CP violation in b-decays

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Outline

- Introduction
- CP violation in B^0 mixing: $\sin(2\beta)$
- CP violation in mixing B_S: ϕ_s
- Charmless decays
- The CKM angle γ
- Future look

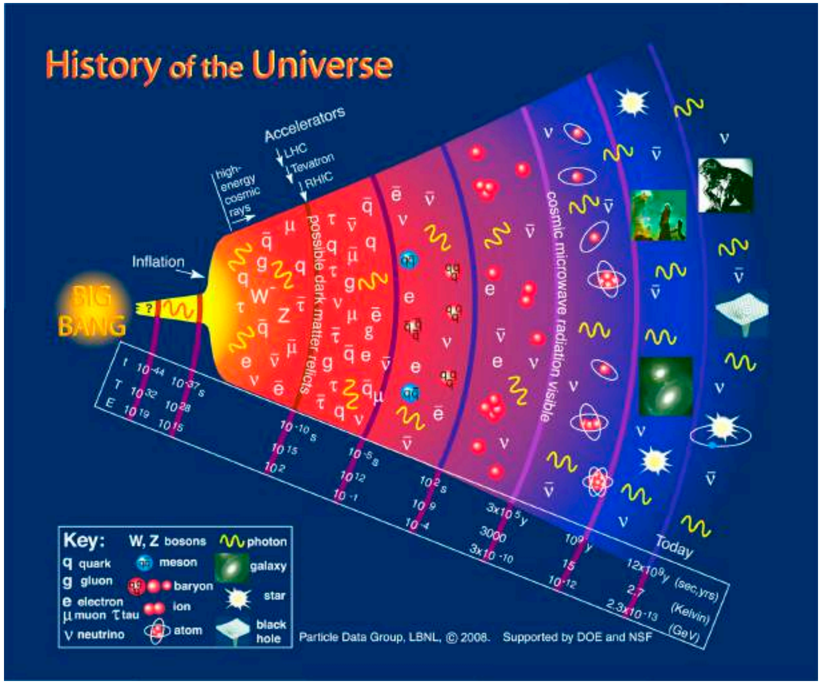
A lot of recent results, my selective summary

Introduction

CP violation is one of the Sakharov conditions for the generation of a matter-antimatter asymmetry in the early Universe

CP violation in the quark sector in the Standard Model arises from the complex phase in the CKM mixing matrix. Not enough to explain baryon asymmetry

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

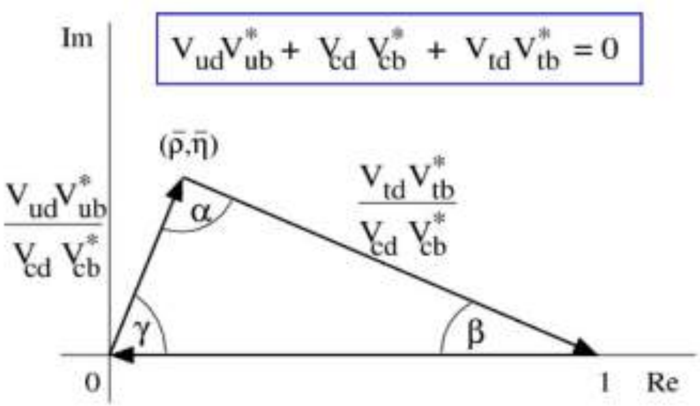


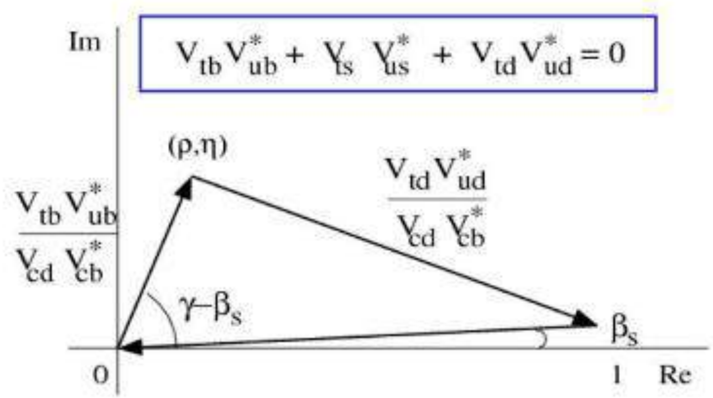
Introduction

Wolfenstein parameterization

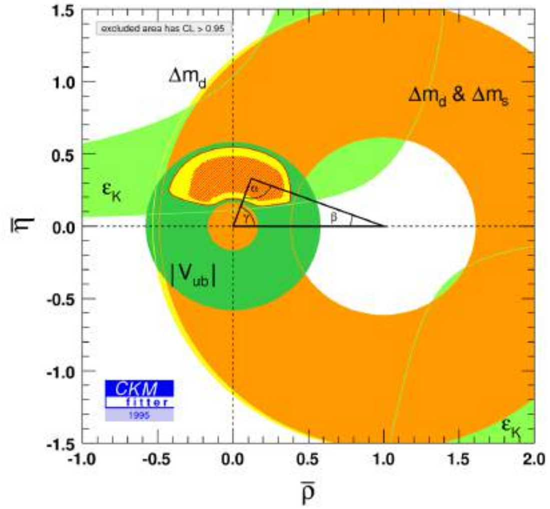
$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Unitarity of the CKM matrix leads to triangles in the complex (ρ, η) plane

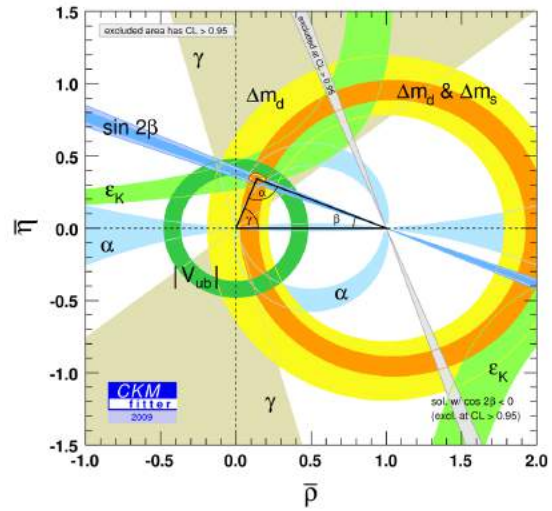




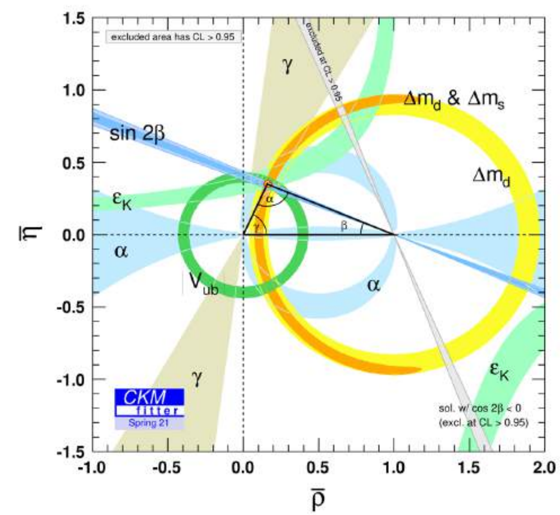
Introduction



1995



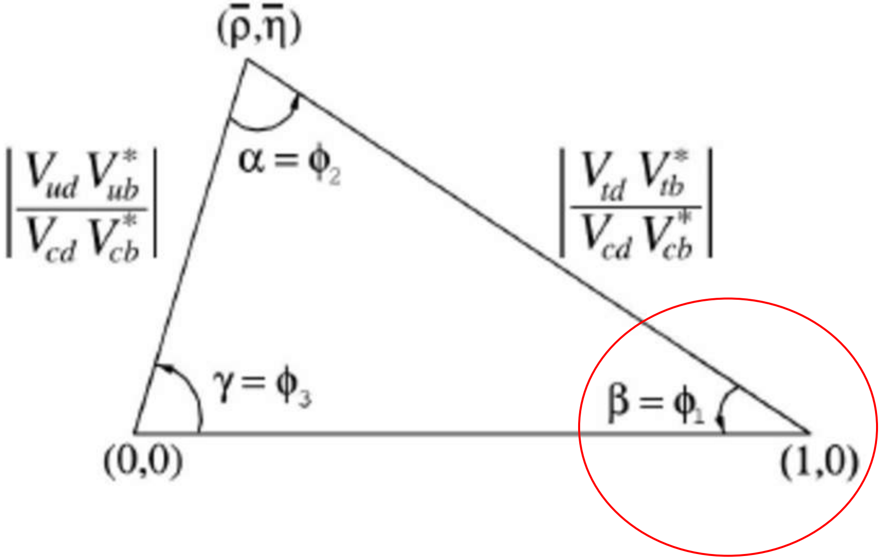
2009



2021

Huge experimental and theoretical progress in last 25 years - so far confirms the CKM picture

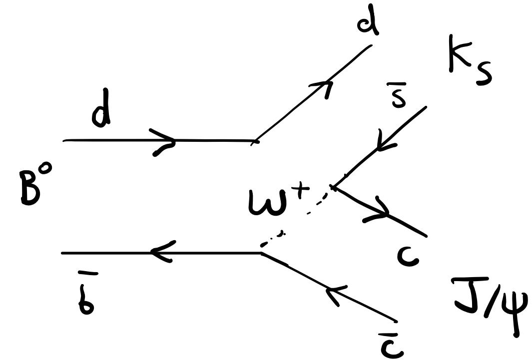
sin 2β



$(\bar{\rho},\bar{\eta})$
$\alpha = \phi_2$
$\left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|$
$\left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|$
$\gamma = \phi_3$
$\beta = \phi_1$
(0,0)
(1,0)

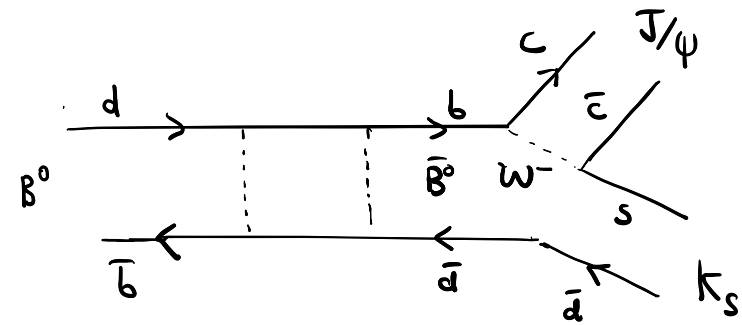
sin 2β

Golden measurement channel $B_d \to J/\psi K_s$
tree dominated $b \to c\bar{c}s$ transition



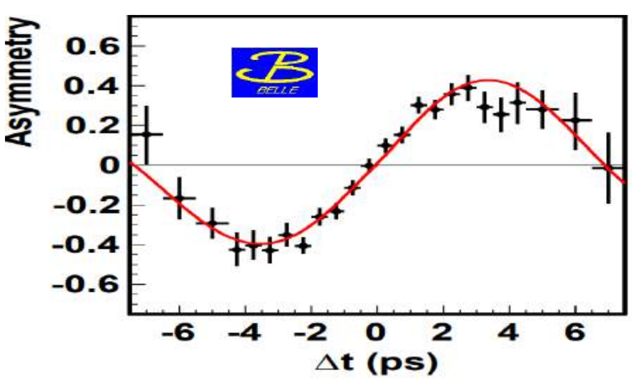
Measurement primary goal of the b-factories

Interference between decays with and
and without mixing leads to CP asymmetry

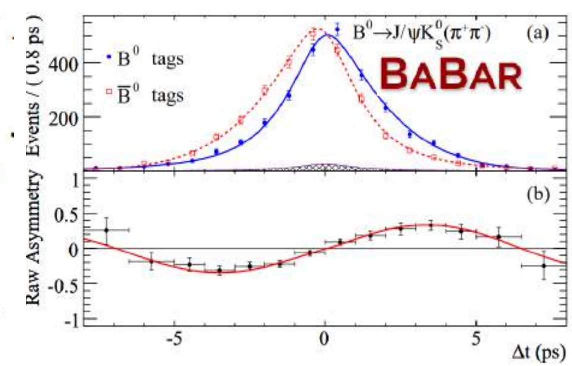


$$A_{CP}(t) = -\eta_f \sin 2\beta \sin(\Delta m_d t)$$

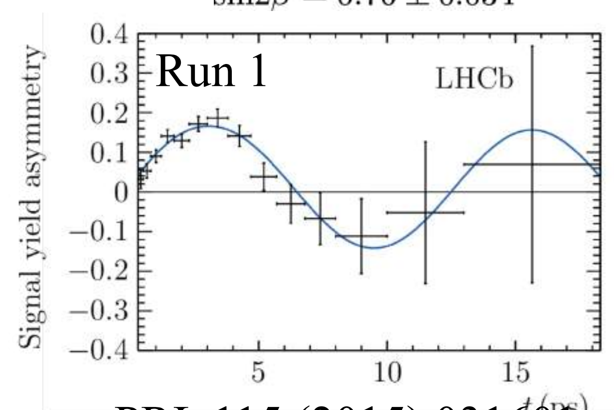
$\sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012$



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



$\sin 2\beta = 0.76 \pm 0.034$



PRD 79 (2009) 072009

PRL 108 (2012) 171802

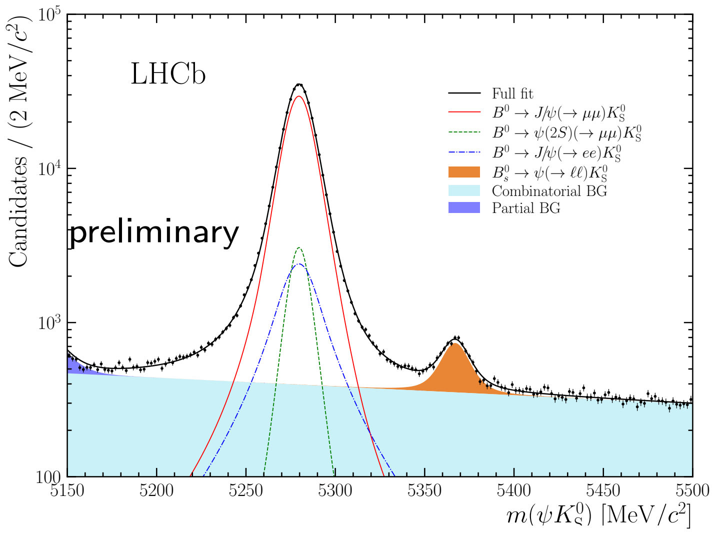
PRL 115 (2015) 031601,
JHEP 11 (2017) 170

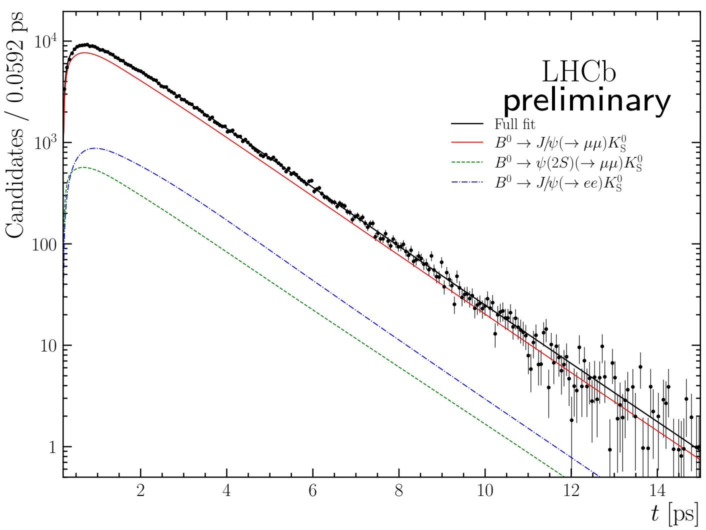
sin 2β

New

New LHCb Run 2 (6 fb^{-1}) results using $B_d \to J/\psi K_s$ (both muons and electrons) and $B_d \to \psi(2S) K_s$

Tagged time dependent analysis to determine sin2β





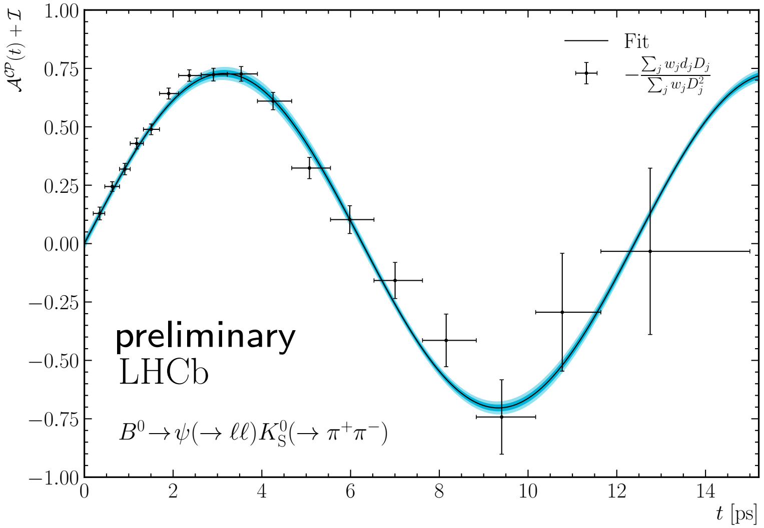
$$N_{J/\psi(\to\mu\mu)K^0_S} = 306\,322 \pm 619$$
$$N_{J/\psi(\to ee)K^0_S} = 42\,870 \pm 269$$
$$N_{\psi(2S)(\to\mu\mu)K^0_S} = 23\,570 \pm 164$$

Parallel talk
Veronika Chobanova

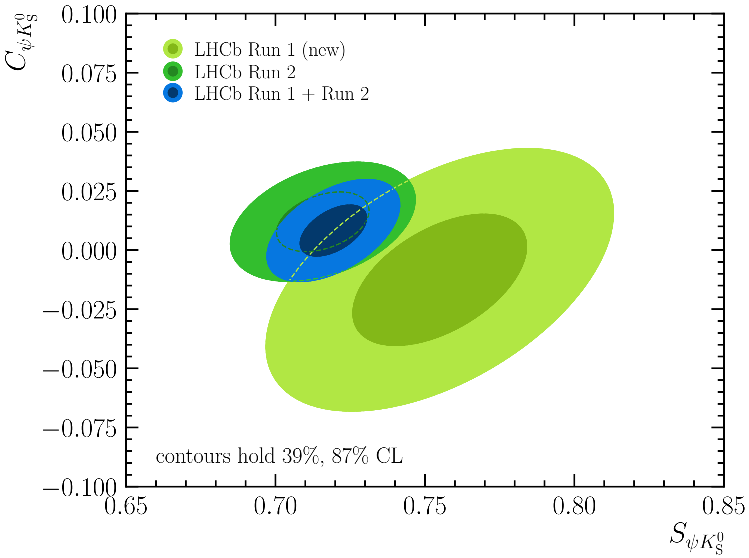
LHCb-Paper-2023-013

sin 2β

New



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



Run 1+2 combination all modes

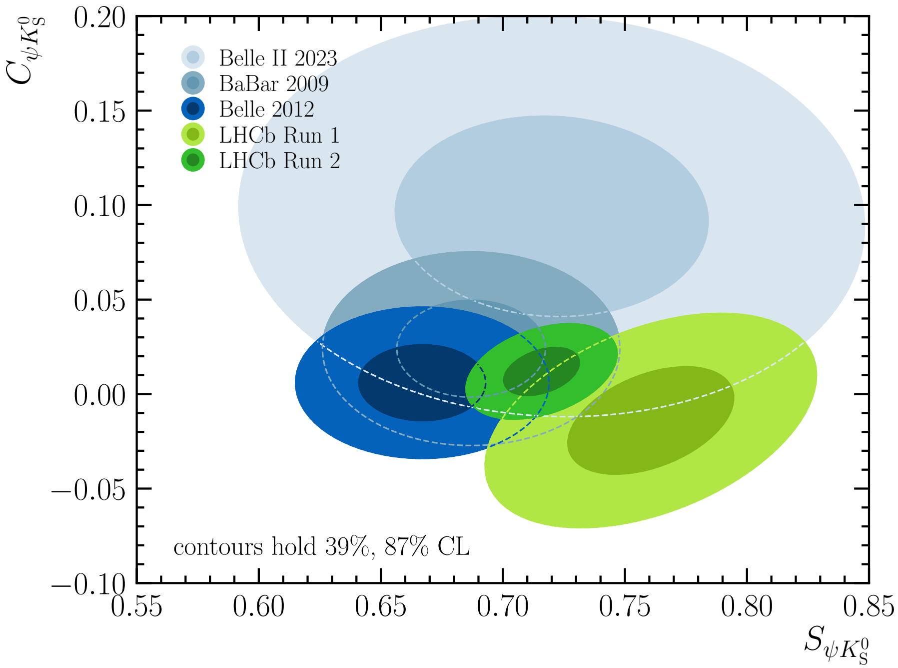
$$S^{\text{Run 1+2}}_{\psi K^0_S} = 0.723 \pm 0.014\,(\text{stat+syst})$$
$$C^{\text{Run 1+2}}_{\psi K^0_S} = 0.007 \pm 0.012\,(\text{stat+syst})$$

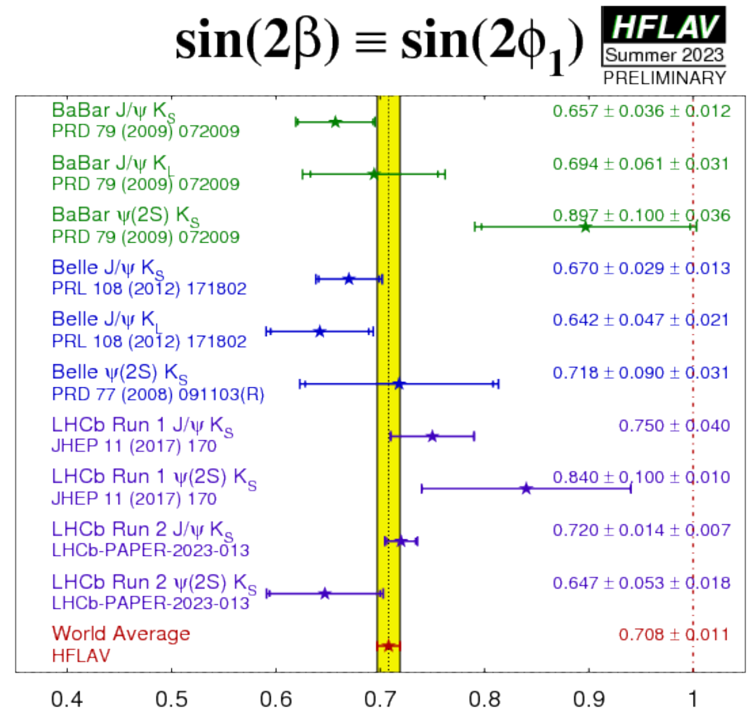
cf Belle (2012) precision of 0.031

LHCb-Paper-2023-013

LHCb-Paper-2023-013

sin 2β





LHCb Run 2 result most precise to date

Still dominated by statistical uncertainty

Run 2 achieved precision (0.015) is close to 0.012 expected in the 2000 yellow report

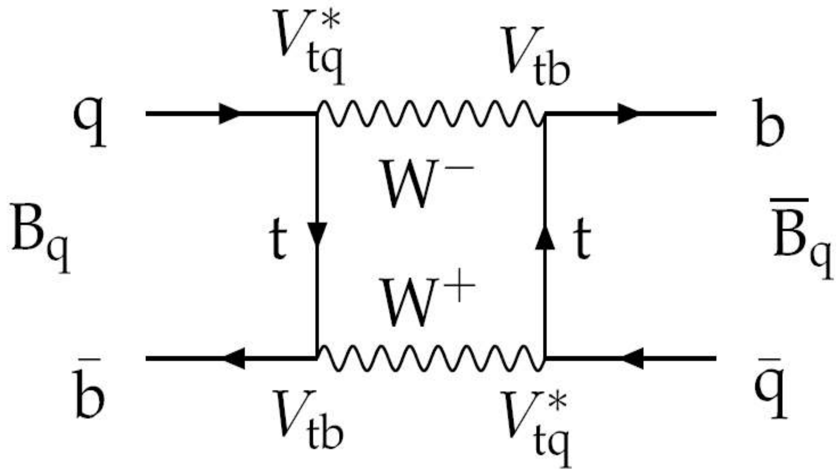
Source	$\sigma(S)$	$\sigma(C)$
Fitter validation	0.0004	0.0006
$\Delta\Gamma_d$ uncertainty	0.0055	0.0017
FT calibration portability	0.0053	0.0001
FT $\Delta\epsilon_{tag}$ portability	0.0014	0.0017
Decay-time bias model	0.0007	0.0013

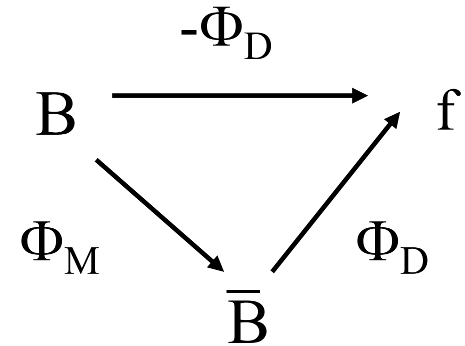
PROCEEDINGS OF THE WORKSHOP ON
STANDARD MODEL PHYSICS (AND MORE) AT THE LHC

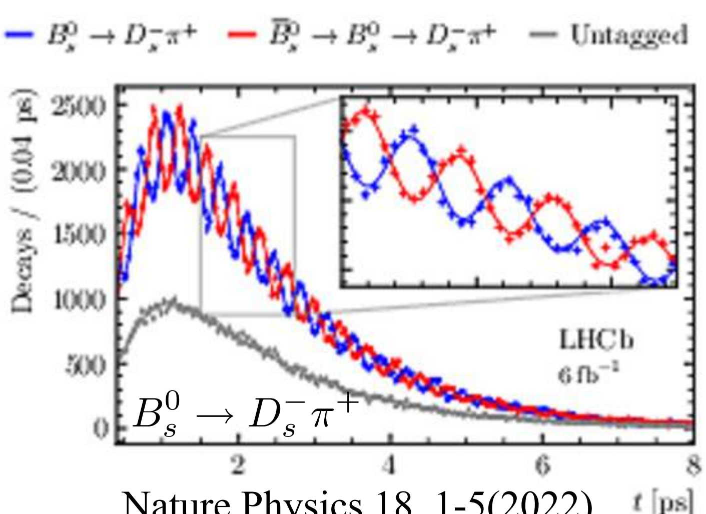
CP violation in B_s mixing

B_s mixing

Interference of decays with/without mixing gives measurable phase







Nature Physics 18, 1-5(2022)

Excellent vertex detector needed to resolve fast B_s oscillations

HFLAV $\Delta m_s = 17.765 \pm 0.006\,\mathrm{ps}^{-1}$

SM prediction JHEP 12 (2019) 009

$\Delta m_s = 18.4^{+0.7}_{-1.2}\,\mathrm{ps}^{-1}$

CP violation in B_s mixing

$$\phi_s = arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

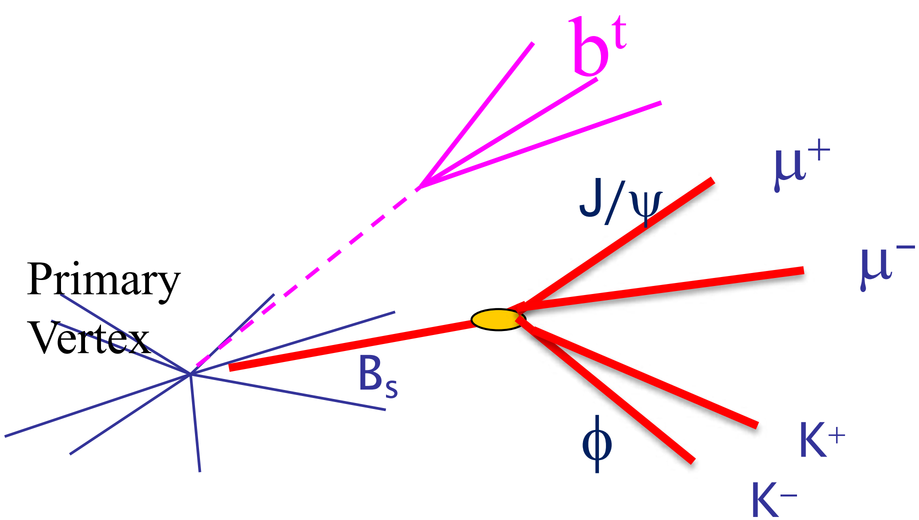
$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$

$$\Delta m_s = M_H - M_L$$

- Observable phase $\phi_s = -2\beta_s = \Phi_M - 2\,\Phi_D$
- In the Standard Model expected to be small $\phi_s = -0.0368$ radians
- Larger values possible in models of New Physics

Golden mode used by all LHC experiments $B_S \to J/\psi\,\phi$

- LHCb also studied $B_S \to J/\psi\,K^+K^-$, $B_S \to J/\psi\,\pi^+\pi^-$, $B_S \to \psi(2s)\phi$, $B_S \to D_s^+D_s^-$



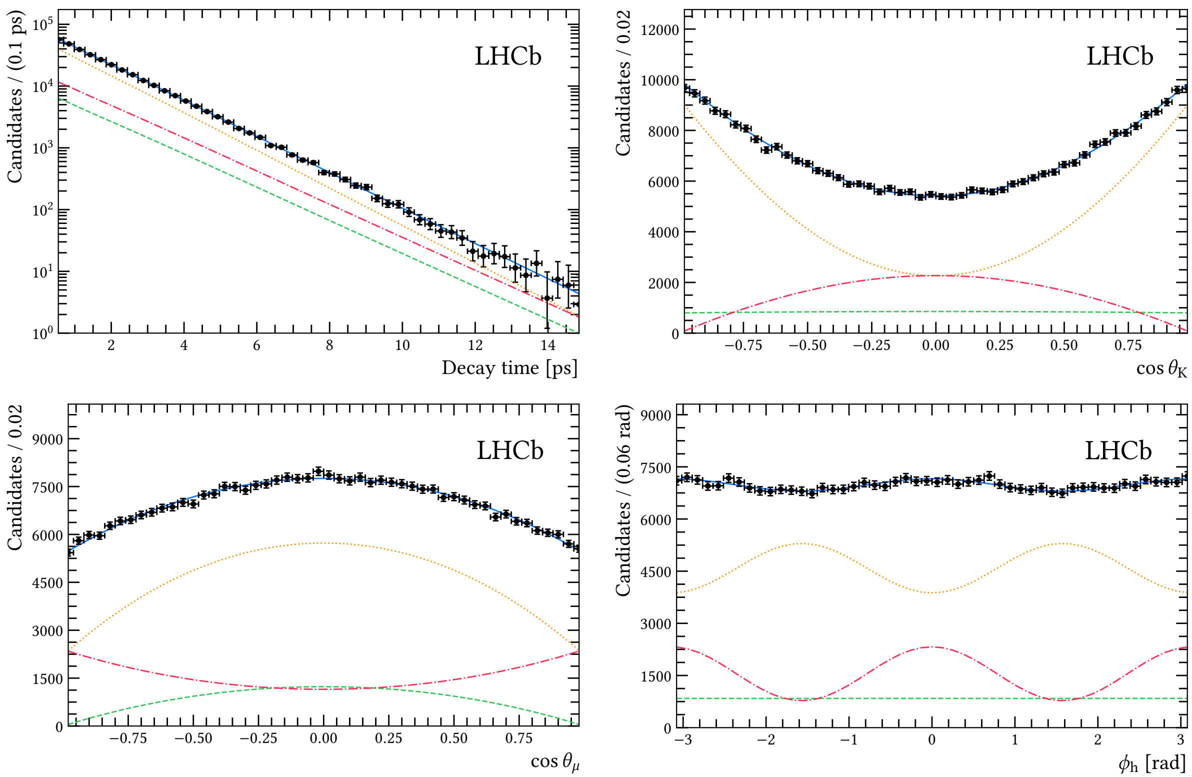
Since $B_S \to J/\psi\,\phi$ is not a CP eigenstate time-dependent angular analysis needed to determine ϕ_s

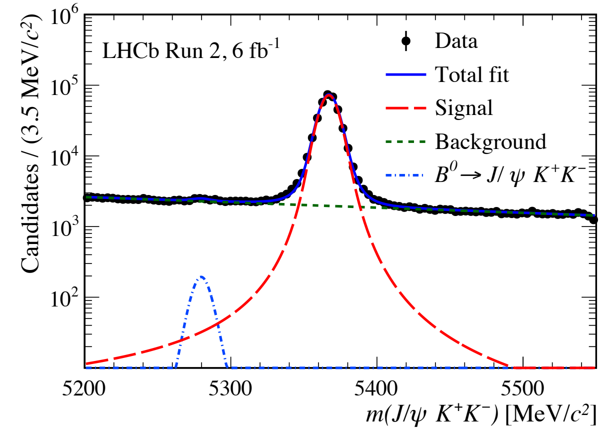
New

ϕ_s: LHCb

arxiv./2308.01468

New LHCb result using $B_S \to J/\psi\ \phi$ and the full Run 2 dataset (6 fb^{-1})





Parallel talk
Veronika Chobanova

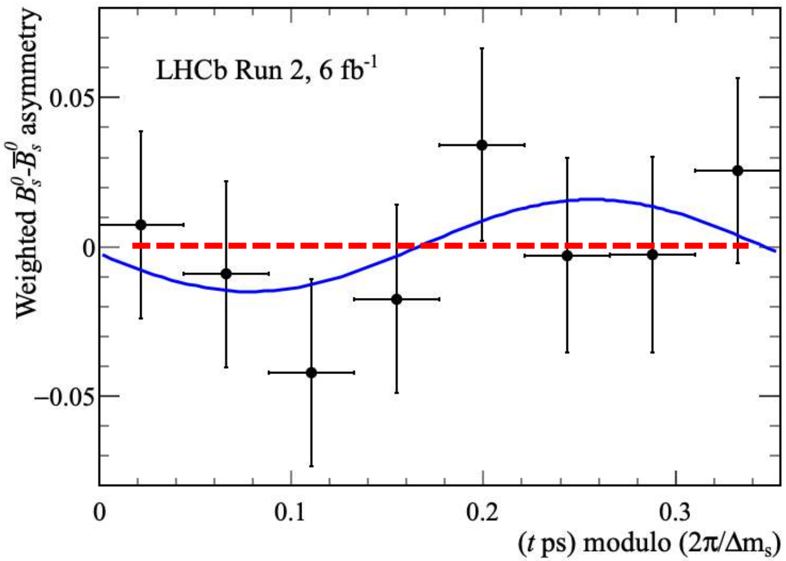
New

ϕ_s: LHCb

arxiv./2308.01468

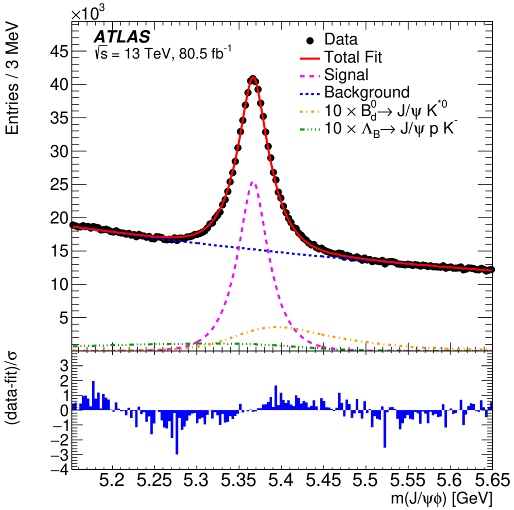
arxiv./2308.01468

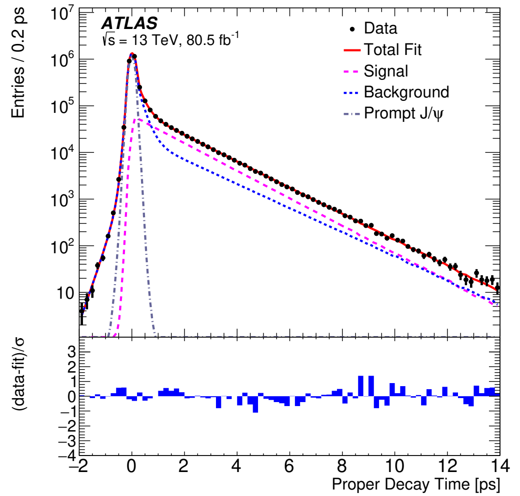
Parameter	Values
ϕ_s [rad]	$-0.039 \pm 0.022 \pm 0.006$
$\lvert\lambda\rvert$	$1.001 \pm 0.011 \pm 0.005$
$\Gamma_s - \Gamma_d$ [ps^{-1}]	$-0.0056 ^{+0.0013}_{-0.0015} \pm 0.0014$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0845 \pm 0.0044 \pm 0.0024$
Δm_s [ps^{-1}]	$17.743 \pm 0.033 \pm 0.009$
$\lvert A_\perp\rvert^2$	$0.2463 \pm 0.0023 \pm 0.0024$
$\lvert A_0\rvert^2$	$0.5179 \pm 0.0017 \pm 0.0032$
$\delta_\perp - \delta_0$ [rad]	$2.903 ^{+0.075}_{-0.074} \pm 0.048$
$\delta_\parallel - \delta_0$ [rad]	$3.146 \pm 0.060 \pm 0.052$



Results consistent with Standard Model prediction of small CP violating asymmetry

ϕ_s: GPD results



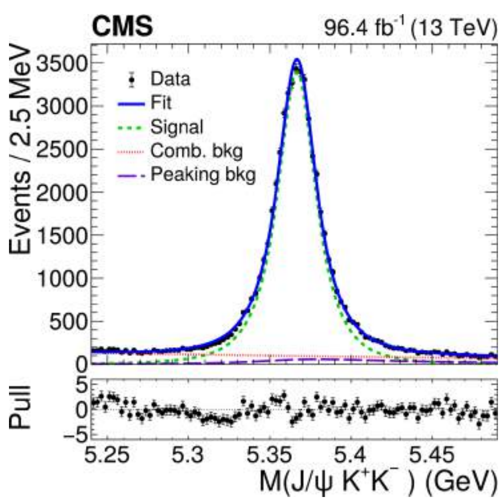


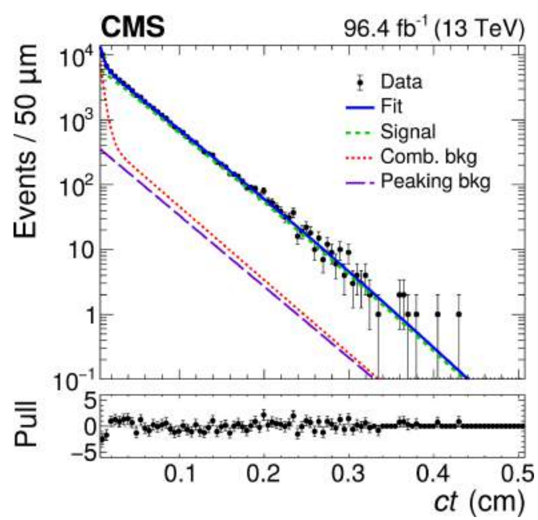
ATLAS

Data taken up to 2017

$$\phi_s = -0.087 \pm 0.036\ (\text{stat.}) \pm 0.021\ (\text{syst.})\text{rad}$$
$$\Delta\Gamma_s = 0.0657 \pm 0.0043(\text{stat.}) \pm 0.0037(\text{syst.})\text{ps}^{-1}$$
$$\Gamma_s = 0.6703 \pm 0.0014(\text{stat.}) \pm 0.0018(\text{syst.})\text{ps}^{-1}$$

Eur. Phys. J. C 81 (2021) 342





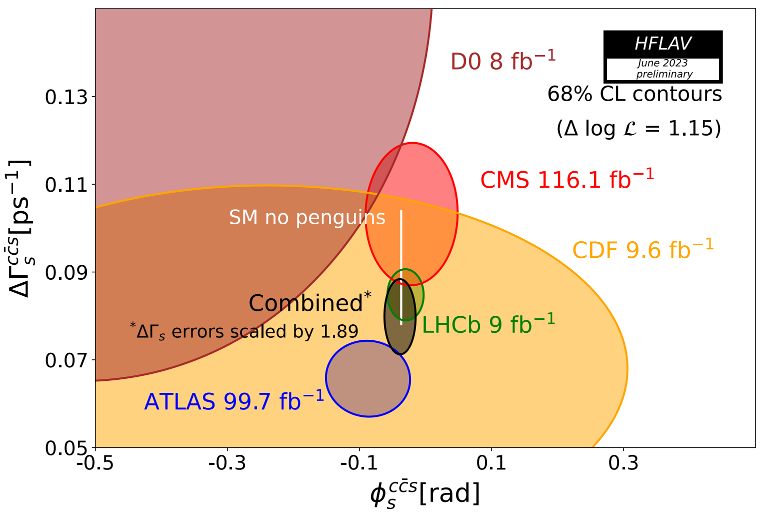
CMS

8 TeV data plus 96.4 fb^{-1} at 13TeV up from 2017-18

$$\phi_s = -21 \pm 44\,(\text{stat}) \pm 10\,(\text{syst})\,\text{mrad},$$
$$\Delta\Gamma_s = 0.1032 \pm 0.0095\,(\text{stat}) \pm 0.0048\,(\text{syst})\,\text{ps}^{-1}$$

Phys. Lett. B 816 (2021) 136188

Summary of ϕ_s



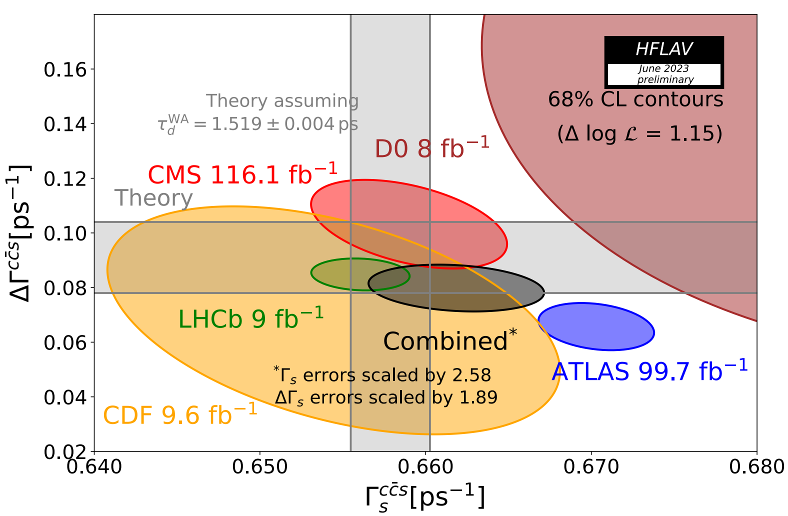
Combining with ATLAS, CMS

$$\phi_s^{J/\psi KK} = -0.050 \pm 0.017\,\text{rad}$$

In agreement with the SM predictions

Large scale factor on $\Delta\Gamma_s$, Γ_s

reflecting tensions in experimental data



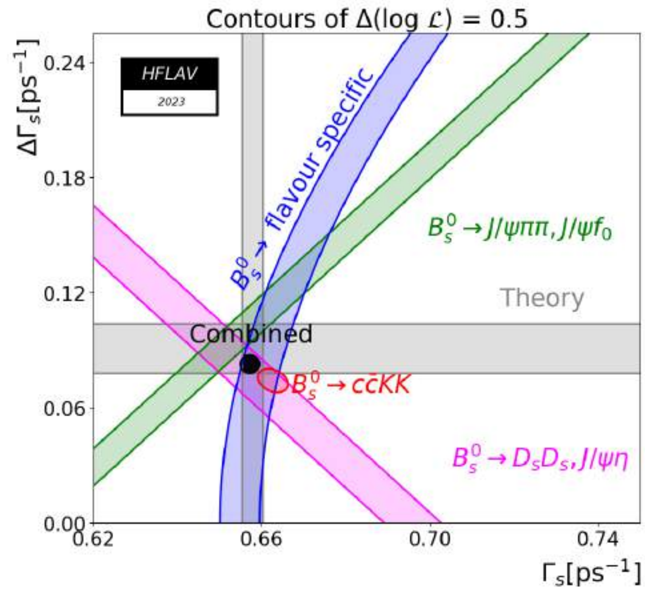
Combining with LHCb measurements in other modes gives

$$\phi_s^{c\bar{c}s} = -0.039 \pm 0.016\,\text{rad}$$

New

B_s lifetime summary

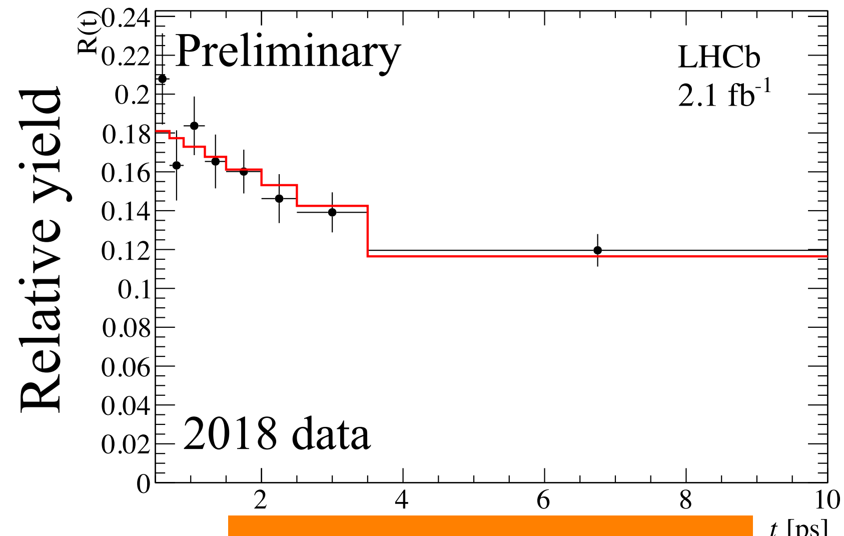
Effective lifetime measurements also probe $\Delta\Gamma_s$, Γ_s consistent with $B_s \to J/\psi\phi$ but less precise



New LHCb measurement using $B_s \to J/\psi\eta'$ (CP even) and $B_s \to J/\psi\pi^+\pi^-$ (CP odd) in $f_0(980)$ region

Relative yield versus decay time gives $\Delta\Gamma_s$

$$\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009\ \mathrm{ps}^{-1}$$



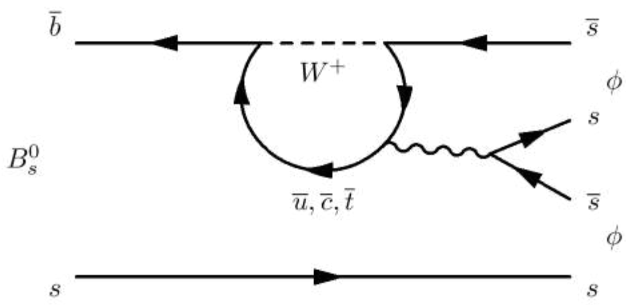
In agreement with HFlav averages

LHCb-PAPER-2023-025

Parallel talk
Veronika Chobanova

Charmless decays

$B_s \to \phi\phi$



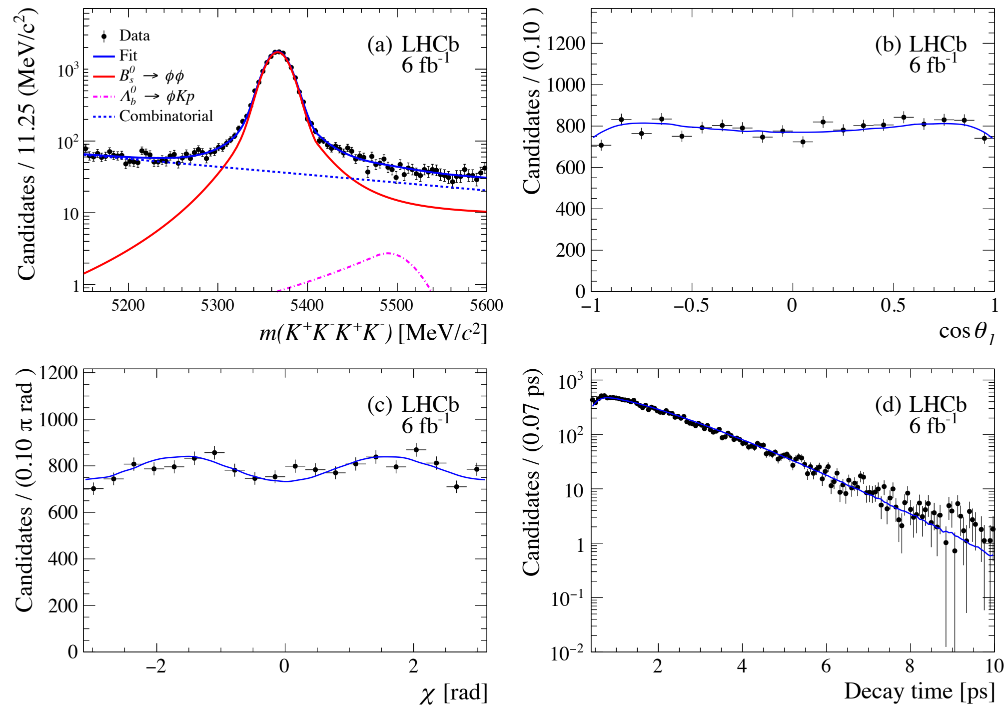
CP violation in B_s mixing in loop diagrams e.g. $B_s \to \phi\phi$

Tiny CP violation in SM

$$\phi_s^{s\bar{s}s} = 0.00 \pm 0.02\,\mathrm{rad}$$

LHCb update with full Run 2 dataset earlier this year

Tagged time dependent angular analysis to determine $\phi_s^{s\bar{s}s}$

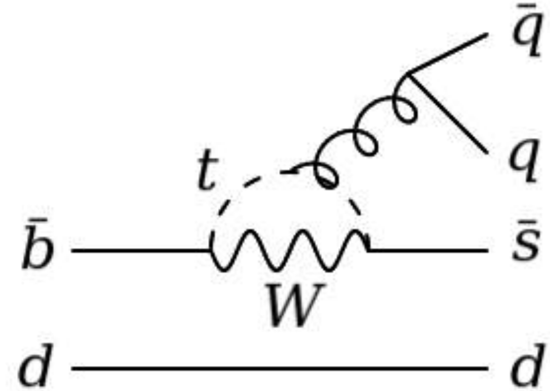


arxiv: 2304.06198

$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009\,\mathrm{rad}$$ Run 2

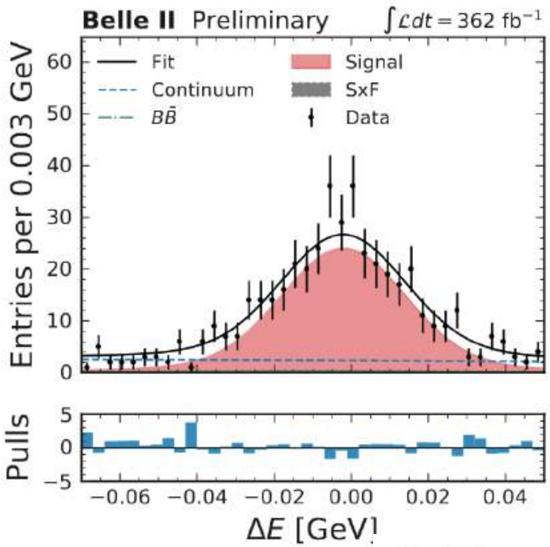
$$\phi_s^{s\bar{s}s} = -0.074 \pm 0.069\,\mathrm{rad}$$ Run 1+2 combination

$B^0 \to \eta' K_s$

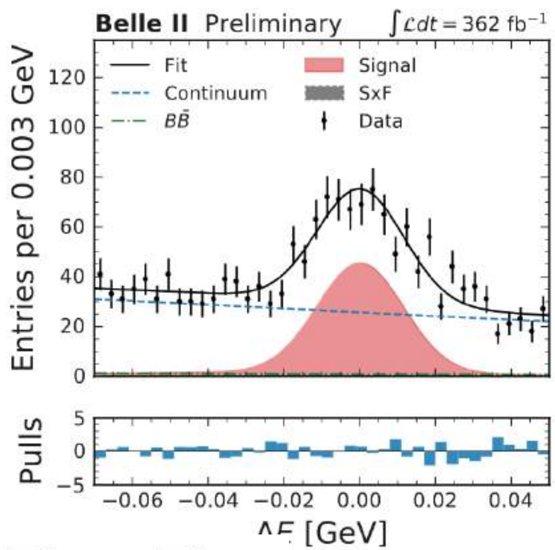


Loop suppressed $\bar{b} \to \bar{s} q \bar{q}$ transition with relatively high BF

$\eta'[\to \eta\pi^+\pi^-]$



$\eta'[\to \rho\gamma]$



Clear signal above Combinatorial background after MVA

$$\Delta E = E_B^* - E_{\text{beam}}^*$$

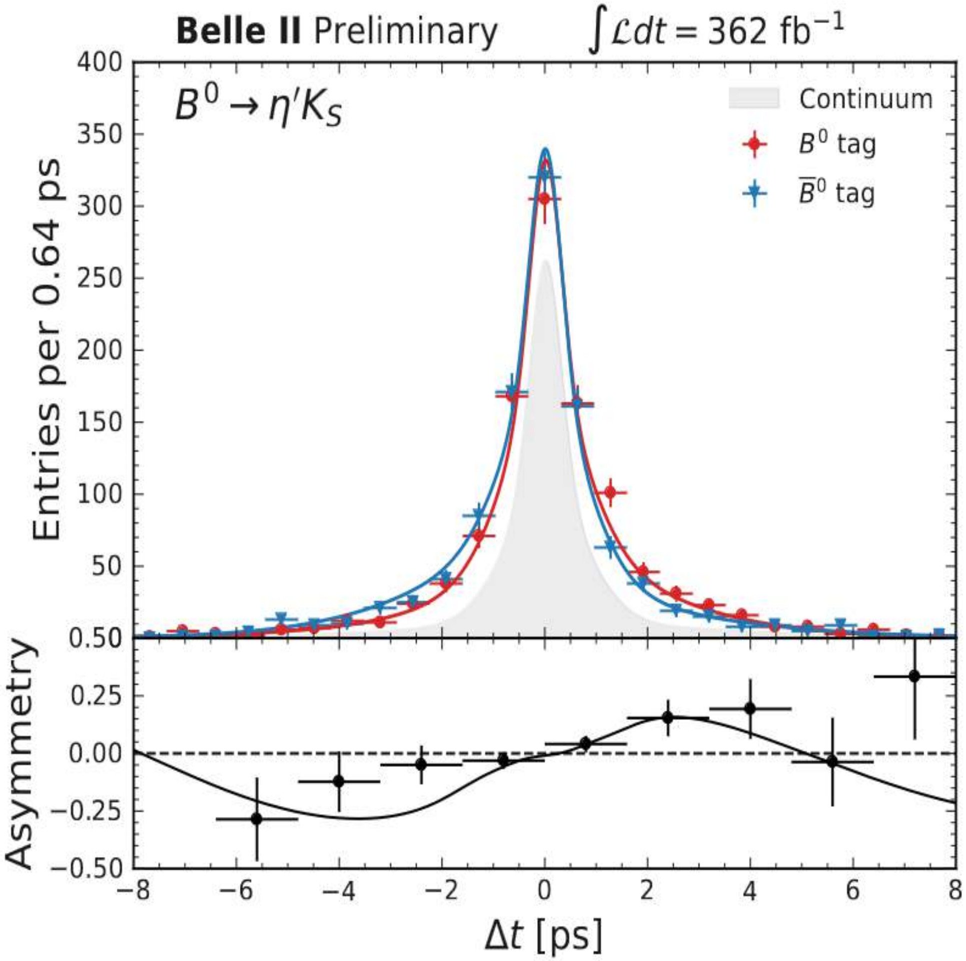
$$n_{sig} = 829 \pm 35$$

New for EPS!

Parallel talk Oskar Tittel

$B^0 \to \eta' K_s$

New for EPS!



Background shape validated from sideband

Fit validated with $B^+ \to \eta' K^+$

$$C_{CP} = 0.19 \pm 0.08 \pm 0.03$$
$$S_{CP} = 0.67 \pm 0.10 \pm 0.04$$

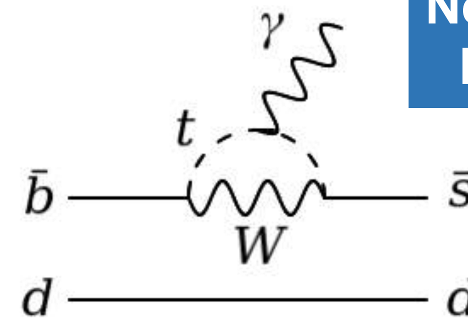
HFLAV: $C_{CP} = -0.05 \pm 0.04$ $S_{CP} = 0.63 \pm 0.06$

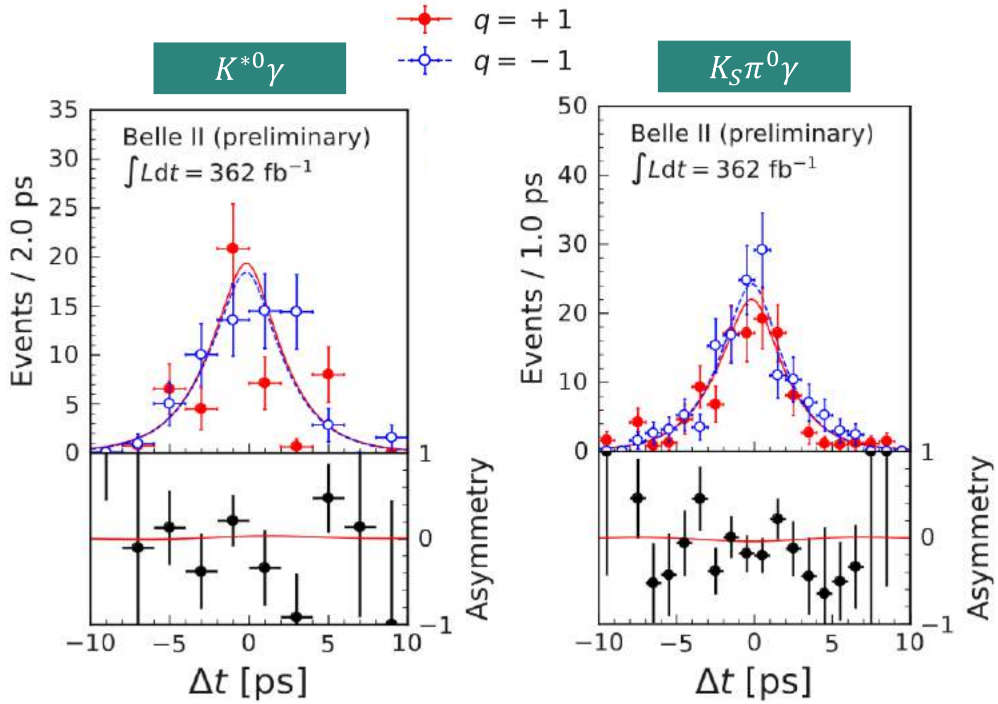
$$S_{CP} = sin2\beta, \quad O(\sim 1\%)$$

arXiv:hep-ph/0505075

$B^0 \to K_s \pi^0 \gamma$

New for EPS!





Challenging mode as no tracks directly from b-vertex

$C_{CP} = 0.10 \pm 0.13 \pm 0.03$
$S_{CP} = 0.00^{+0.27+0.03}_{-0.26-0.04}$

$C_{CP} = -0.06 \pm 0.25 \pm 0.07$
$S_{CP} = 0.04^{+0.45}_{-0.44} \pm 0.10$

Most precise result to date

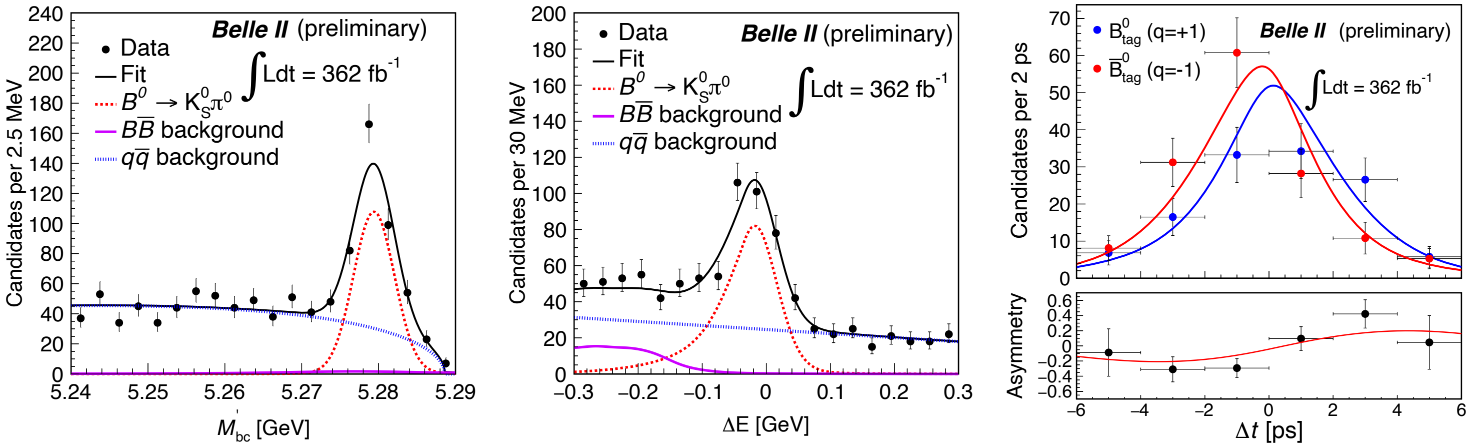
Theory: $S_{CP} = -0.035 \pm 0.017$

$K\pi$ isospin sum rules

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

WA: $I_{K\pi} = (-13 \pm 11)\%$, precision limited by $K_S^0\pi^0$

SM predicts $I_{K\pi} = 0$ to ~ 1 %



Time dependent measurement, with 415 candidates

$$A_{CP} = 0.04 \pm 0.15(stat) \pm 0.05(syst),\ S_{CP} = 0.75^{+0.20}_{-0.23}(stat) \pm 0.04(syst)$$

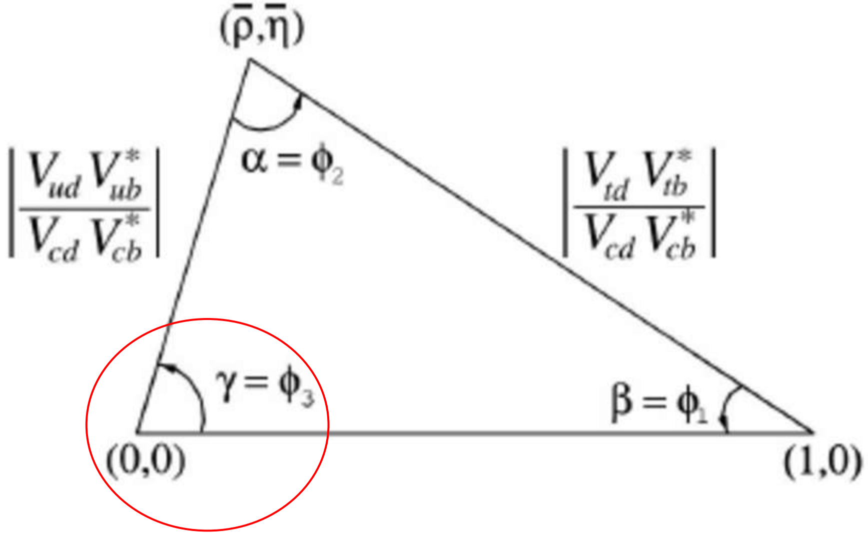
Precision comparable with world's best result even with smaller sample

$$A_{K^0\pi^0} = -0.01 \pm 0.12(stat) \pm 0.05(syst)$$

$$I_{K\pi} = -0.03 \pm 0.13(stat) \pm 0.05(syst)$$

Including time integrated study

CKM angle γ



CKM angle γ

γ accessed in many ways using $b \to c \to u$ transitions

B decays

$$B^+ \to Dh^+, B^+ \to D^*h^+, B^+ \to DK^{*+}, B^+ \to Dh^+\pi^+\pi^-$$

$$B^0 \to DK^{*0}, B^0 \to D^\mp\pi^\pm$$

$$B_s \to D_s^\mp K^\pm, B_s^+ \to D_s^\mp K^\pm\pi^+\pi^-$$

D decays: wide range of 2,3 and 4 body modes

$$D^0 \to K^+\pi^-, D^0 \to h^+h^-$$

$$D^0 \to K_s h^+h'^-, D^0 \to h^+h'^-\pi^0$$

$$D^0 \to K^-\pi^+\pi^-\pi^+, D^0 \to K^+K^-\pi^-\pi^+, D^0 \to K_s\pi^+\pi^-\pi^0, D^0 \to \pi^+\pi^-\pi^+\pi^-$$

Several methods: ADS/GLW, GGBPGZ

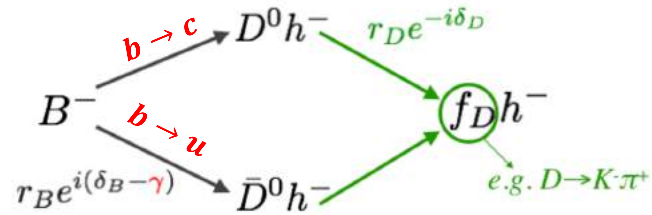
Theoretically clean measurement at 10^{-7} level (Brod+Zupan arXiv:1308.5663)

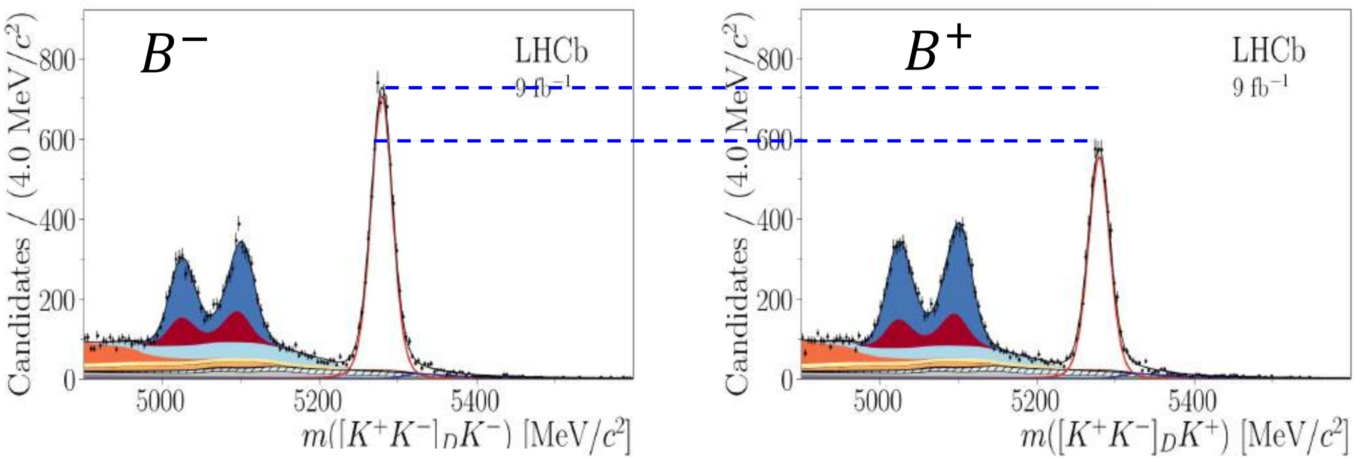
BaBar and Belle achieved precision of around 15^{o}. LHCb has achieved 4^{o} precision

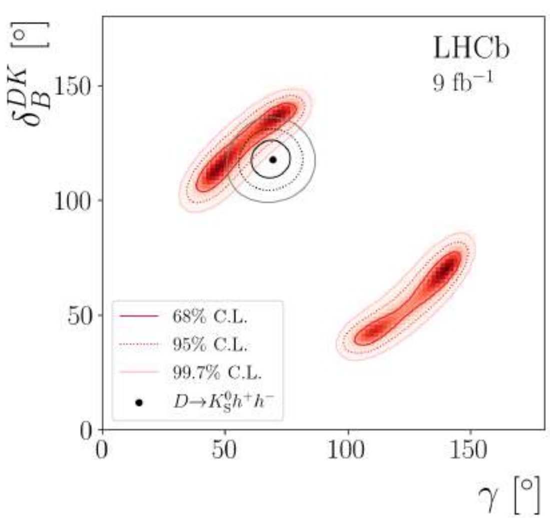
Important role for BESIII (Quantum correlated measurements at the $\psi(3770)$)

γ in $B^+ \to D^{(*)} h^+$, $h = \pi, K$

e.g. interference of $b \to u$ and $b \to c$ transitions in $B^\pm \to Dh^\pm$ decays







e.g. ADS/GLW analysis in JHEP 04 (2021) 081

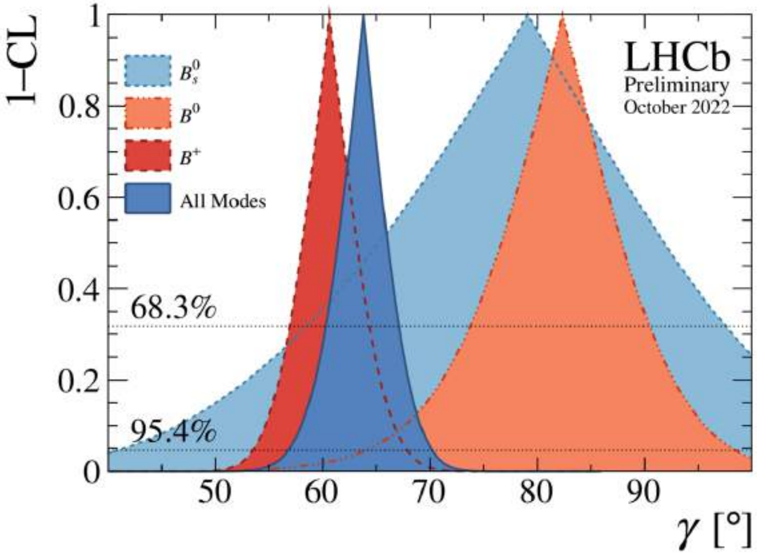
28 observables measured

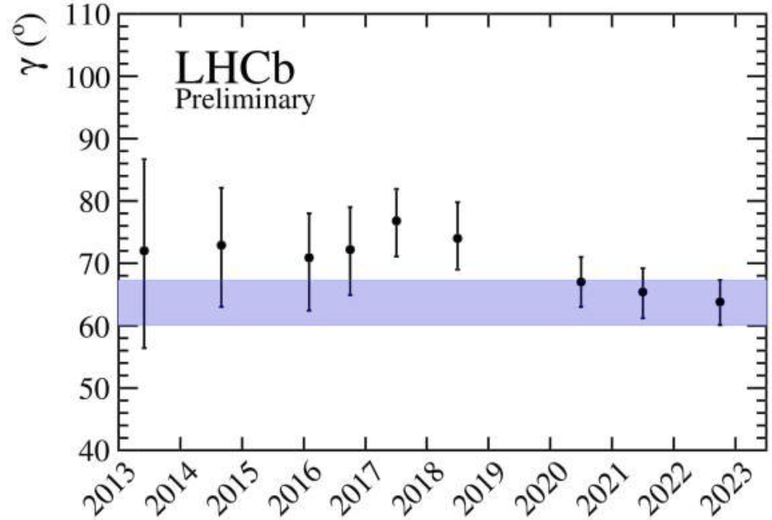
γ determined up to 4-fold ambiguity

LHCb γ combination

Combined fit to all LHCb measurements and charm mixing data

- $B^{\pm} \to DK^{(*)\pm}$
- $B^0 \to DK^{*0}$
- $B^0 \to D^{\mp}\pi^{\pm}$
- $B_s^0 \to D_s^{\mp}K^{\pm}(\pi\pi)$
- $D \to K^+\pi^-$
- $D \to K^+\pi^-$
- $D \to h^+h^-\pi^0$
- $D \to \pi^+\pi^-\pi^+\pi^-$
- $D \to K^+\pi^-\pi^0$
- $D \to K^{\pm}\pi^{\mp}\pi^+\pi^-$
- $D \to K_S^0K^{\pm}\pi^{\mp}$
- $D \to K_S^0K^{\pm}\pi^{\mp}$





$$\gamma = (63.8^{+3.5}_{-3.7})^{\circ}$$

Consistent with the CKMFitter prediction

$$\gamma = (65.5^{+1.1}_{-2.7})^{\circ}$$

LHCb met its goal of 4° precision with Run 1+2 data (LHCb-TDR-012)

Recent LHCb results

arXiv:2209.03692

$B^+ \to D^0 h^+$ with $D^0 \to K^\mp \pi^\pm \pi^\pm \pi^\mp$

$$\gamma = (54.8^{+3.8}_{-5.8}\,{}^{+0.6}_{-0.6}\,{}^{+6.7}_{-4.3})^\circ$$

Large uncertainty from external inputs of strong phases/coherence factor from CLEO/BES

EPJC 83 (2023) 547

$B^+ \to D^0 h^+$ with $D^0 \to K^+ K^- \pi^+ \pi^-$

$$\gamma = (116^{+12}_{-14})^\circ$$

Model dependent amplitude analysis, will benefit from BES3 measurements

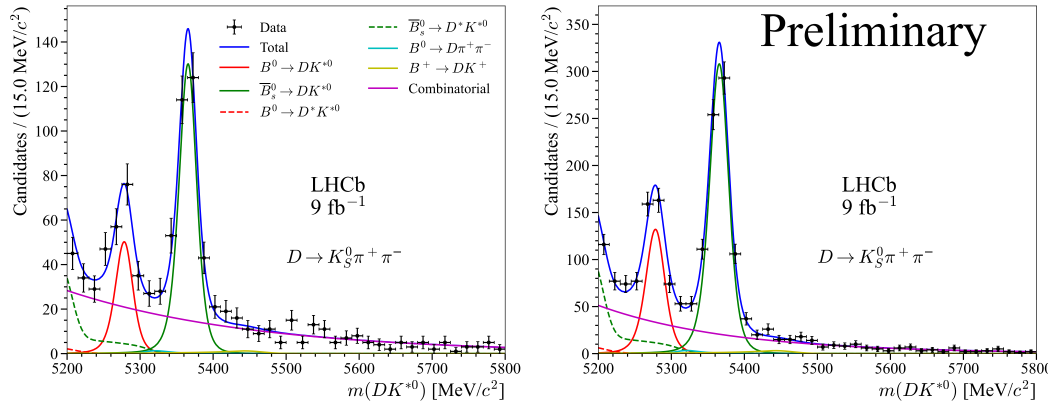
Recent LHCb results

New

$B^0 \to D^0 K^*$ with $D^0 \to K_s h^+ h^-$

$$\gamma = (49^{+23}_{-18})^\circ$$

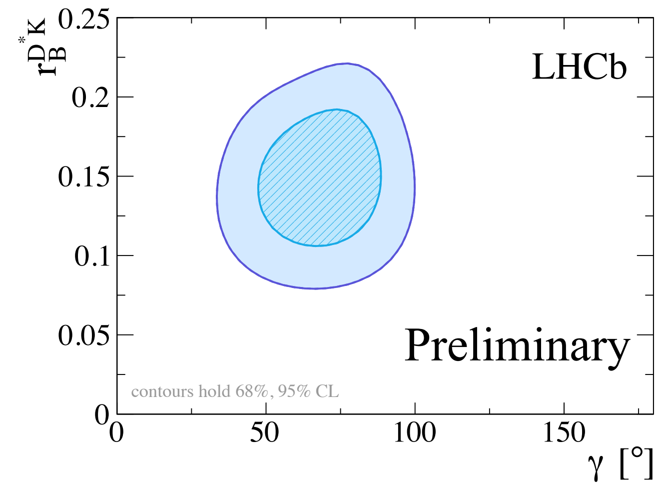
LHCb-PAPER-2023-009



$B^+ \to D^* h^+$ with $D^* \to D\pi^0/\gamma$ with $D^0 \to K_s h^+ h^-$

$$\gamma = (65 \pm 14)^\circ$$

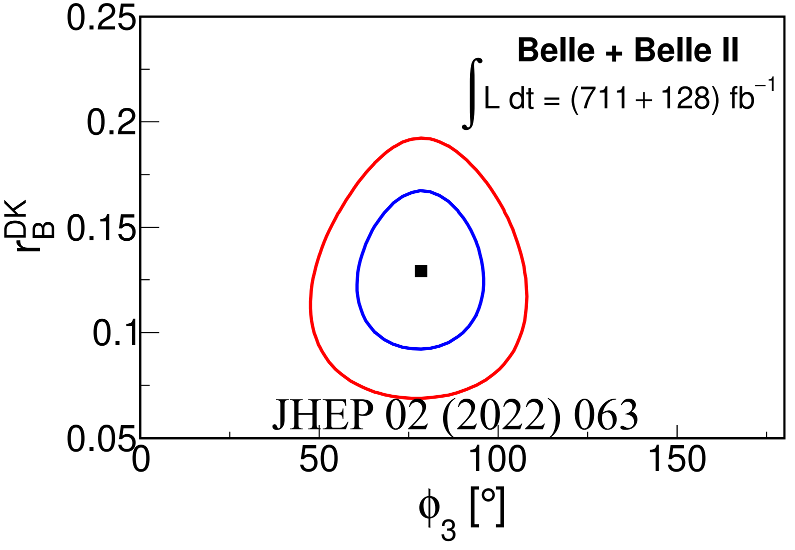
LHCb-PAPER-2023-012



Parallel talk Lei Hao

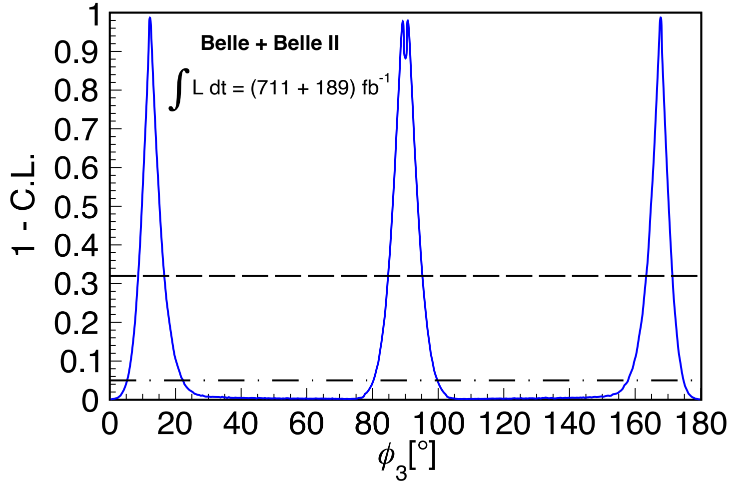
Belle 2

Belle 2 starting to produce results in combination with Belle data



BPGGZW analysis of $B^+ \to D^0 h^+$, with $D^0 \to K_s h^+ h^-$

$$\gamma = \phi_3 = (78.4 \pm \underset{\text{stat}}{11.4} \pm \underset{\text{syst}}{0.5} \pm \underset{\text{ext}}{1.0})^\circ$$



GLW analysis of $B^+ \to D_{CP} K^\pm$

$$\gamma \in [84.5, 95.5]^\circ$$

90 % CL

arxiv: 2308.05048

Parallel talk Marcus Reif

Future Prospects

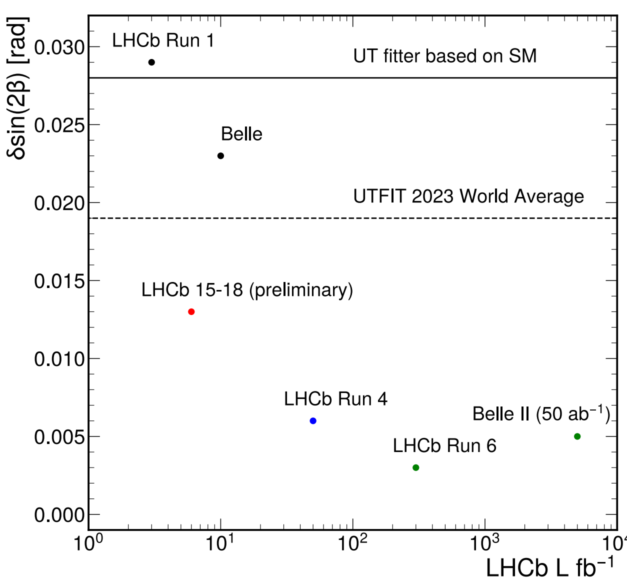
Prospects for B-mixing

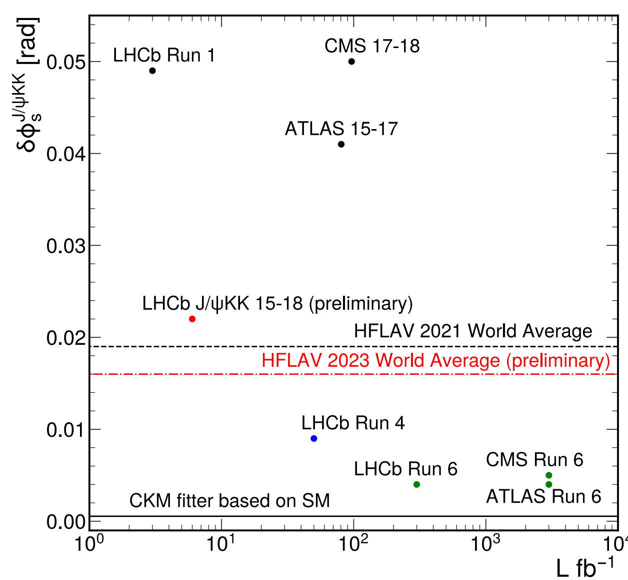
Still room for New Physics amplitude at level of 10 % in B_d, B_s mixing ☺
In the next decades move from 10 fb^{-1} to 300 fb^{-1} with LHCb upgrades plus ATLAS/CMS/Belle 2

← 9 fb^{-1} → ← Goal: 50 fb^{-1} → ← Goal: 300 fb^{-1} →

Upgrade I — Upgrade Ib — Upgrade II

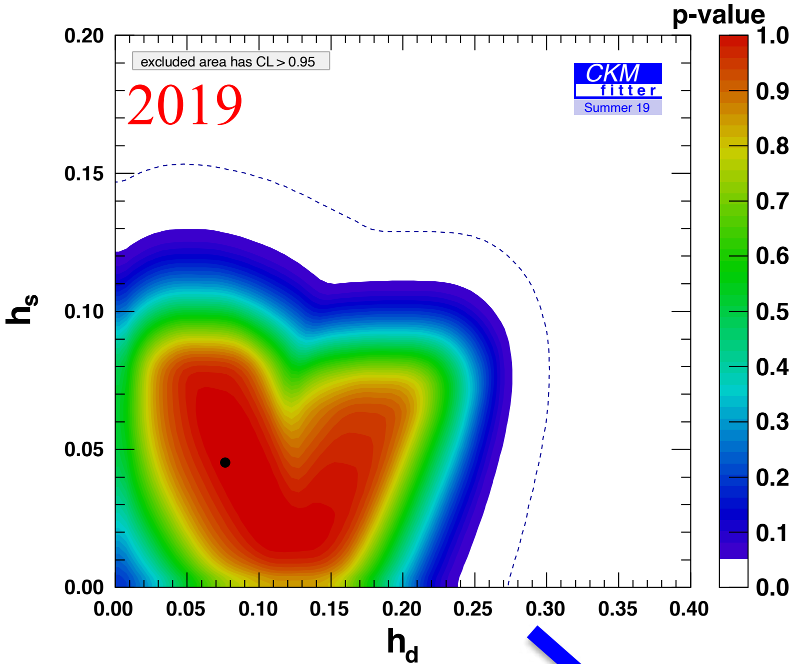
Run 1	LS1	Run 2	LS2		Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
2011 2012	2013 2014	2015 2016 2017 2018	2019 2020 2021	2022	2023 2024 2025	2026 2027 2028	2029 2030 2031 2032	2033 2034	2035 2036 2037 2038	2039	2040 2041



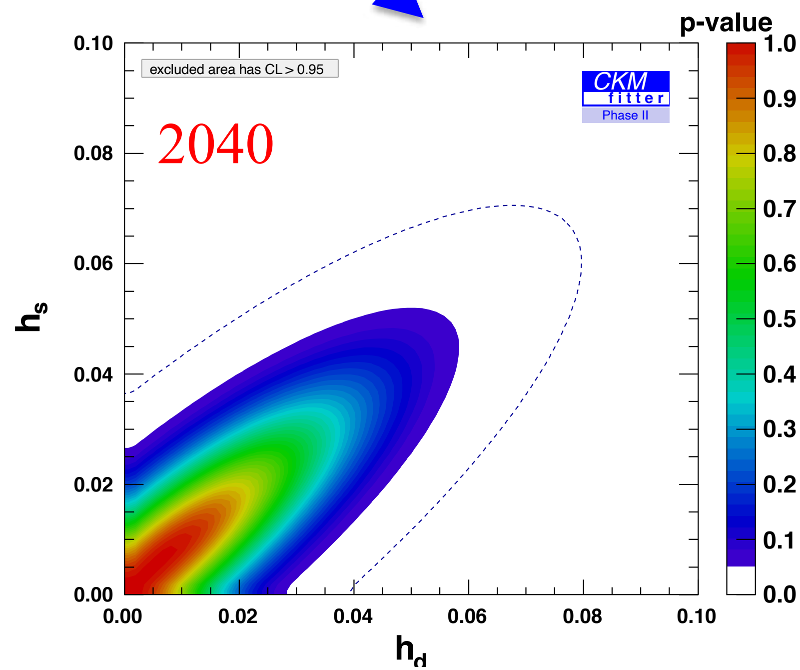


LHCb-PUB-2018-009, ATL-PHYS-PUB-2018-041, CMS-PAS-FTR-18-041, https://pos.sissa.it/294/005/pdf

Prospects for B-mixing



arxiv:2006.04824



$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

Prospects for γ

2023

At present $\sigma_\gamma \sim 4^o$

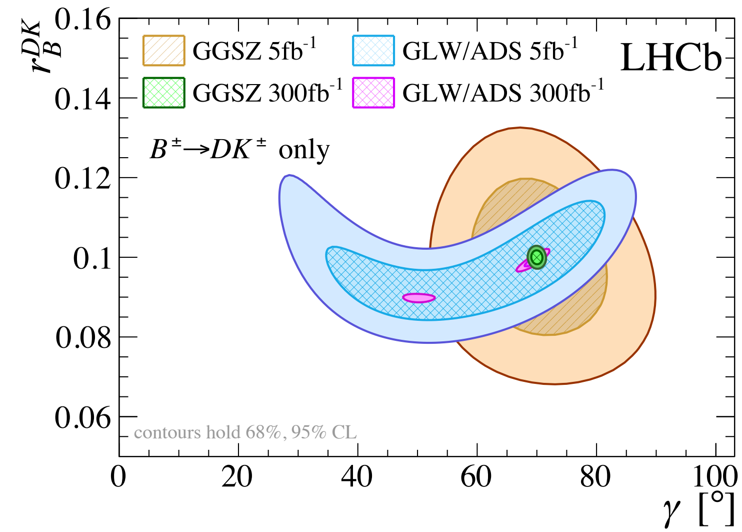
2030

Belle 2 with 50 ab^{-1} $\sigma_\gamma \sim 1 - 2^o$

LHCb Upgrade I (50 fb^{-1}) $\sigma_\gamma \sim 1^o$

2040

LHCb Upgrade II (300 fb^{-1}) $\sigma_\gamma \sim 0.4^o$

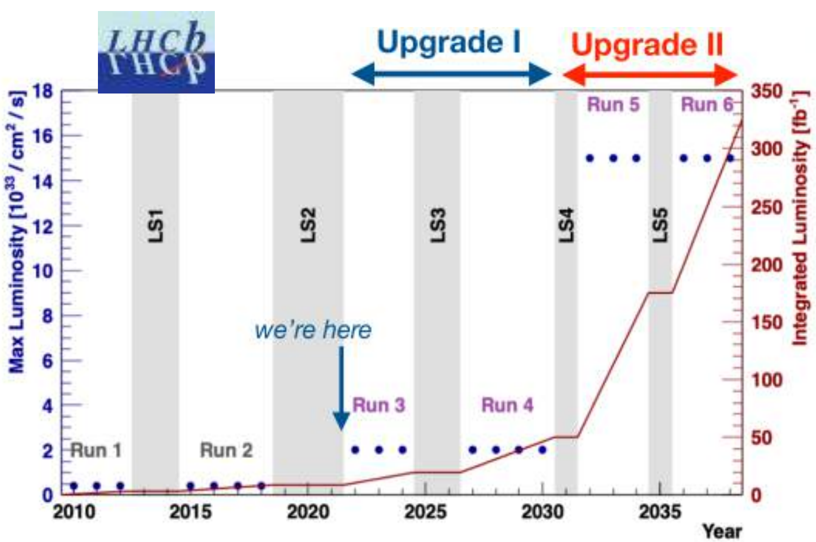


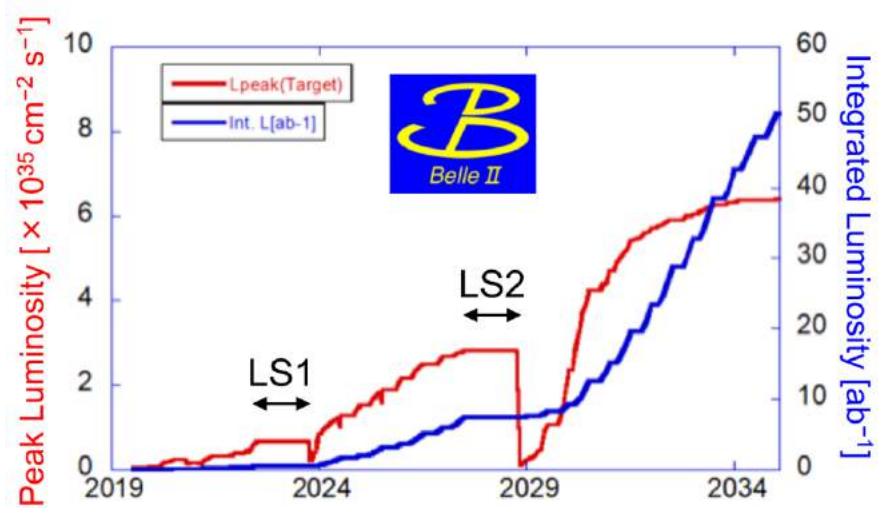
arXiv:1808.08865

To fully exploit precision improved estimates of strong phases from BESIII will be needed

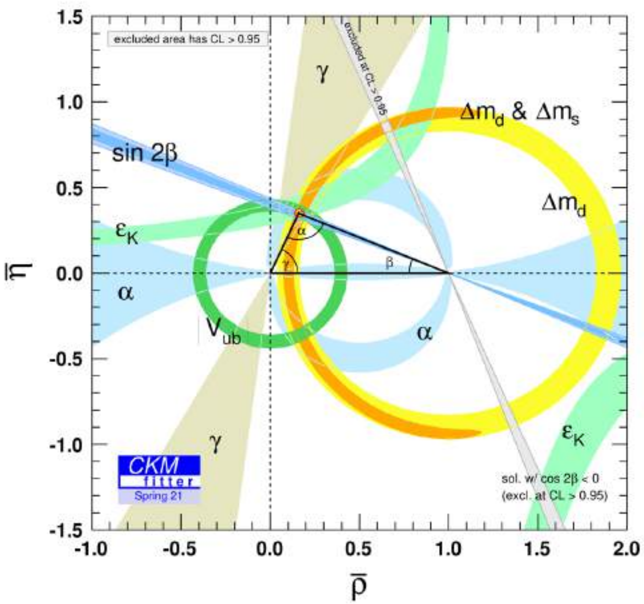
Summary

- New precise measurements of $\sin(2\beta)$ and ϕ_s from LHCb
- γ known to better than 4°: no longer the least precisely known CKM angle
  - New results on γ from LHCb, Belle always coming
- Belle 2: Ramping up and producing wide range of interesting results
  - e.g $B^0 \to \eta' K_s$
- A lot more to come in the next decades from LHCb Upgrade(s), ATLAS/CMS and Belle 2



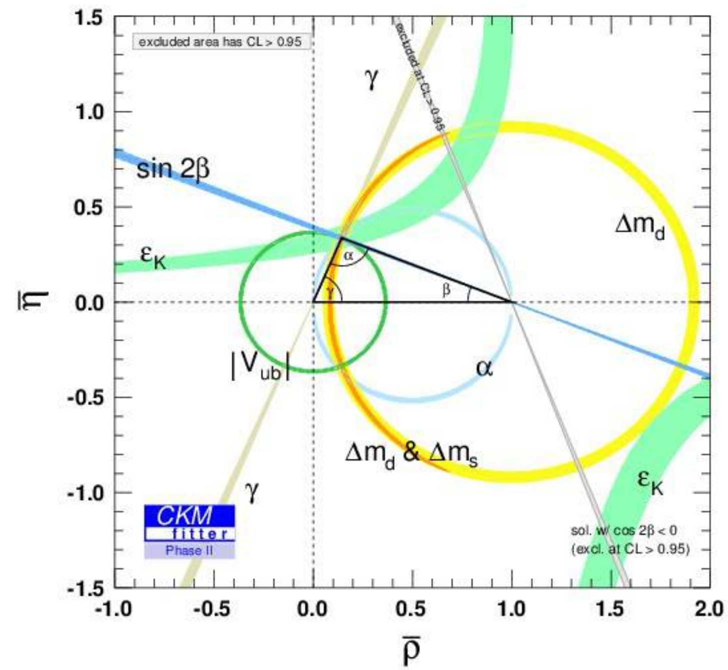


Summary



2021

?



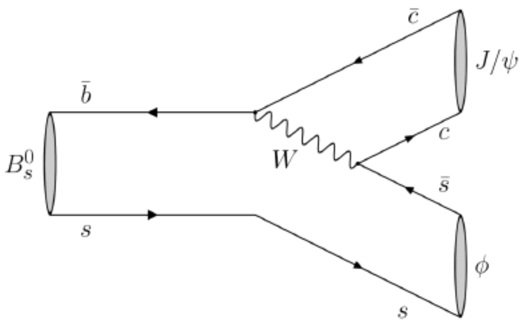
2040

arxiv:2006.04824

Backup

Penguin Pollution

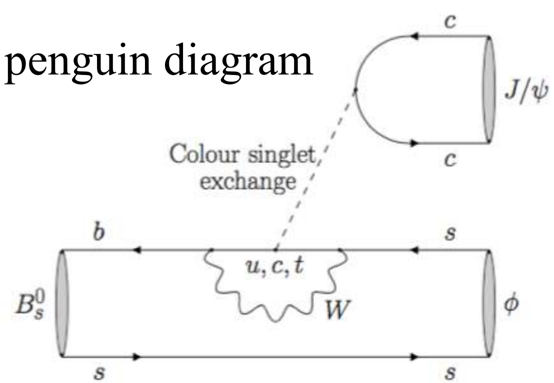
tree



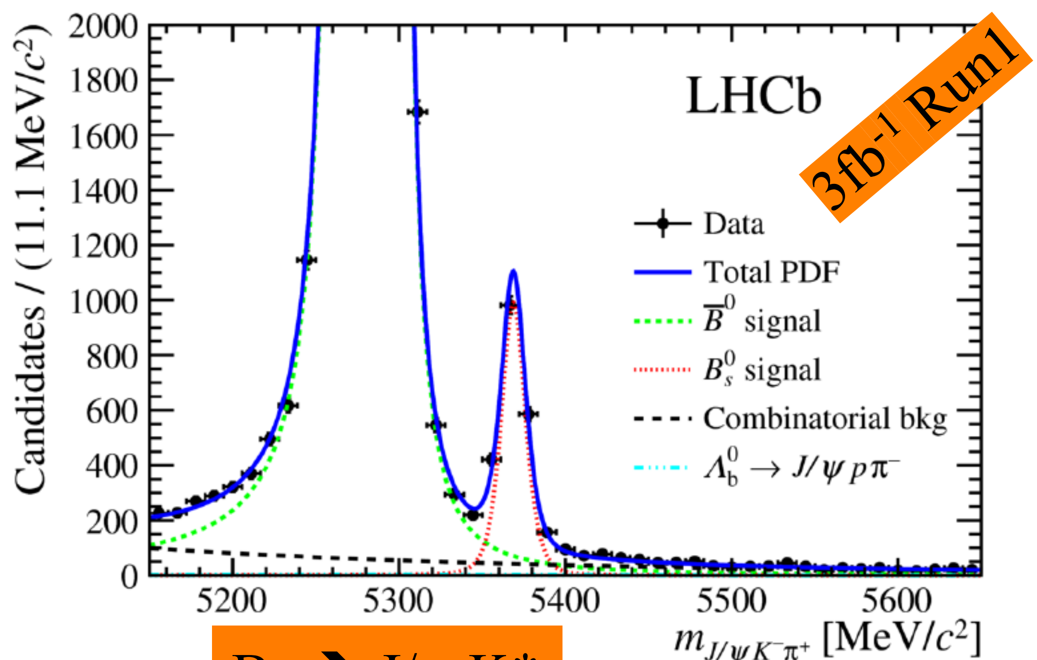
Penguin contributions could mimic NP effects

Study using other modes related by SU(3) symmetry to limit size using data
e.g. B_s ➔ $J/\psi\ K^*$, B^0 ➔ $J/\psi\rho$

penguin diagram



$$A\left(B_s^0 \to (J/\psi\,\overline{K}^{*0})_i\right) = -\lambda \mathcal{A}_i \left[1 - a_i e^{\mathrm{i}\theta_i} e^{\mathrm{i}\gamma}\right]$$

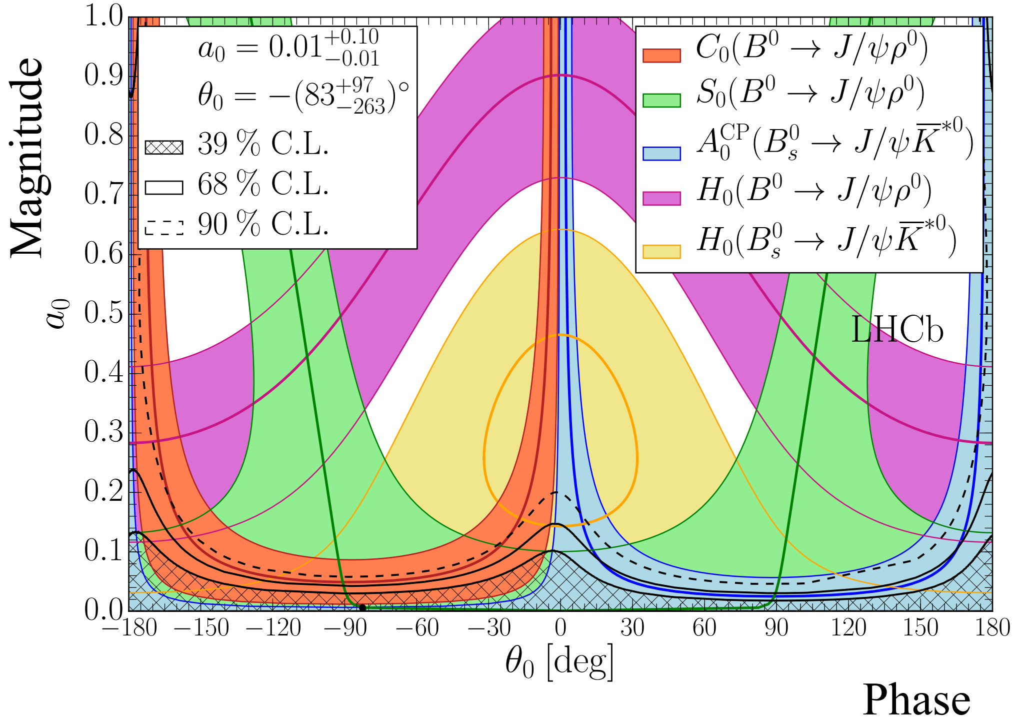


JHEP 11 (2015) 082
Phys Lett B742 (2015) 38

B_s ➔ $J/\psi\ K^*$

Penguin Pollution

Fit to CP observables + polarization amplitudes in B_s ➔ J/ψ K*, B^0 ➔ J/ψρ



JHEP 11 (2015) 082
Phys Lett B742 (2015) 38

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

Effect of penguins bounded to be less than current uncertainties

Predictions for $\Delta\Gamma_s$

Value $[\times 10^{-2}\text{ps}^{-1}]$	Renormalization scheme	Reference
7.7 ± 2.2	Pole mass	Asatrian *et. al.* [1]
8.8 ± 1.8	$\overline{MS}$	Asatrian *et. al.* [1]
9.2 ± 1.4	$\overline{MS}$	Davies *et. al.* [2]
9.1 ± 1.3	$\overline{MS}$	Lenz *et. al.* [3]
7.6 ± 1.7	Avg. $\overline{MS}$ + PS	Gerlach *et. al.* [4]

[1] Hrachia M. Asatrian et al. Penguin contribution to the width difference and asymmetry in mixing. *Phys. Rev. D*, 102(3):033007, 2020.

[2] Christine T. H. Davies et al. Lattice qcd matrix elements for the $B_s^0 - \bar{B}_s^0$ width difference. *Phys. Rev. Lett.*, 124(8):082001, 2020.

[3] Alexander Lenz and Gilberto Tetlalmatzi-Xolocotzi. Model-independent bounds on new physics effects. *JHEP*, 07:177, 2020.

[4] Marvin Gerlach et al. The width difference in $B - \bar{B}$ mixing at order α_s and beyond. *JHEP*, 04:006, 2022.

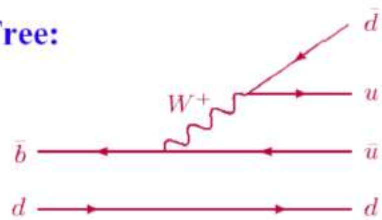
Belle2 potential for α/ϕ_2

Access α from TD-CPV in $B^0 \to \pi\pi, B^0 \to \rho\rho$

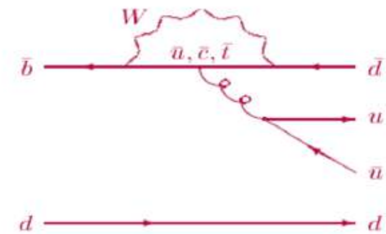
$$\alpha = (85.2^{+4.8}_{-4.3})^\circ \text{ HFLAV}$$

$$A_{CP}(t) = C\cos(\Delta m_d t) - S\sin(\Delta m_d t)$$
$$S = \sin 2\alpha + 2\, r\cos\delta \sin(\alpha+\beta)\cos 2\alpha$$

Tree:



Penguin:



$$A(B^0 \to \pi^+\pi^-) = T\, e^{i\gamma} + P\, e^{i\delta},\ r = |P|/|T|$$

Control hadronic parameter r and $\boldsymbol{\delta}$ using BFs and CPV of all isospin-related $B \to \pi\pi$ ($B \to \rho\rho$) channels, which are all accessible at Belle II

$\mathcal{B}(\rho^+\rho^-) = (2.67 \pm 0.28 \pm 0.28) \times 10^{-5}$, $f_L = 0.956 \pm 0.035 \pm 0.033$ — arXiv:2206.12362

$\mathcal{B}(\rho^+\rho^0) = (2.32 \pm 0.22 \pm 0.27) \times 10^{-5}$, $f_L = 0.943 \pm 0.035 \pm 0.060$
$A_{CP} = -0.069 \pm 0.068 \pm 0.060$ — arXiv:2208.03554

$\mathcal{B}(\pi^+\pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$,
$\mathcal{B}(\pi^+\pi^0) = (5.10 \pm 0.29 \pm 0.32) \times 10^{-6}$, $A_{CP} = -0.081 \pm 0.054 \pm 0.008$ — Talk by Xiaodong Shi at Lepton-Photon

$\mathcal{B}(\pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$, $A_{CP} = 0.14 \pm 0.46 \pm 0.07$ — PRD 107(2023)112009