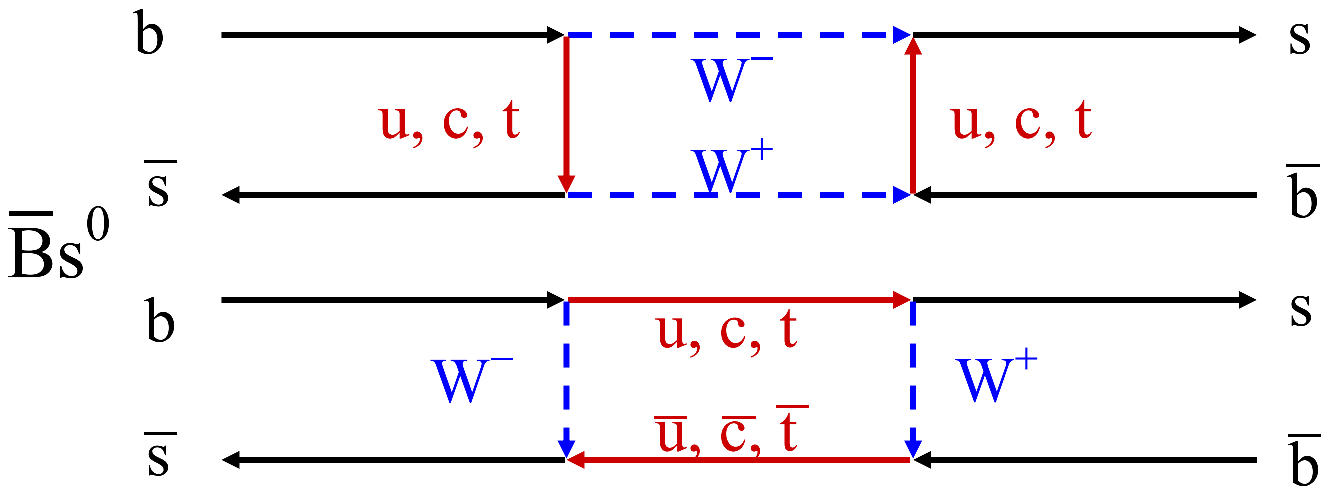
Improved measurement of CP violation parameters in B0s→J/ψK+K− decays in the vicinity of the φ(1020) resonance, PHYS. REV. LETT. 132 (2024) 051802

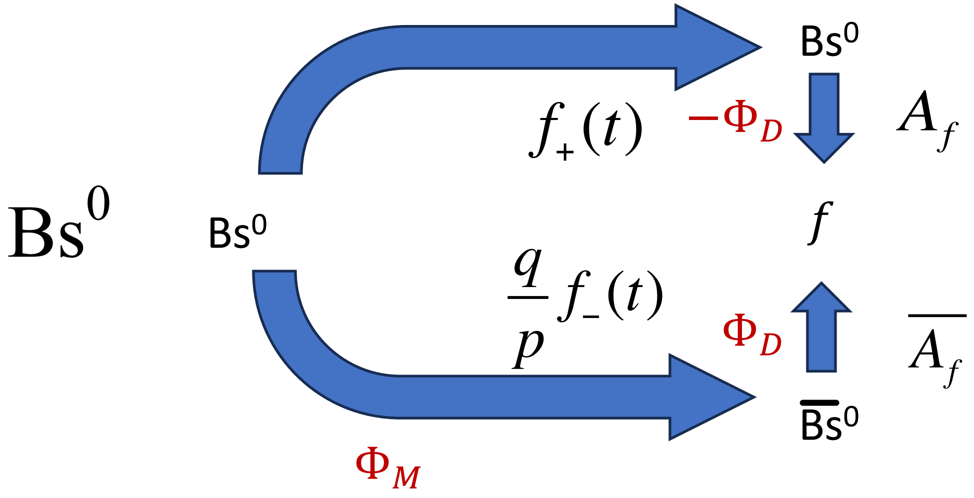
Precision Measurement of CP Violation in the Penguin-Mediated Decay B0s→ φφ, PHYS. REV. LETT. 131 (2023) 171802



B_s mixing

- Interference of decays with/without mixing gives measurable phase

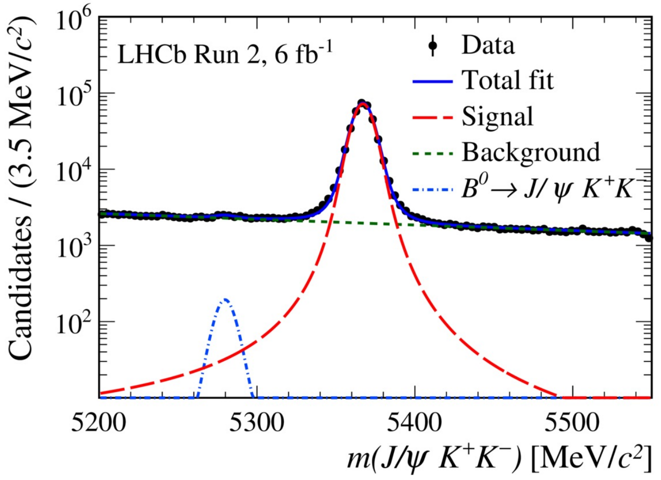


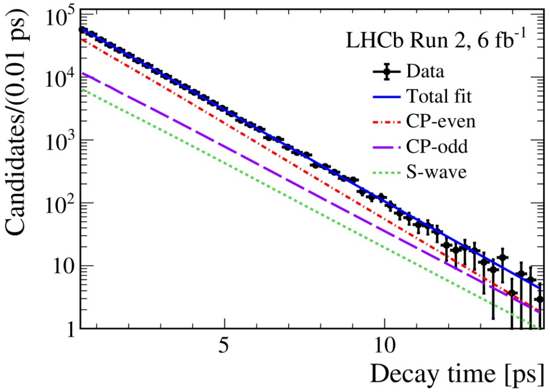


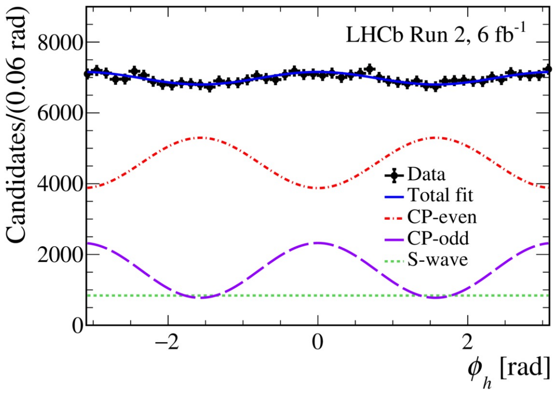
- Observable phase $\phi_s = -2\beta_s = \Phi_M - 2\Phi_D$
- In the Standard Model expected to be small, ϕ_s = - 0.0368 radians
- Larger values possible in models of New Physics
- Golden channel: $B_s \to J/\psi\phi$

ϕ_s from $B_s \to J/\psi KK$

- Measure ϕ_s and $\Delta\Gamma_s$ using the decay Bs → J/ψ K^+K^- with M(K^+K^-) in the vicinity of ϕ(1020) meson
- Specific background from B^0 and Λ_b suppressed with mass and PID requirements;
  remaining background from Λ_b statistically subtracted
- Entire run-2 dataset, 48 sub-samples
- A mixture of CP-even & CP-odd components
  → angular analysis
- Fits for decay time and angular distributions







ϕ_s from $B_s \to J/\psi KK$

Parameter	Values		
ϕ_s [rad]	-0.039	± 0.022	± 0.006
$\lvert\lambda\rvert$	1.001	± 0.011	± 0.005
$\Gamma_s - \Gamma_d$ [ps^{-1}]	-0.0056	$^{+0.0013}_{-0.0015}$	± 0.0014
$\Delta\Gamma_s$ [ps^{-1}]	0.0845	± 0.0044	± 0.0024
Δm_s [ps^{-1}]	17.743	± 0.033	± 0.009
$\lvert A_\perp\rvert^2$	0.2463	± 0.0023	± 0.0024
$\lvert A_0\rvert^2$	0.5179	± 0.0017	± 0.0032
$\delta_\perp - \delta_0$ [rad]	2.903	$^{+0.075}_{-0.074}$	± 0.048
$\delta_\parallel - \delta_0$ [rad]	3.146	± 0.061	± 0.052

Combined with run 1

$$\phi_s = -0.044 \pm 0.020 \text{ rad}$$

$$|\lambda| = 0.990 \pm 0.010$$

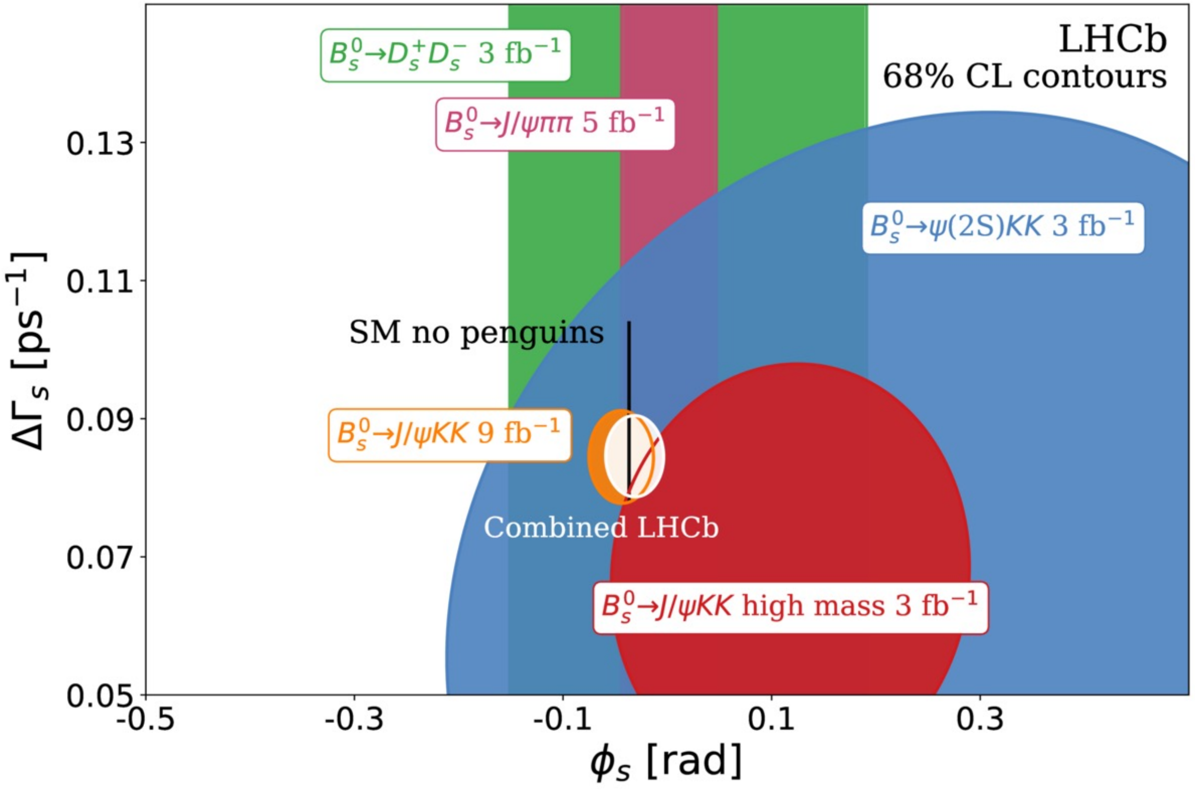
Combined over $b \to c\bar{c}s$ transitions

$$\phi_s = -0.031 \pm 0.018 \text{ rad}$$

Most precise measurement to date

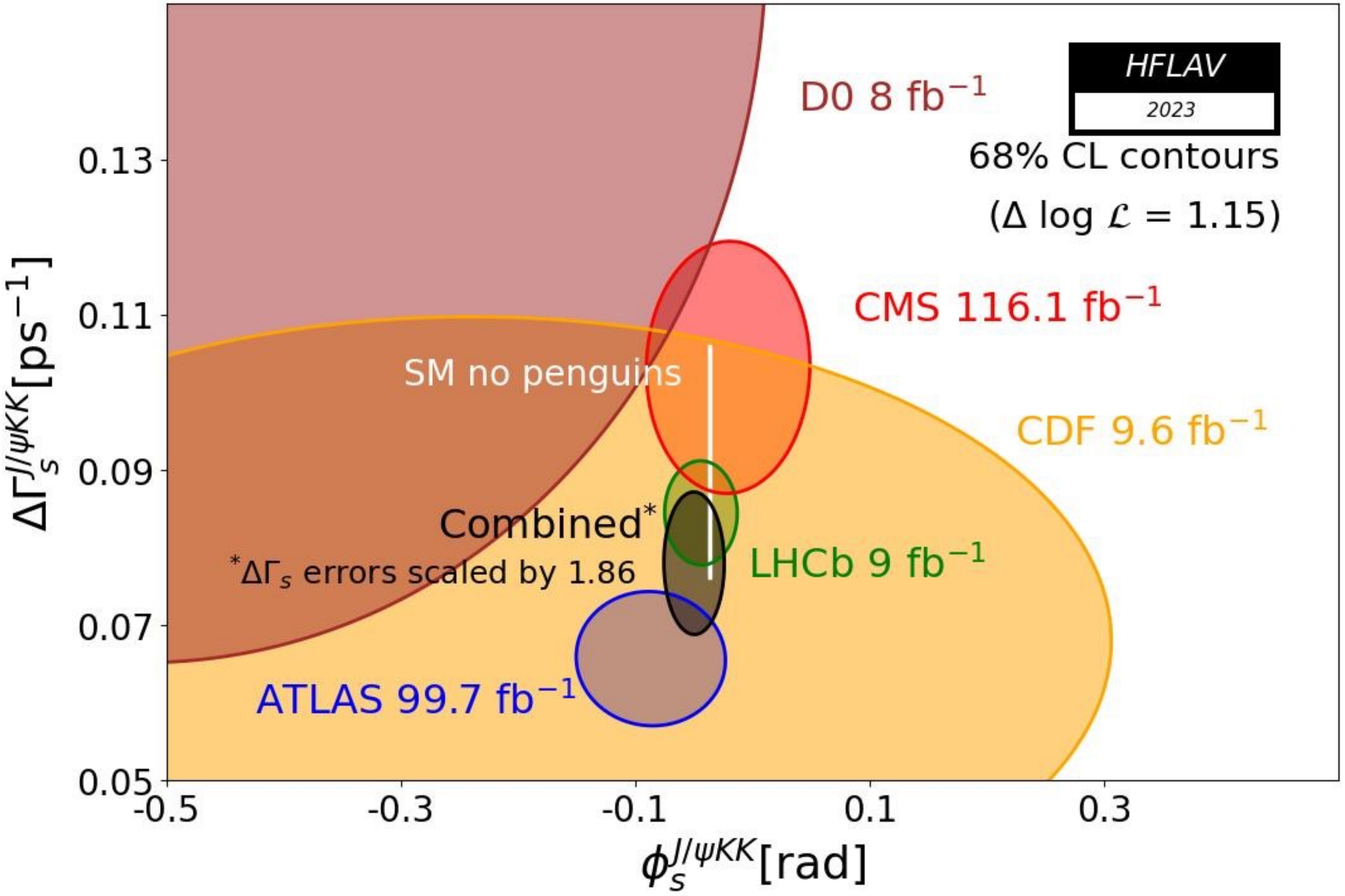
Consistent with SM

- The phase ϕ_s measured independently for each polarization of the K^+K^- system
- No evidence for polarization dependence



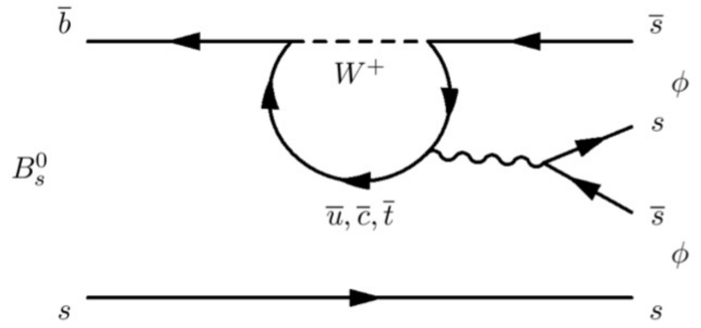
ϕ_s from $B_s \to J/\psi KK$

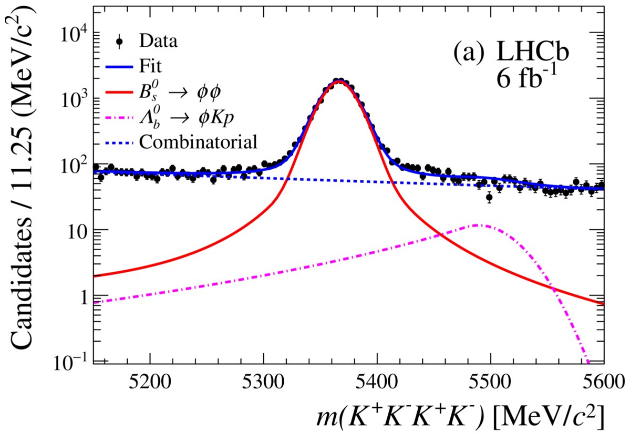
- Tension in measurements of $\Delta\Gamma_s$ using $B_s \to J/\psi$ KK decays by ATLAS, CMS and LHCb, large scale factor on the uncertainty for HFLAV average

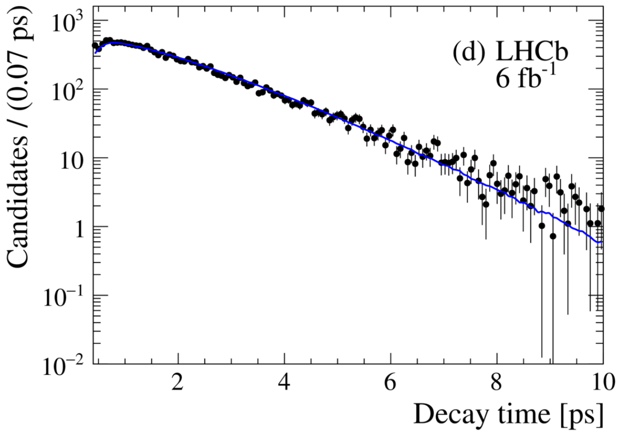


$\phi_s^{s\bar{s}s}$ from $B_s \to \phi\phi$

- CPV in FCNC via penguin dominated b → sss transitions
- NP contributes to mixing and penguin processes
- Very similar analysis strategy as $B_s \to J/\psi$ KK
- In $B_s \to \phi\phi$, CPV may be polarization dependent
- Time-dependent flavor-tagged angular analysis
- Entire run 2 dataset

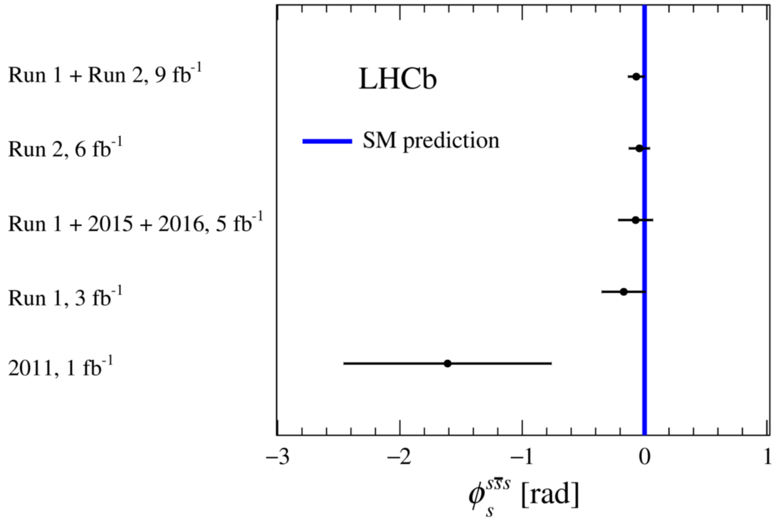






Parameter	Result
$\phi_s^{s\bar{s}s}$ [rad]	$-0.042 \pm 0.075 \pm 0.009$
$\lvert\lambda\rvert$	$1.004 \pm 0.030 \pm 0.009$
$\lvert A_0\rvert^2$	$0.384 \pm 0.007 \pm 0.003$
$\lvert A_\perp\rvert^2$	$0.310 \pm 0.006 \pm 0.003$
$\delta_\parallel - \delta_0$ [rad]	$2.463 \pm 0.029 \pm 0.009$
$\delta_\perp - \delta_0$ [rad]	$2.769 \pm 0.105 \pm 0.011$

$\phi_s^{s\bar{s}s}$ from $B_s \to \phi\phi$



- Combined with Run 1

$$\phi_s^{s\bar{s}s} = -0.074 \pm 0.069\,\text{rad}$$
$$|\lambda| = 1.009 \pm 0.030$$

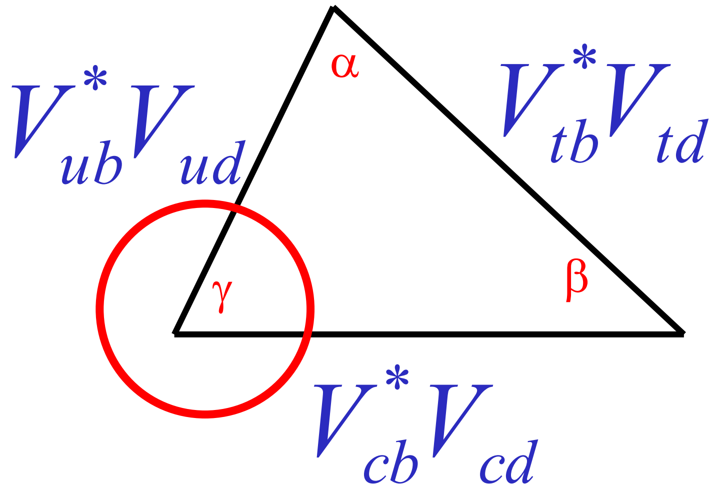
- Polarization dependent results (statistical uncertainty only):

$$\begin{aligned} \phi_{s,0} &= -0.18 \pm 0.09 \text{ rad} , & |\lambda_0| &= 1.02 \pm 0.17 , \\ \phi_{s,\parallel} - \phi_{s,0} &= \quad 0.12 \pm 0.09 \text{ rad} , & |\lambda_\perp/\lambda_0| &= 0.97 \pm 0.22 , \\ \phi_{s,\perp} - \phi_{s,0} &= \quad 0.17 \pm 0.09 \text{ rad} , & |\lambda_\parallel/\lambda_0| &= 0.78 \pm 0.21 , \end{aligned}$$

- Most precise measurement of time-dependent CP asymmetry in Bs → ϕϕ and in any penguin-dominated B-decay
- Consistent with SM
- Polarization-dependent CPV parameters measured for the first time, no significant difference between three polarizations

γ (See Xiaokang's talk)

Study of CPV in B(s)→DK*(892)0 decays with D-> Kπ(ππ), ππ(ππ), and KK final states, JHEP 05 (2024) 025
A model-independent measurement of the CKM angle γ in partially reconstructed B±→D*h± decays with D→K0Sh+h- (h=π,K), JHEP 02 (2024) 118
Measurement of the CKM angle γ using the B±→D*h± channels, JHEP 12 (2023) 013
Measurement of the CKM angle γ in the B0→DK*0 channel using self-conjugate D→K0Sh+h- decays, EPJC 84 (2024)206



Summary

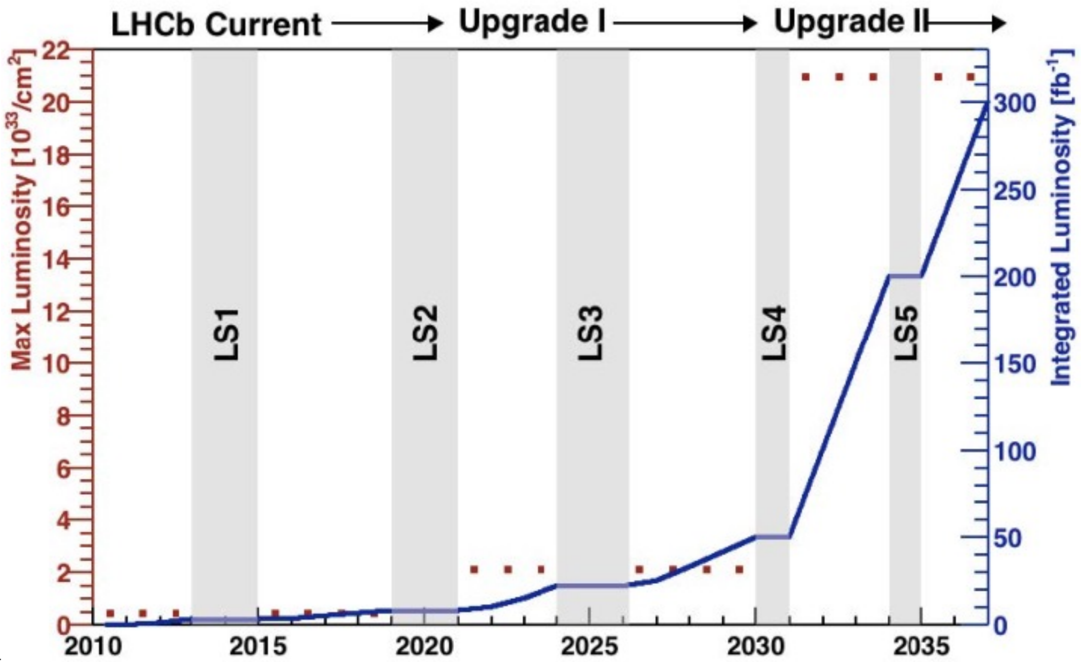
- New precise measurements of CKM angles from LHCb

- All available measurements of CPV observables, including amplitude and phase measurements are so far consistent with the Standard Model

- A lot more to come in the next decades from LHCb Upgrade(s), we expect to be more precise

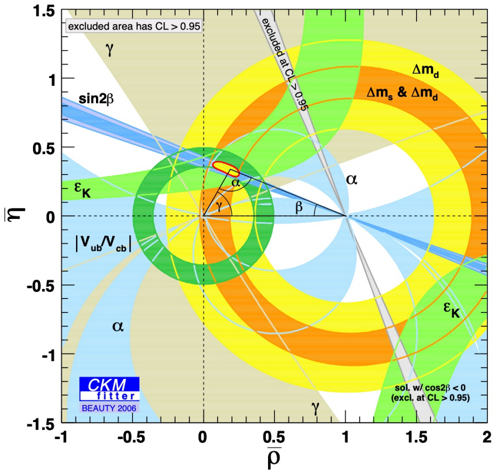
Future prospects

- LHCb expect ~300fb^{-1} in run-6

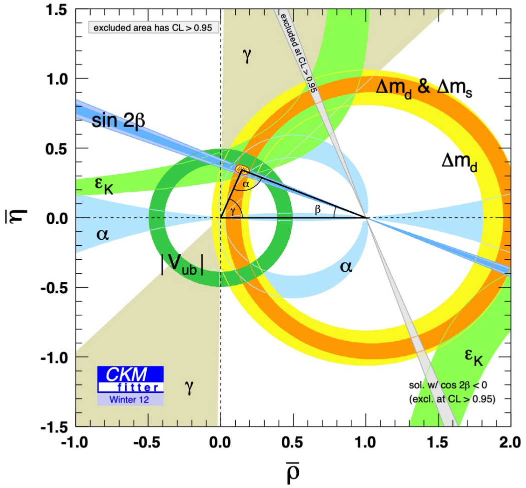


Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05
CKM tests				
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [606] Now 0.014	0.011	0.005	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44] Now 20 mrad	14 mrad	–	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94] Now 69 mrad	39 mrad	–	11 mrad
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%

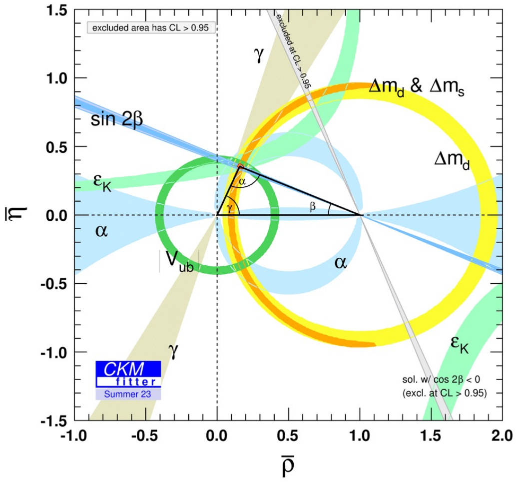
Prospects on CKM unitarity triangle



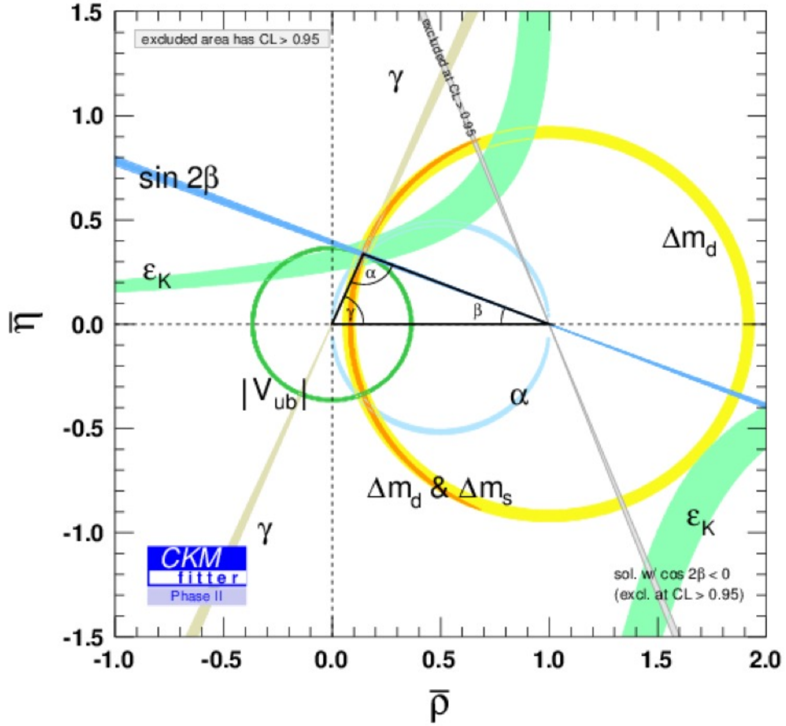
2006



2012



2023



Prospect: $300fb^{-1}$