第十六届粒子物理、核物理和宇宙学交叉学科前沿问题研讨会
南开大学，天津，2023年7月1-3日

CP violation in beauty decays

谢跃红 （华中师范大学）

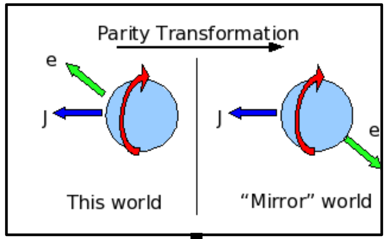
Courtesy Symmetry Magazine

Outline

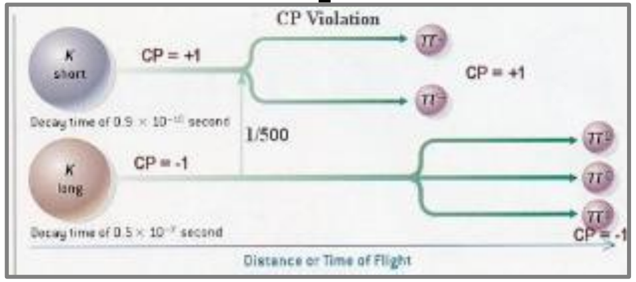
- CP violation and CKM mechanism
- Time-dependent CP violation & detection
- B^0 CP violating phase 2β
- B_s^0 CP violating phase ϕ_s
- CKM angle γ
- Summary

Discoveries of P & CP violation

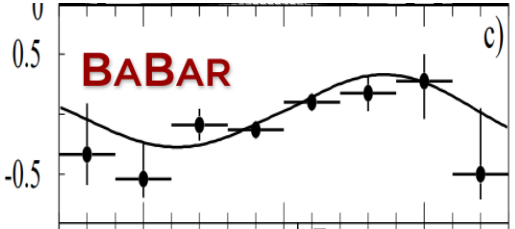
P violation
1956, Wu e al.

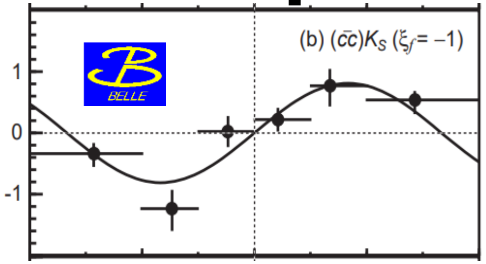


CP violation in K^0 mixing
1964, Cronin, Fitch et al.

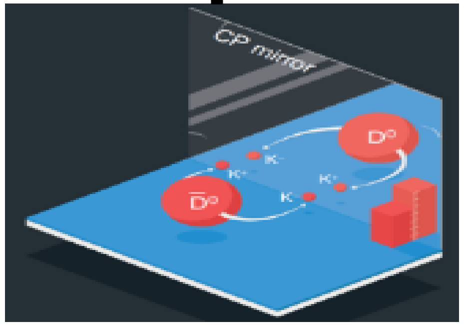


Time-dependent CP violation in B^0 decays
2001, BaBar & Belle

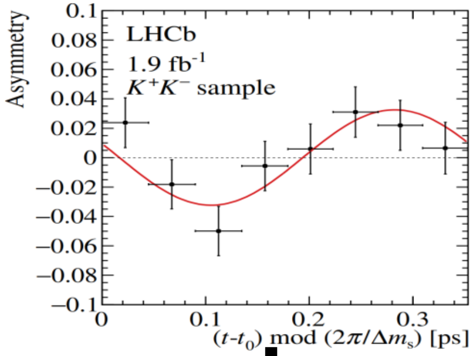




CP violation in D^0 decay
2019, LHCb



Time-dependent CP violation in B_s^0 decays
2020, LHCb



CKM mechanism

$$\mathcal{L}_{\rm SM} = \underbrace{\mathcal{L}_G(\psi, W, \phi)}_{\text{kinetic energy + gauge IA}} + \underbrace{\mathcal{L}_H(\phi)}_{\text{Higgs potential} \rightarrow \text{spontaneous symmetry breaking}} + \underbrace{\mathcal{L}_Y(\psi, \phi)}_{\text{Yukawa IA} \rightarrow \text{fermion masses}}$$

EWSB & diagonalisation of Yukawa mass matrix ⇒ CKM quark mixing matrix

$$\mathcal{L}_{W\pm} = \frac{g}{\sqrt{2}}\left(\bar{U}_L \gamma^\mu W_\mu^+ V_{CKM} D_L + \bar{D}_L \gamma^\mu W_\mu^- V_{CKM}^+ U_L\right)$$

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

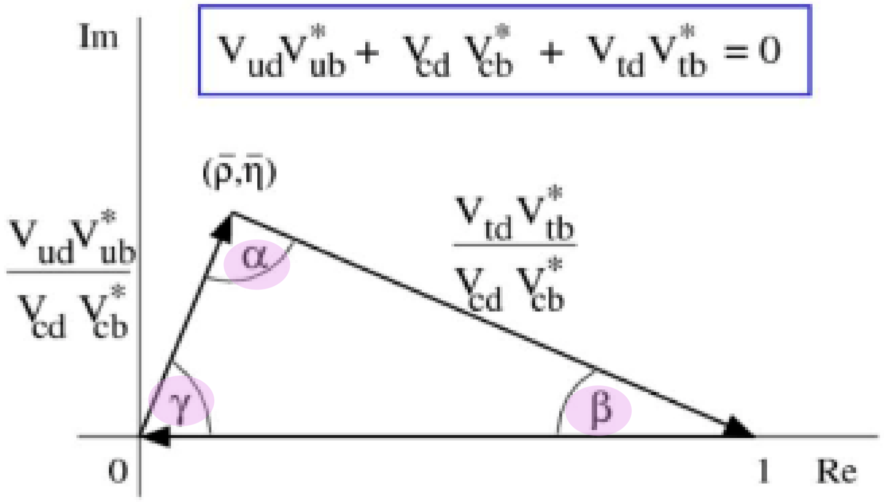
$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

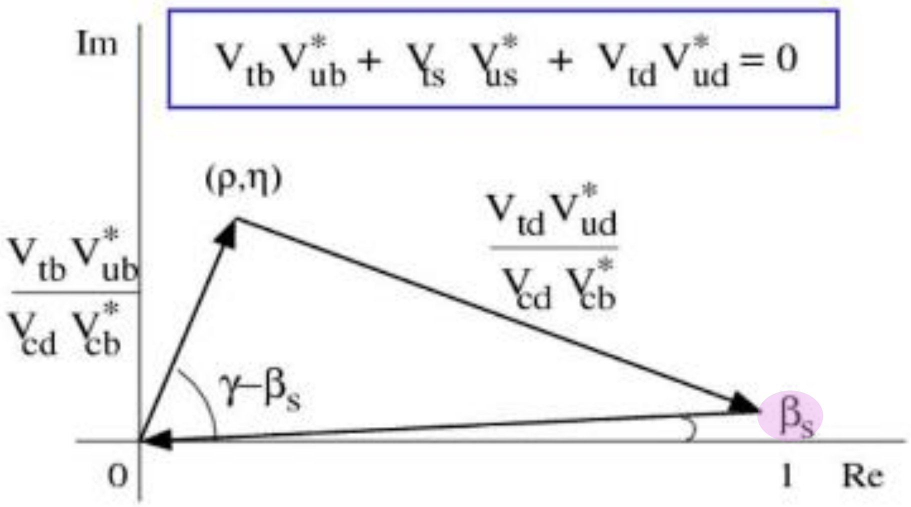
L.Wolfenstein PRL 51 (1983) 1945

Four parameters (A, λ, ρ, η) to be measured in data.

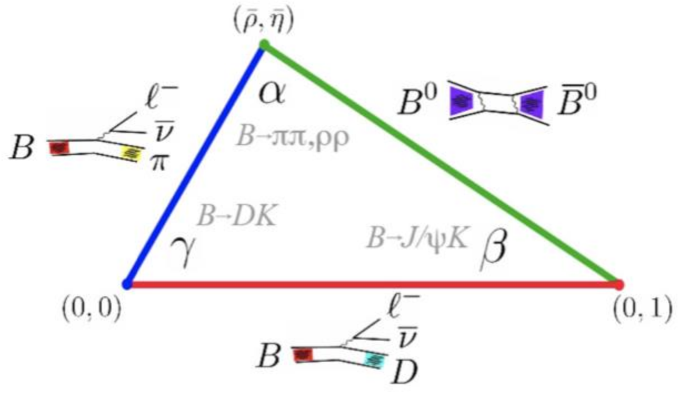
$\eta \neq 0$ ⇒ source of CP violation (CPV) in quark sector.

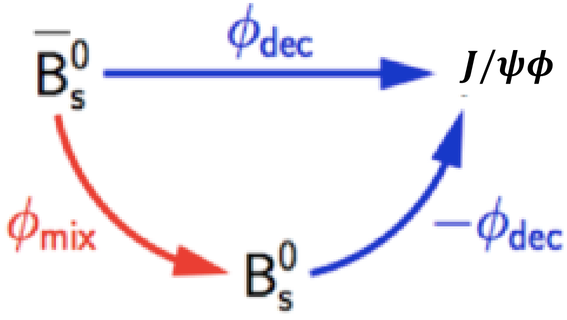
Unitarity of CKM matrix





B **decays plays huge roles in measurements of sides (rates, B_q^0 mixing) and angles (CP asymmetries)**

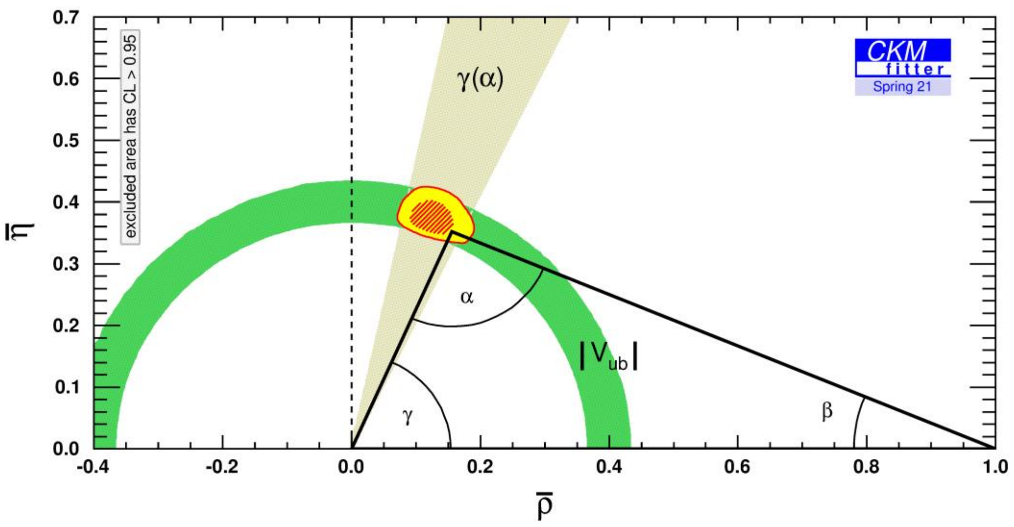


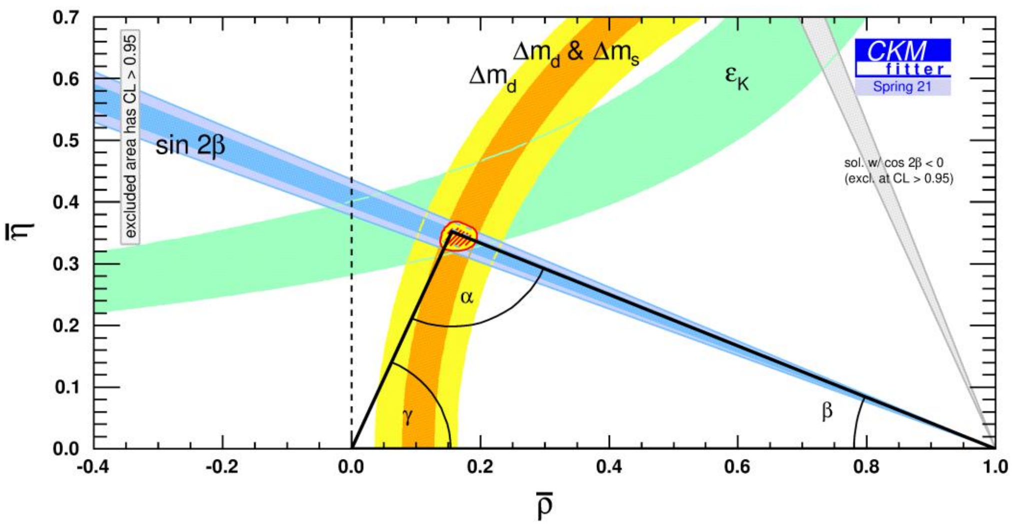


Over-constraining CKM matrix

- **Measurements from tree-level processes provide the SM benchmark**
  - γ in$B \to Dh$
  - V_{ub} in $B \to \pi l^- \bar{\nu}$

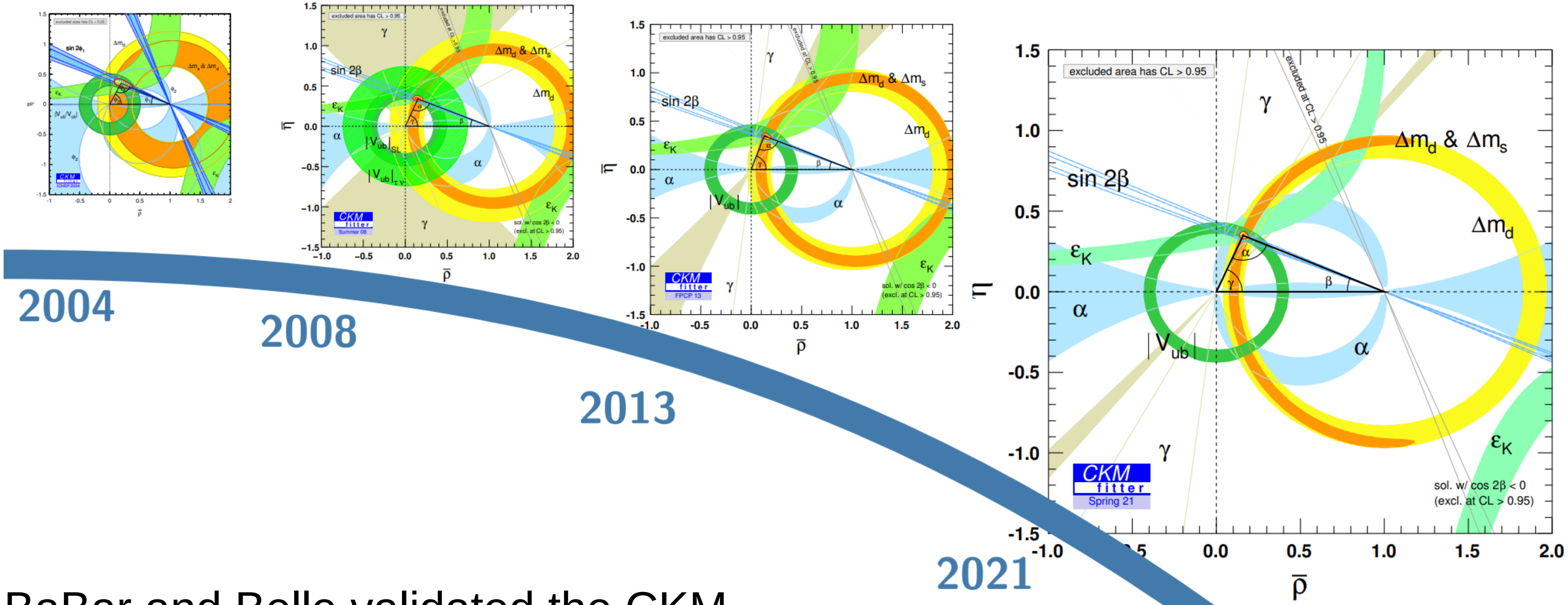
- **Measurements from loop processes provide sensitivity to NP**
  - β in $B^0 \to J/\psi K_S^0$
  - Mixing parameters Δm_d and Δm_s
  - CPV in kaon mixing
  - …





通过全局拟合确定CKM参数，考察不同测量之间一致性检验CKM机制

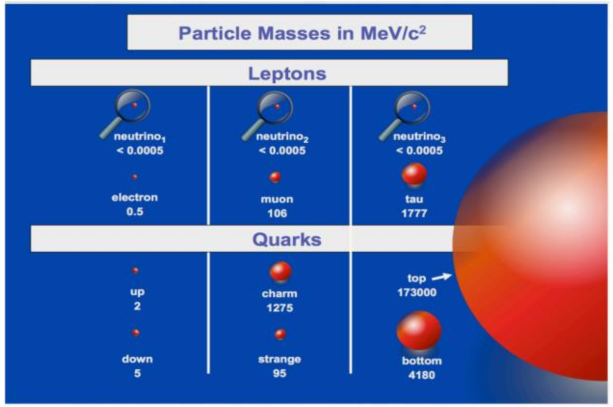
Great successes



- BaBar and Belle validated the CKM mechanism in the first decade of 21 century
- LHCb has taken over the baton to further test it and improve the parameter precision

2023

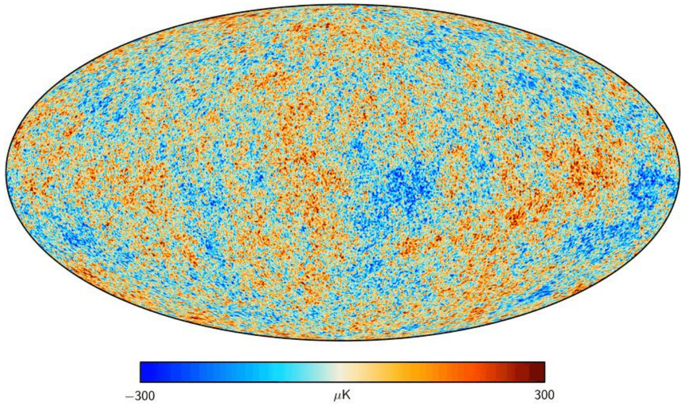
Open questions in flavour



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

→ CKM prediction

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-20}$$



→ Cosmological observation

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

- **What is the dynamic origin of the patterns of quark mass and flavour mixing?**
- **Is there any source of CP violation beyond the Yukawa couplings?**

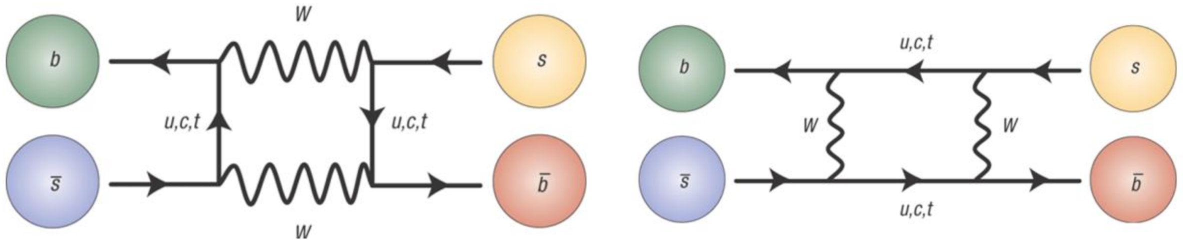
⇒ **New physics beyond the SM is expected at very high energy scale**

Time-dependent CP violation & detection

Neutral B mixing and CPV

- **Neutral B mesons:** $B^0 = (\bar{b}d)$ $\bar{B}^0 = (b\bar{d})$ $B_s^0 = (\bar{b}s)$ $\bar{B}_s^0 = (b\bar{s})$

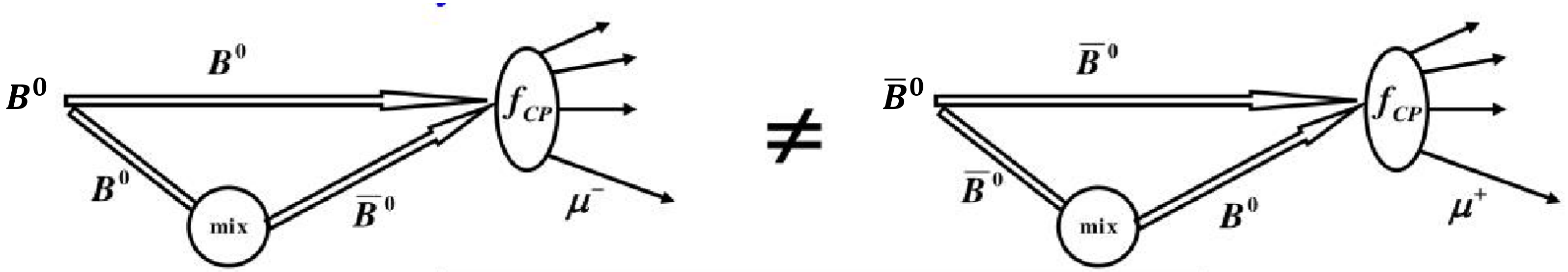
- $B_q^0 - \bar{B}_q^0$ $(q = d, s)$ **oscillation**



$$B_L = p|B_q\rangle + q|\bar{B}_q\rangle$$
$$B_H = p|B_q\rangle - q|\bar{B}_q\rangle$$

$$\Delta m_q = m_H - m_L,\ \Delta\Gamma_q = \Gamma_L - \Gamma_H$$

- **CPV in interference of B_q^0 decay to CP eigenstate with and w/o mixing**



$$\Gamma(B^0 \to f_{CP}) \neq \Gamma(\bar{B}^0 \to f_{CP})$$

Measuring TD-CPV

$$A_{CP}(t) = \frac{\Gamma(\bar{B}_q^0(t) \to f_{CP}) - \Gamma(B_q^0(t) \to f_{CP})}{\Gamma(\bar{B}_q^0(t) \to f_{CP}) + \Gamma(B_q^0(t) \to f_{CP})} = \eta_f \frac{C\cos(\Delta m_q t) + S\sin(\Delta m_q \mathrm{t})}{\cosh\frac{\Delta\Gamma_q t}{2} + A_\Delta \sinh\frac{\Delta\Gamma t}{2}}$$

$S \neq 0$: mixing induced CPV

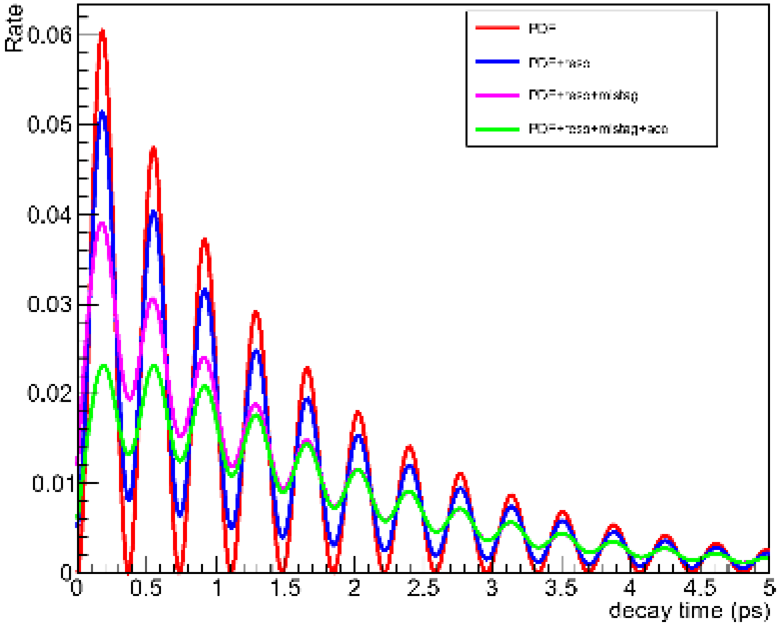
$C \neq 0$: direct CPV in decay

η_f: CP eigen-value

- **Requirements**
  - Identify the initial flavour B or $\bar{B}$
  - Reconstruct the proper decay time t
  - If the final state is a mixture of CP-even and CP-odd states, such as $B_s^0 \to J/\psi\phi$ and $B_s^0 \to \phi\phi$, perform angular analysis

Experimental effects

$\Delta m_s = 17.7\ \text{ps}^{-1}$
$\sigma_t = 50\ \text{fs}$
$\omega = 0.2$
$\epsilon(t) = 1/(1+\exp(-2t))$



- ❑ Times resolution σ_t

$$S \rightarrow e^{-\frac{(\Delta m \sigma_t)^2}{2}} S = D_{\text{time}} S$$

D_{time} ~0.7 for $\Delta m_s = 17.7\ \text{ps}^{-1}$ with $\sigma_t = 50$ fs
~0.7 for $\Delta m_d = 0.5\ \text{ps}^{-1}$ with $\sigma_t = 1.5$ ps

- ❑ Wrong tag probability ω

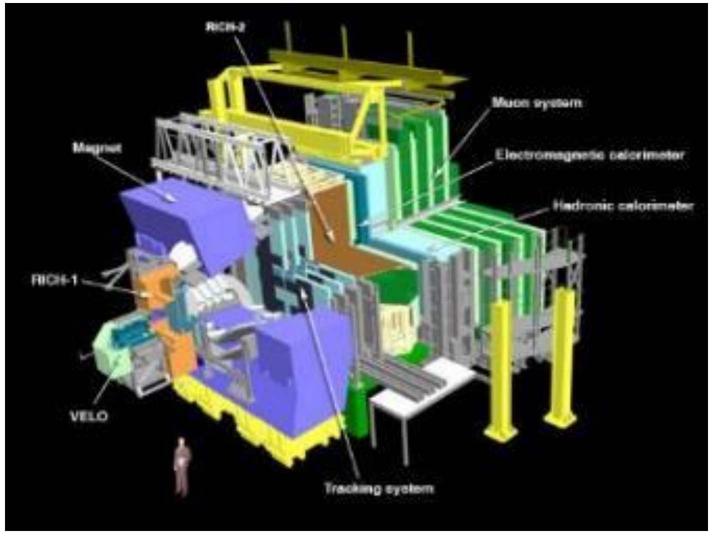
$$S \rightarrow (1-2\omega) S$$

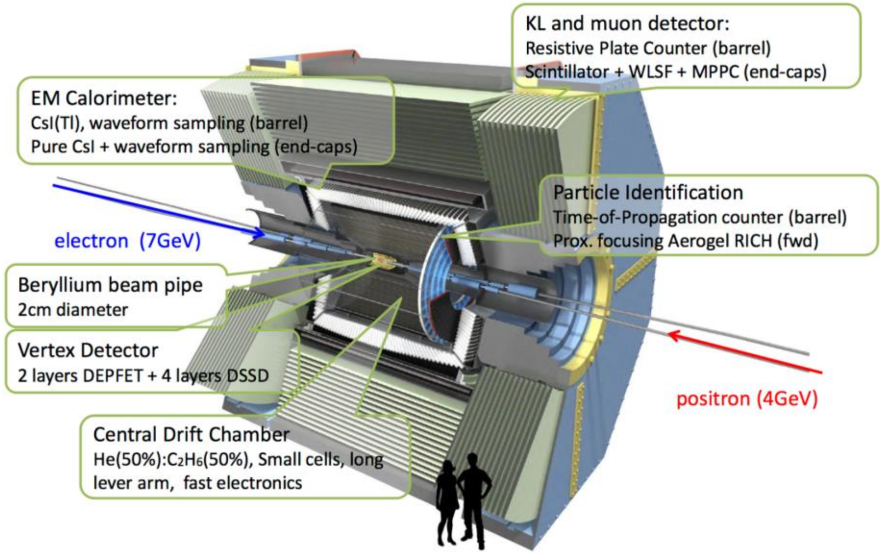
- ❑ Decay-time dependent efficiency $\epsilon(t)$

$$P(t) \rightarrow \epsilon(t)\, P(t)$$

Obtain info on σ_t, ω and $\epsilon(t)$ from data using control channels

Ongoing beauty experiments

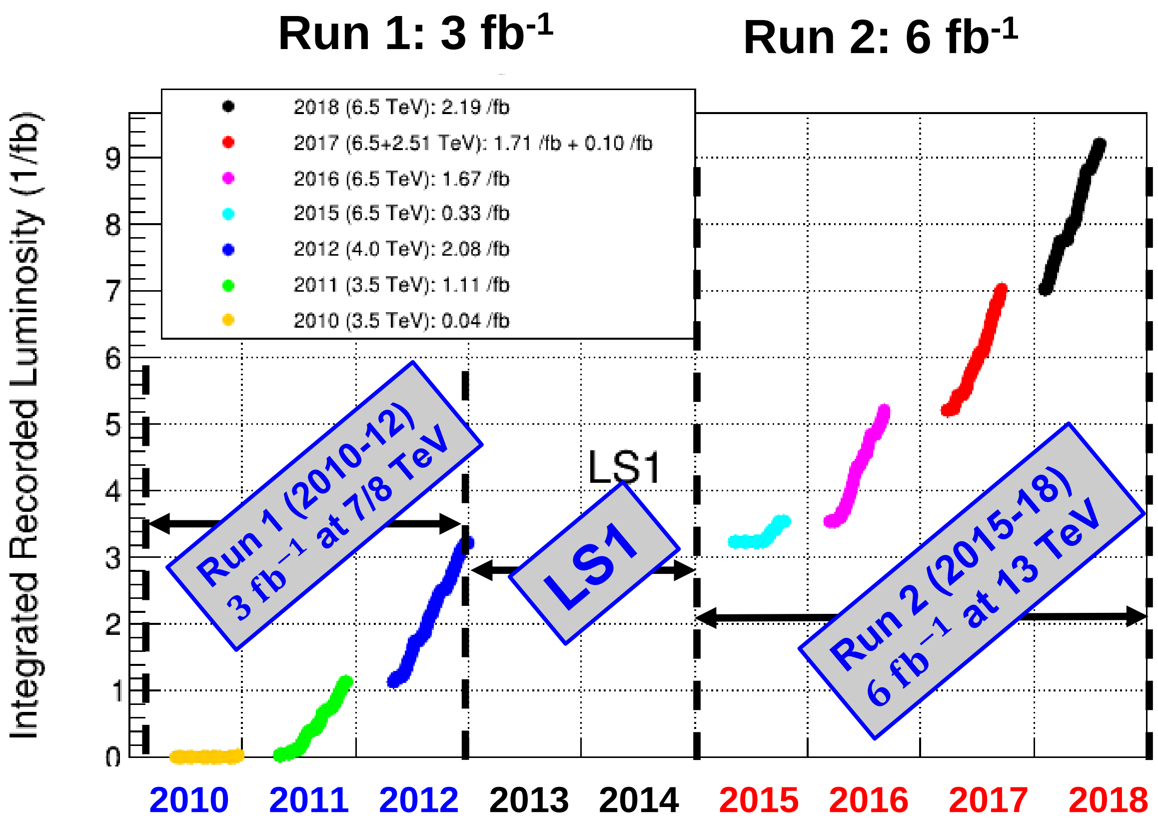




- Flavour experiment at LHC
- All b and c hadron species
- Excellent vertexing, tracking, PID
- $9\ \mathrm{fb}^{-1}$ @ 7, 8, 13 TeV

- SuperB factory at SuperKeKB
- Low background e^+e^- collision
- $B^0, B^\pm$
- $362\ \mathrm{fb}^{-1}$ @ $\Upsilon(4S)$

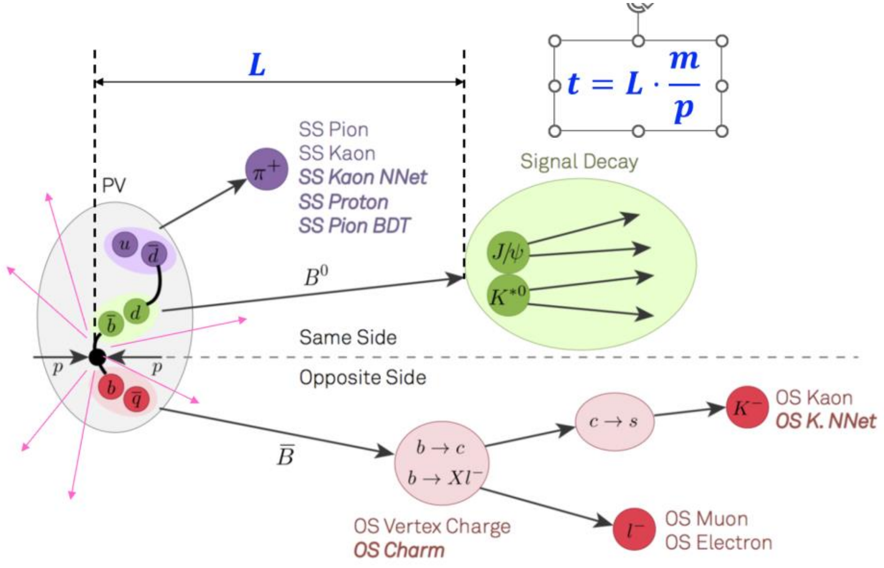
LHCb data taking in Run 1&2



之前的LHCb物理结果大多数基于2017年前采集的数据。

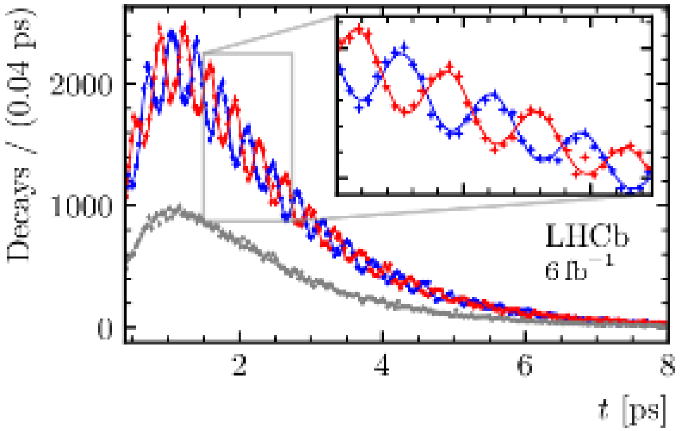
此次报告的结果均利用当前全部可用数据进行了更新。

The LHCb approach



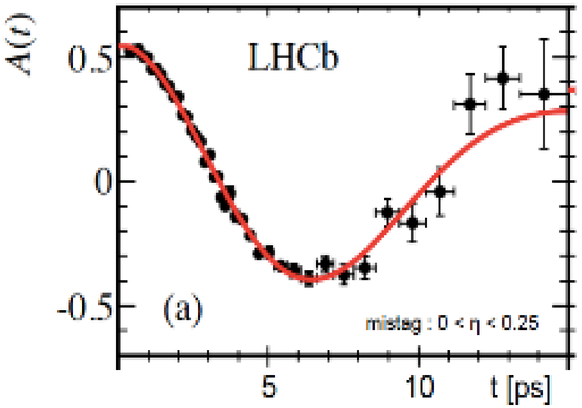
- Large boost from pp colision
  $\beta\gamma \sim 10,\ L \sim 1\ \mathrm{cm}$
- Silicon vertex system
  $\sigma_t \sim 45\ \mathrm{fs}$
- Flavour tagging: info from other B & fragmentation particles
  $\epsilon_{\mathrm{tag}}(1-2\omega)^2) \sim 5\%$

$B_s^0 \to D_s^- \pi^+$ Nature Physics 18 (2022) 1-5



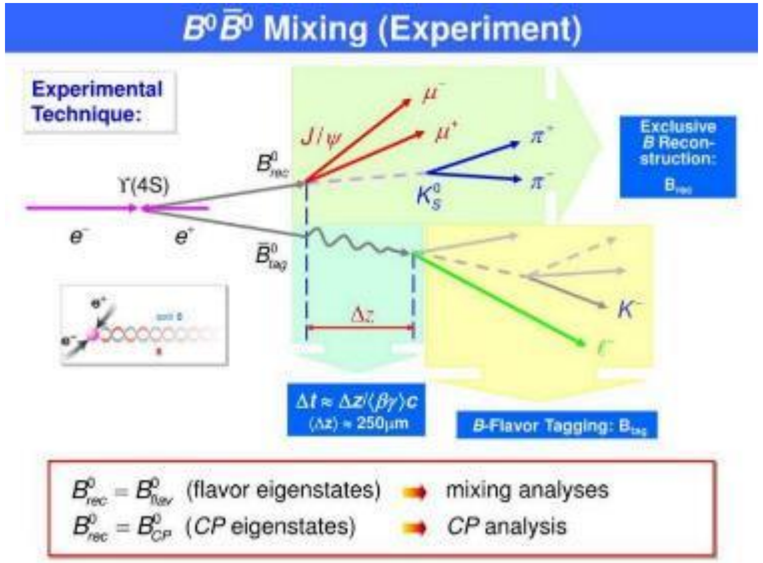
$\Delta m_s = 17.7656 \pm 0.0057\ \mathrm{ps}^{-1}$

$B_d^0 \to D^{(*)-} \mu^+ \nu$ EPJC 76 (2016) 412



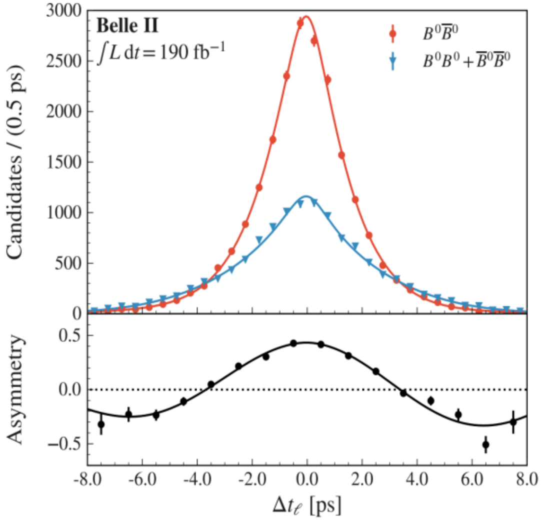
$\Delta m_d = 0.5050 \pm 0.0021 \pm 0.0010\ \mathrm{ps}^{-1}$

The Belle II approach



- Asymmetric e^+e^- collision
  $\beta\gamma = 0.28,\ \Delta z \sim 200\ \mu\mathrm{m}$
- Silicon vertex detector
  $\sigma_t \sim 1.5\ \mathrm{ps}$
- Flavour tagging: info from other B
  $\epsilon_{\mathrm{tag}}(1-2\omega)^2) \sim 40\%$

$B^0_d \to D^{(*)-}\pi^+$

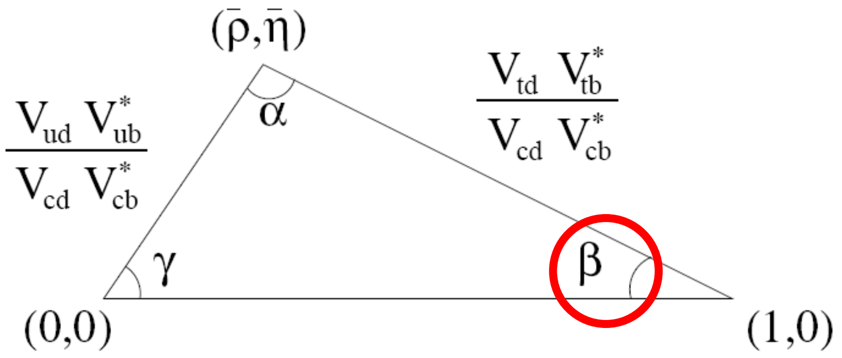


PRD 107 (2023) L091102 **new!**

$$\Delta m_d = 0.516 \pm 0.008 \pm 0.005\ \mathrm{ps}^{-1}$$
$$\tau_{B^0} = 1.499 \pm 0.013 \pm 0.005\ \mathrm{ps}$$

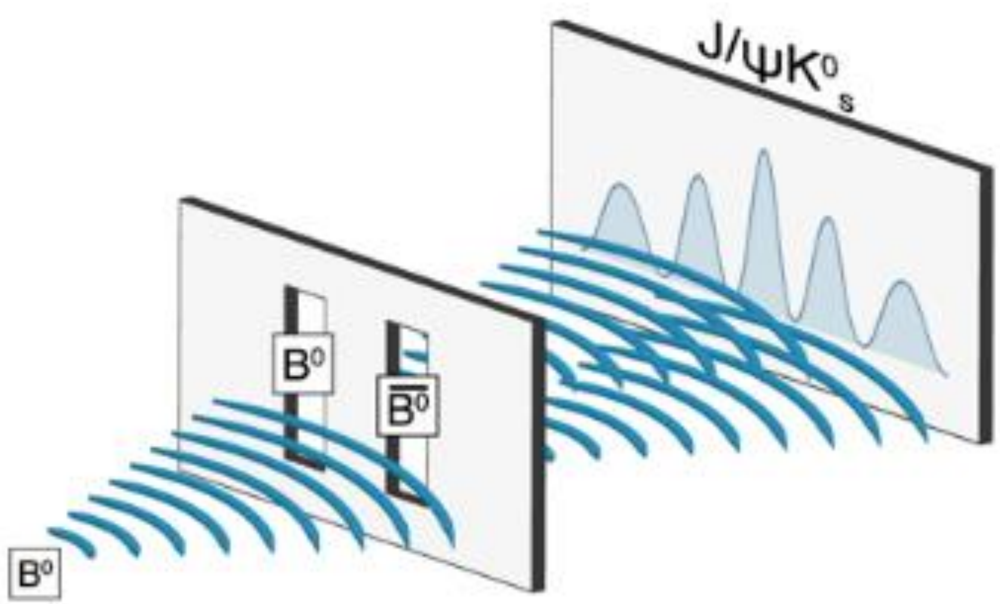
Belle: $\Delta m_d = 0.509 \pm 0.004 \pm 0.005\ \mathrm{ps}^{-1}$

B^0 CP violating phase 2β

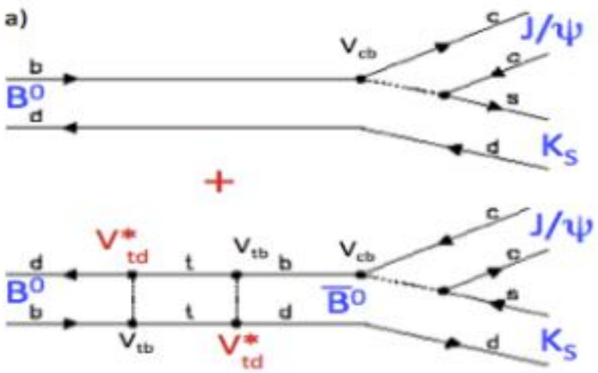


B^0 mixing phase $\phi_d = 2\beta^{\text{eff}}$

B factory flagship!



Golden mode $B^0 \to J/\psi K_S^0$

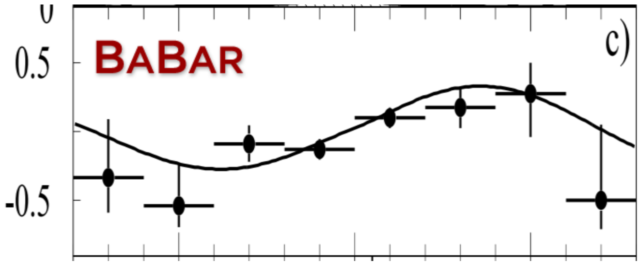


$$A_{CP}(t) \approx -\sin 2\beta \sin(\Delta m_d t)$$

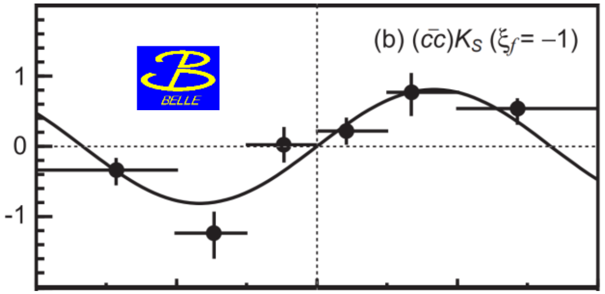
- 1981: I. I. Bigi & A. Santa pointed out the expectation of large CP violation in $B^0 \to J/\psi K_S^0$ decay
- 1987: P. Oddone proposed construction of asymmetric B factories
- 1999: BABAR and BELLE started running

History

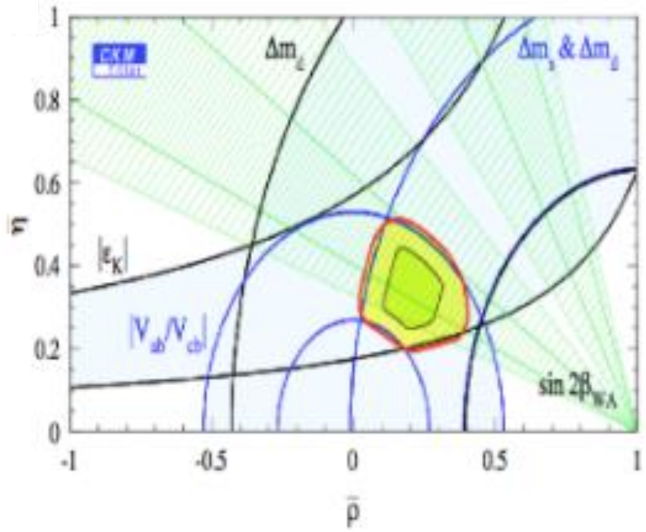
First measurements confirmed CKM prediction



Babar, PRL 87 (2001) 091801



Belle, PRL 87 (2001) 091802



Status before 2023

Belle: $\sin 2\beta = 0.67 \pm 0.02 \pm 0.01$

PRL 108 (2012) 171802

BaBar: $\sin 2\beta = 0.69 \pm 0.03 \pm 0.01$

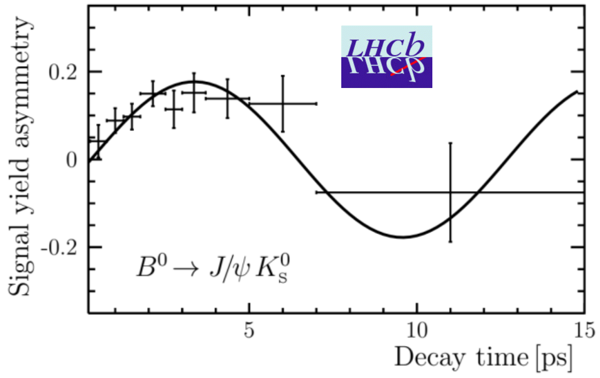
PRD 79 (2009) 072009

LHCb Run 1: $\sin 2\beta = 0.760 \pm 0.034$

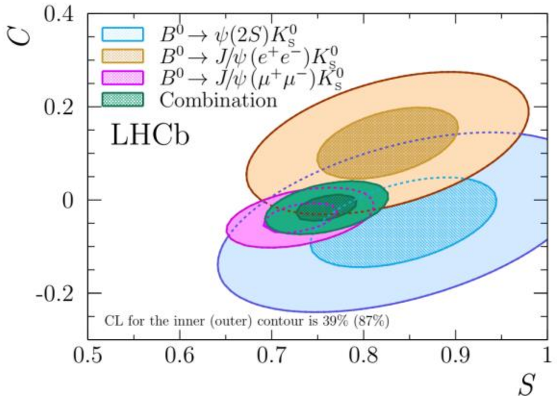
JHEP 11 (2017) 170

→ Recent update using Run2 data follows

黄金道$B^0 \to J/\psi K_S^0$



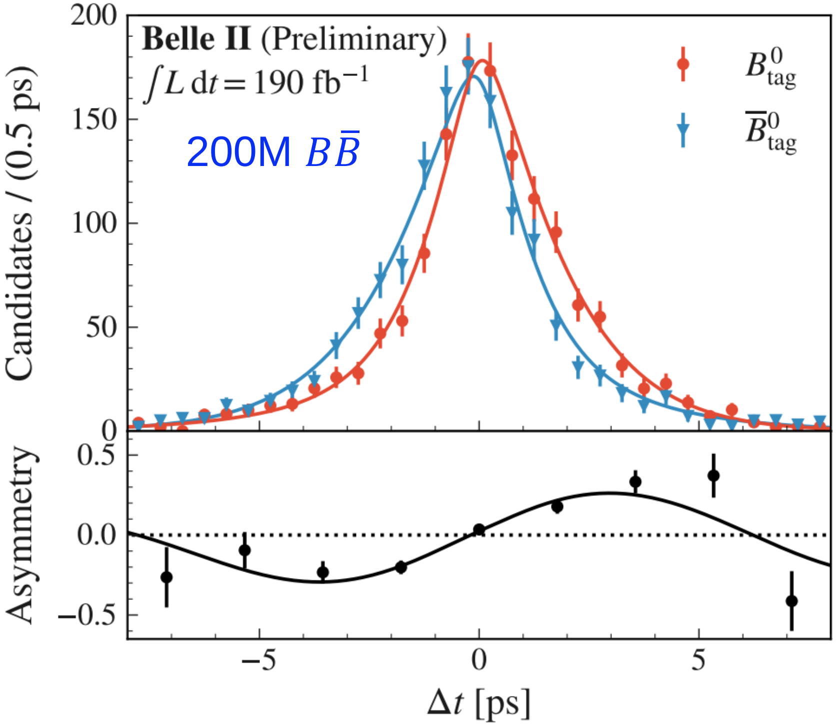
$b \to c\bar{c}s$ 过程联合



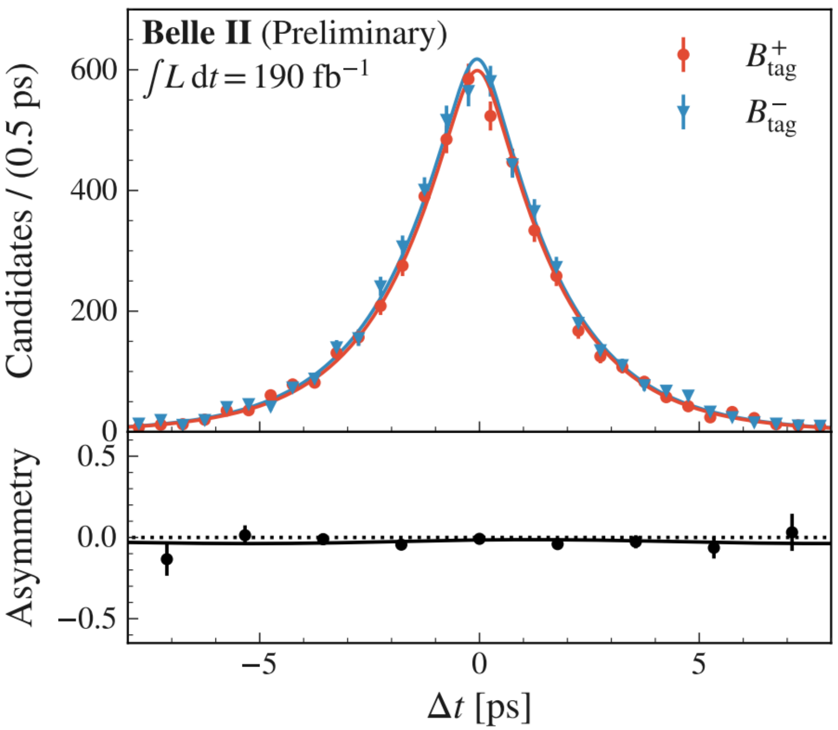
First Belle II result of sin2β

arXiv:2302.12898 **new!**

$B_d^0 \to J/\psi K_S^0$



$B^+ \to J/\psi K^+$ for test of method



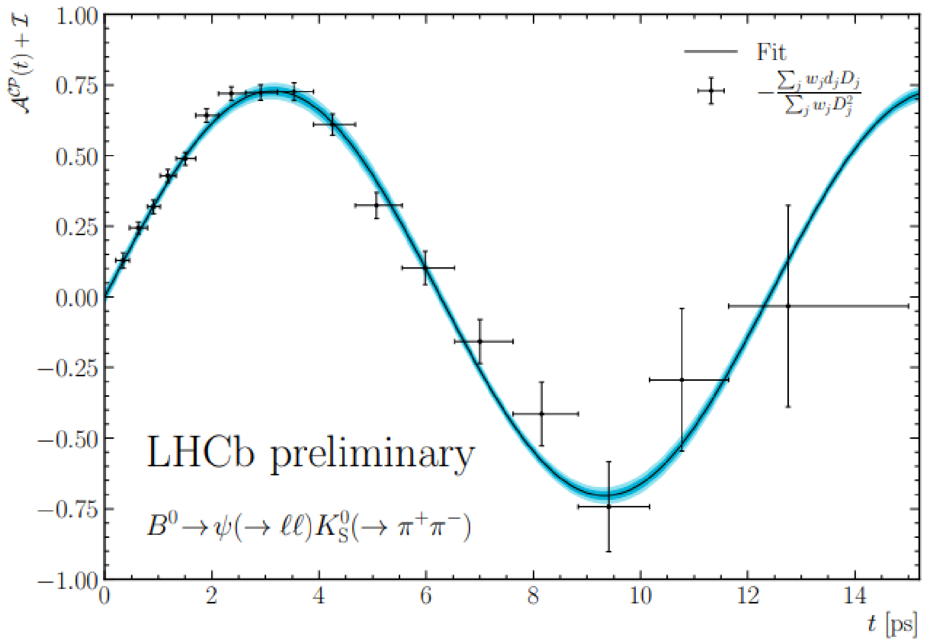
$$\mathbf{sin2\beta = 0.720 \pm 0.062 \pm 0.016, \quad C = 0.094 \pm 0.044\ ^{+0.042}_{-0.017}}$$

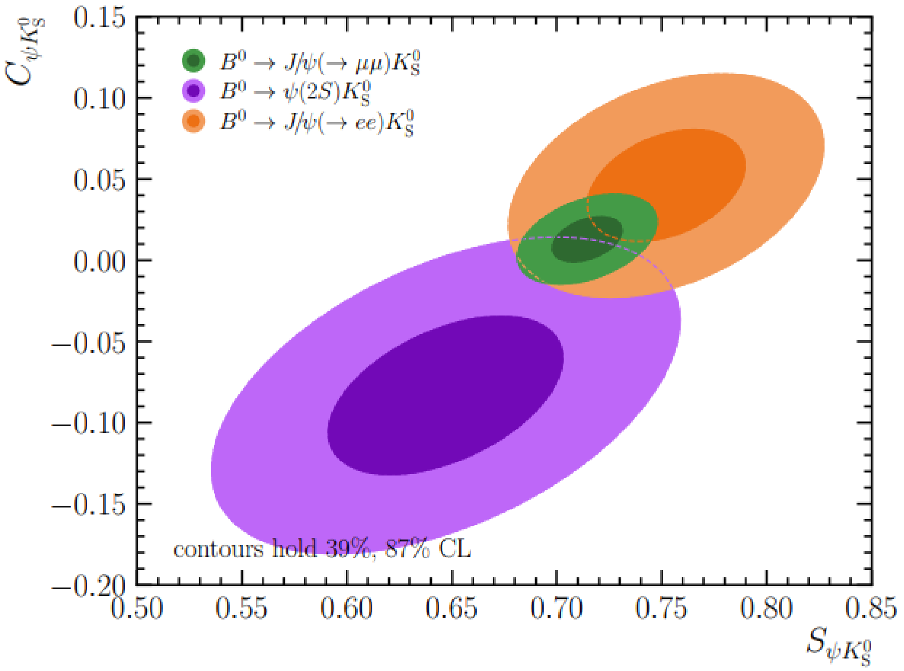
Belle: $\sin 2\beta = 0.67 \pm 0.02 \pm 0.01$ (772M $B\bar{B}$)

LHCb Run2 result of $\sin 2\beta$

LHCb-paper-2023-013

new!





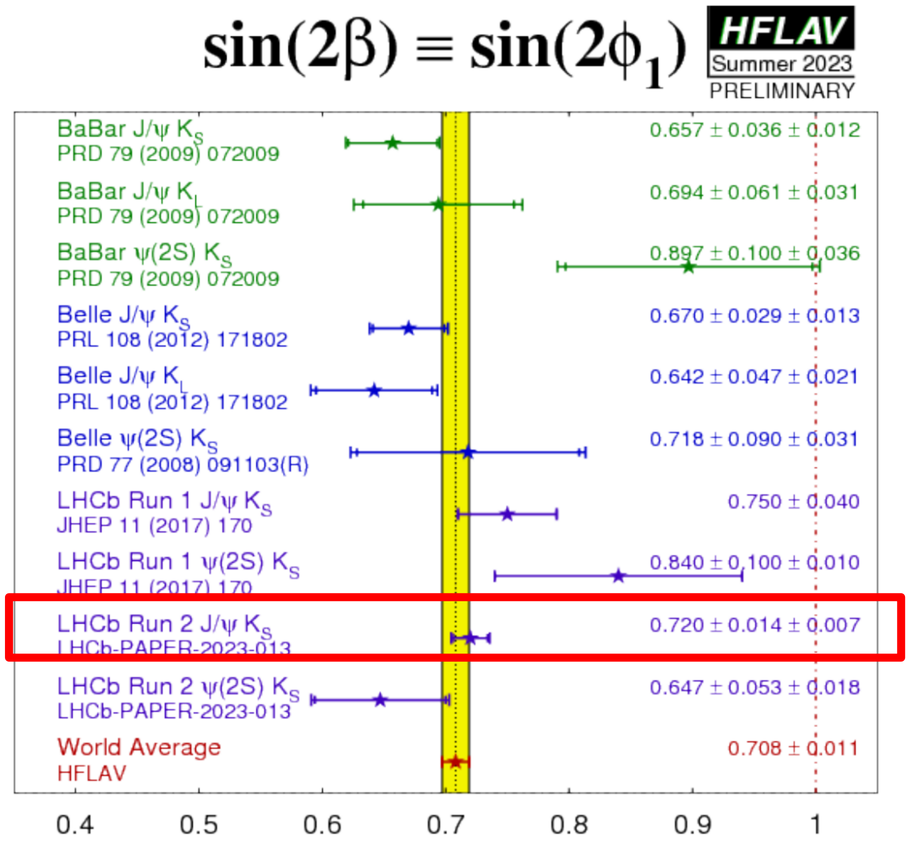
Study of $B^0 \to J/\psi(\to \mu\mu)K_S^0$, $B^0 \to J/\psi(\to ee)K_S^0$, $B^0 \to \psi(2S)K_S^0$ using Run2 data

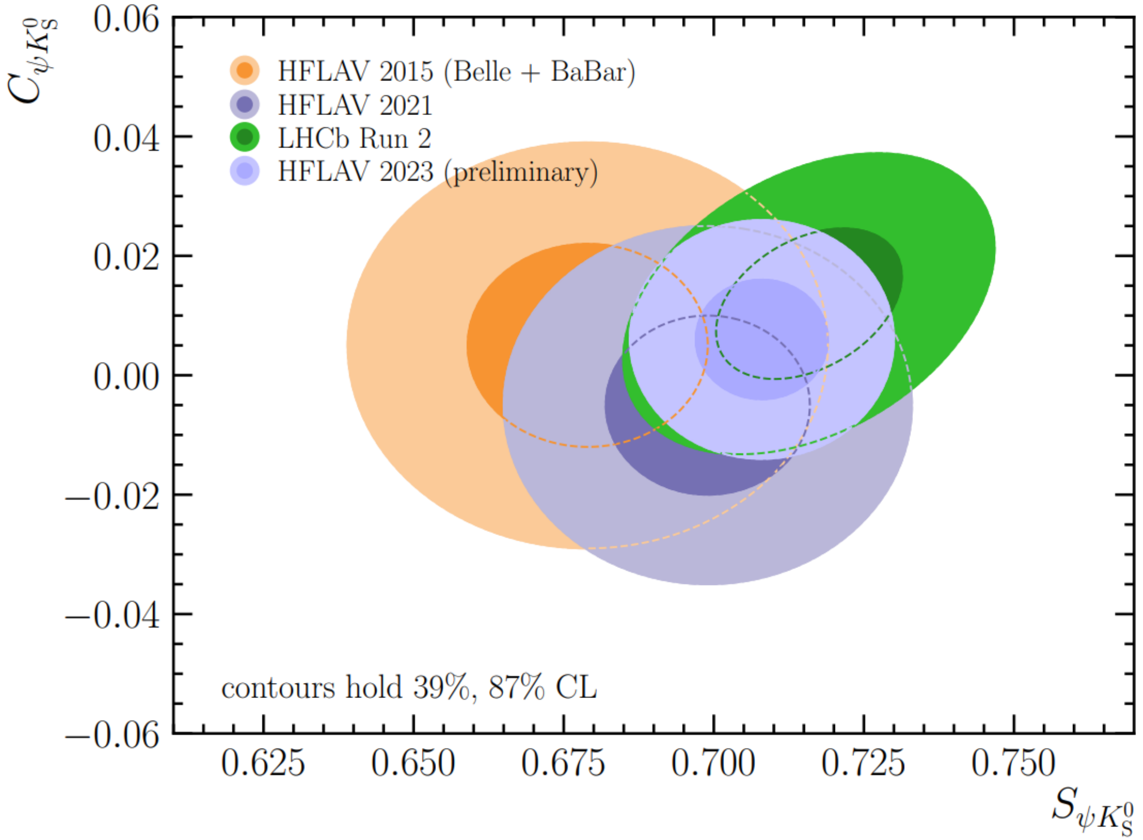
Run2: $\sin 2\beta = 0.716 \pm 0.013 \pm 0.008$, $C = 0.012 \pm 0.012 \pm 0.003$

Run1: $\sin 2\beta = 0.760 \pm 0.034$

Run1+Run2: $\sin 2\beta = 0.724 \pm 0.014$

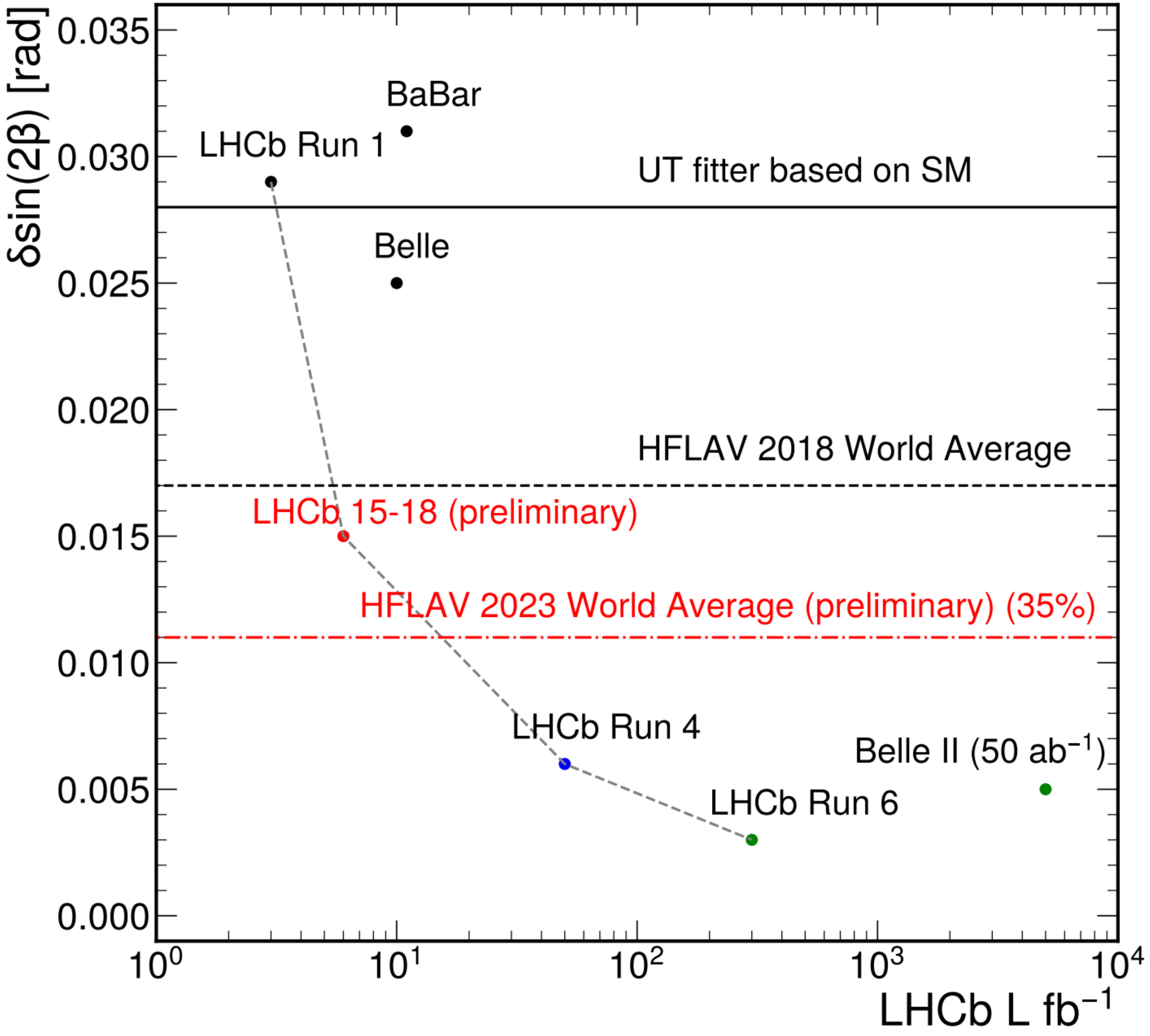
New world average of $\sin 2\beta$



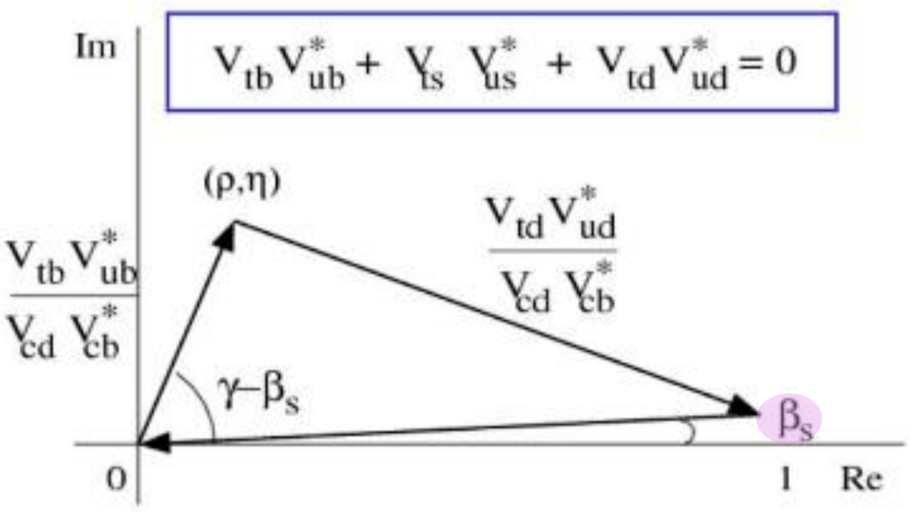


- LHCb has achieved the most precise single measurement, improving WA by 35%
- Consistent with SM prediction: $\sin 2\beta = 0.731^{+0.029}_{-0.016}$ (CKMFitter)

Projection for $\sin 2\beta$



B_s^0 CP violating phase ϕ_s

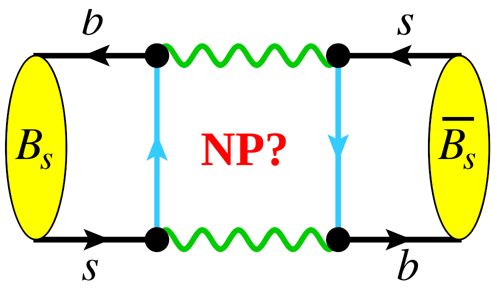


$$\phi_s = -2\beta_s^{eff}$$

B_s^0 mixing phase ϕ_s

LHCb flagship!

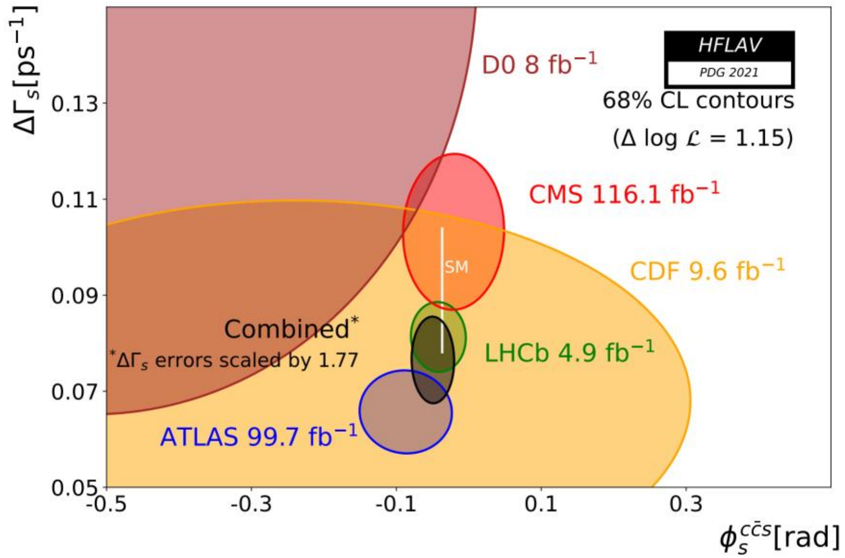
- ϕ_s: sensitive probe of NP in mixing



$$\phi_s = \phi_s^{\rm SM} + \Delta\phi^{\rm NP}$$

$$\phi_s^{\rm SM} \approx -2\beta_s = -0.037 \pm 0.001 \text{ rad (UTFit)}$$

- Major players: LHCb, ATLAS, CMS



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

$$A_{CP}(t) \propto \eta_f \sin\phi_s \sin(\Delta m_s t)$$

- CP eigenvalue of final state $\eta_f = (-1)^L$
- Angular analysis to separate CP even and odd states

Previous LHC analysis of $B_s^0 \to J/\psi K^+K^-$ used Run1+2015+2016 data

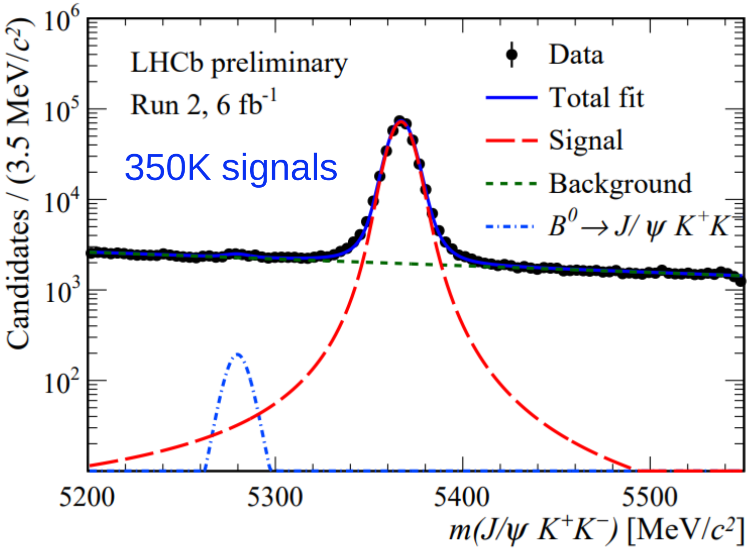
$\phi_s^{J/\psi KK} = -0.081 \pm 0.032$ rad EPJC 79 (2019) 706

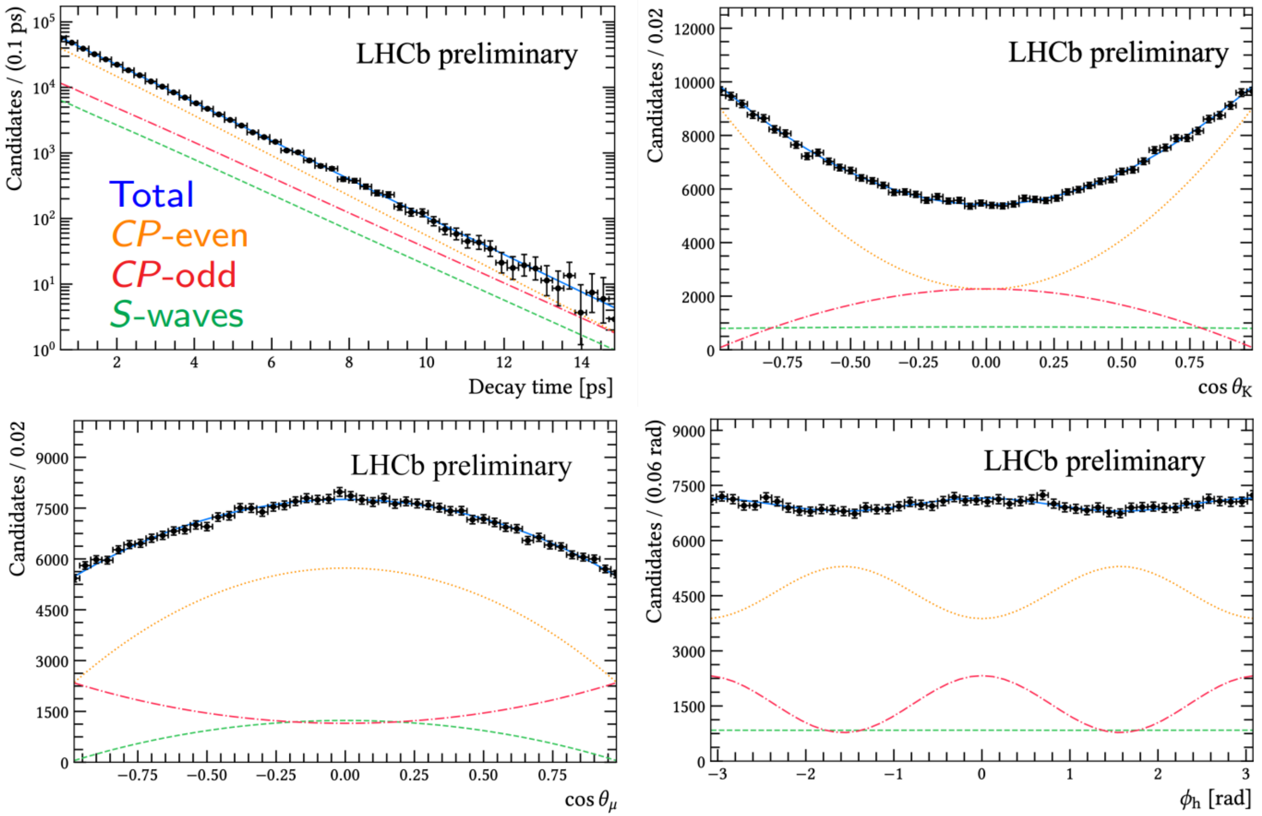
→ New result using also 2017+2018 data

Run2 $B_s^0 \to J/\psi\phi$ analysis

LHCb-paper-2023-016

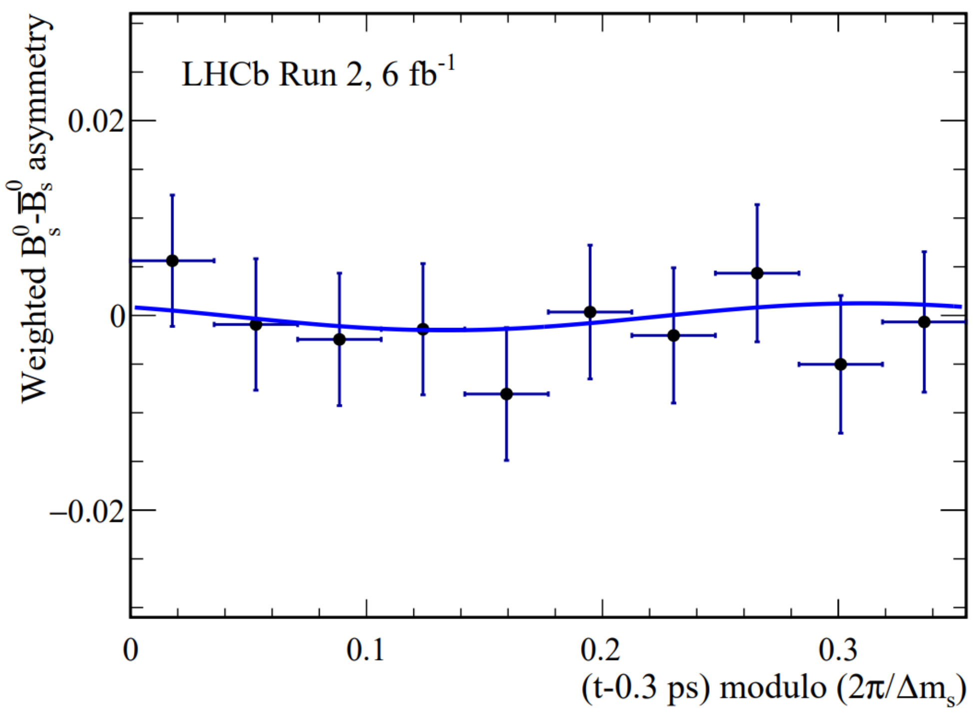
new!





LHCb Run2 result of ϕ_s

LHCb-paper-2023-016 **new!**



No sign of CP violation

Run2: $\phi_s^{J/\psi KK} = -0.039 \pm 0.022 \pm 0.006$ rad

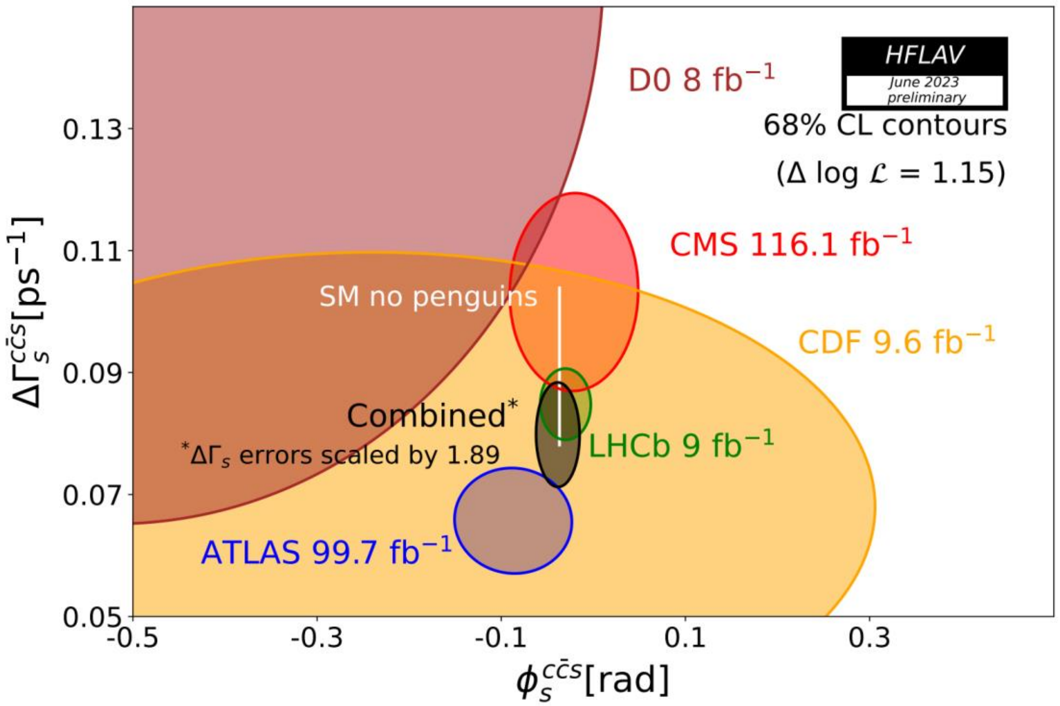
Run1: $\phi_s^{J/\psi KK} = -0.058 \pm 0.049 \pm 0.006$ rad

Run1 + Run2: $\phi_s^{J/\psi KK} = -0.044 \pm 0.020$ rad

Parameters	Values (stat. unc. only)
ϕ_s^0 [rad]	-0.034 ± 0.023
$\phi_s{}^{\parallel} - \phi_s^0$ [rad]	-0.002 ± 0.021
$\phi_s{}^{\perp} - \phi_s^0$ [rad]	$-0.001\,^{+0.020}_{-0.021}$
$\phi_s{}^{S} - \phi_s^0$ [rad]	$0.022\,^{+0.027}_{-0.026}$
$\lvert\lambda^0\rvert$	$0.969\,^{+0.025}_{-0.024}$
$\lvert\lambda^{\parallel}/\lambda^0\rvert$	$0.982\,^{+0.055}_{-0.052}$
$\lvert\lambda^{\perp}/\lambda^0\rvert$	$1.107\,^{+0.082}_{-0.076}$
$\lvert\lambda^{S}/\lambda^0\rvert$	$1.121\,^{+0.084}_{-0.078}$

No sign of polarization dependence

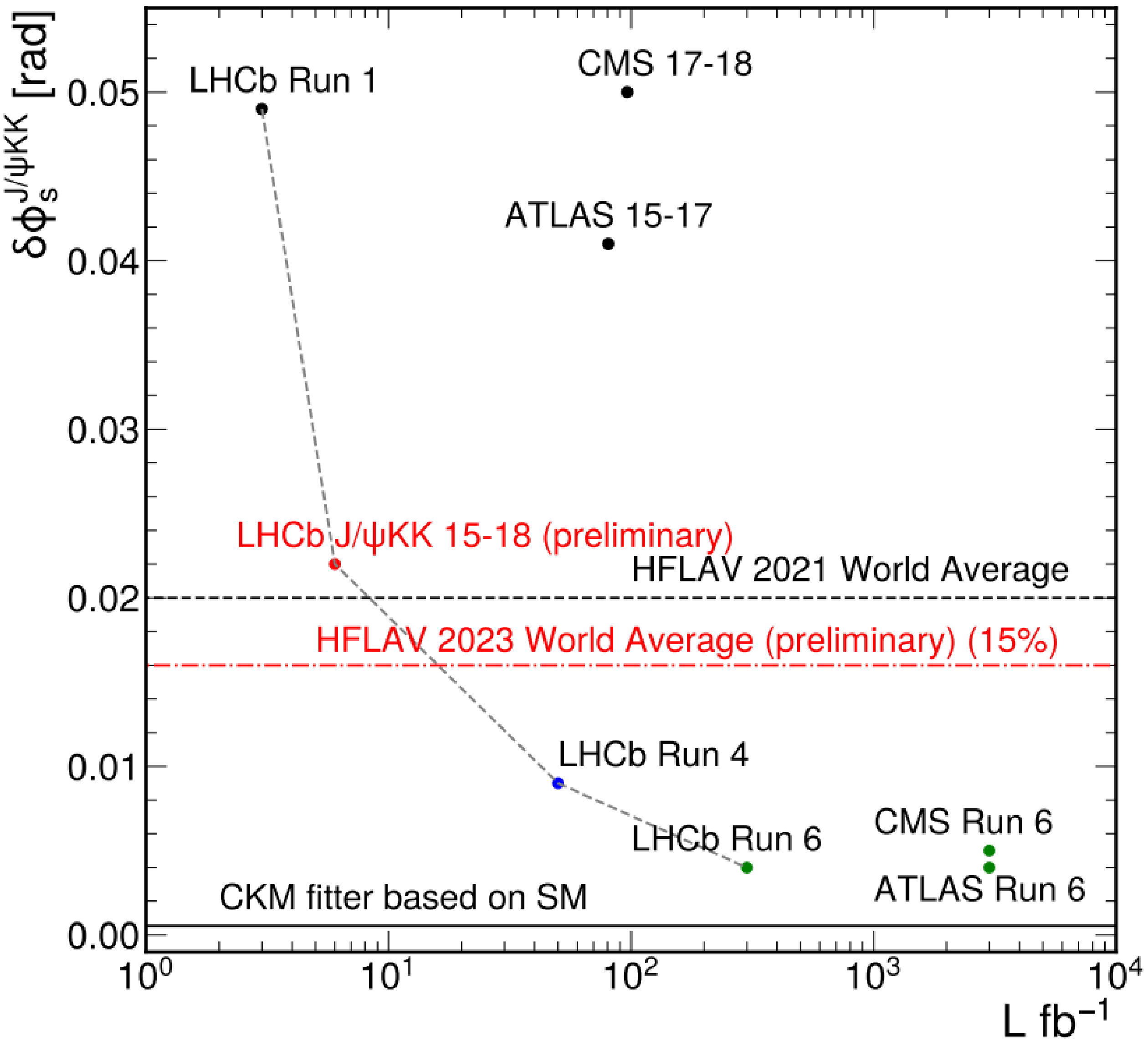
New world average of ϕ_s



- $\phi_s^{J/\psi KK} = -0.050 \pm 0.017$ rad → improved by 23%
- $\phi_s^{c\bar{c}s} = -0.039 \pm 0.016$ rad → improved by 15%
- Consistent with the prediction of Global fits assuming SM:[3]

$$\phi_s^{\text{CKMfitter}} \approx (-0.0368^{+0.0006}_{-0.0009})\ \text{rad},\ \phi_s^{\text{UTfitter}} = -0.0370 \pm 0.0010\ \text{rad}$$

Projection for ϕ_s

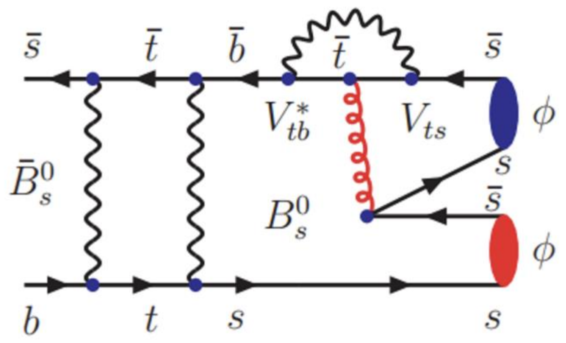


New CPV result in $B_s^0 \to \phi\phi$

arXiv:2304.06198

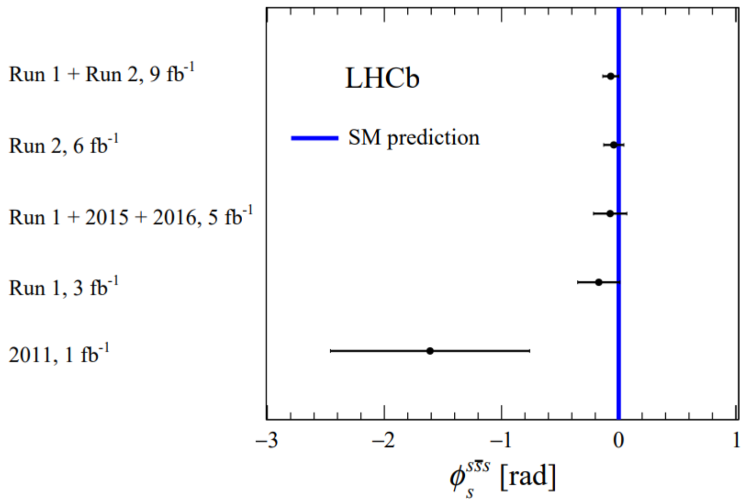
new!

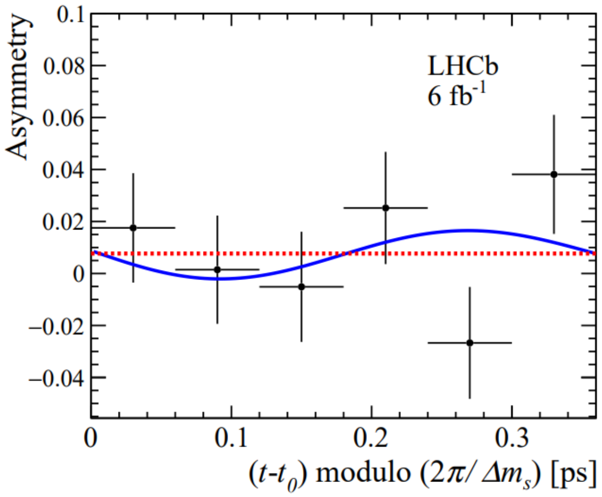
- Penguin-mediated $b \to s\bar{s}s$ decay
- Sensitive to NP in mixing and penguin diagrams
- Tiny CPV expected in SM: $\phi_s^{s\bar{s}s} = 0.00 \pm 0.02$ rad
- Time-dependent angular analysis as for $B_s^0 \to J/\psi\phi$



Previous Run1+2015+2016: $\phi_s^{s\bar{s}s} = -0.073 \pm 0.115 \pm 0.027$ rad — JHEP 12 (2019) 155

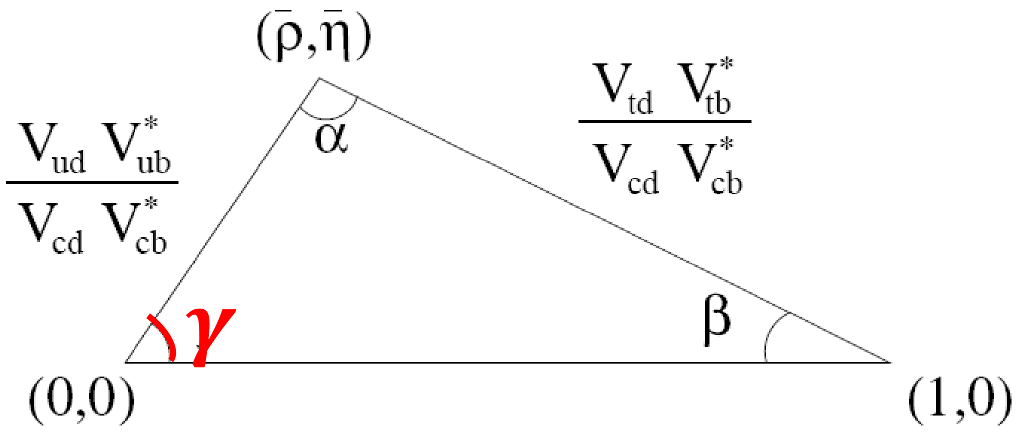
Adding 2016+2018 **Run1+Run2: $\phi_s^{s\bar{s}s} = -0.074 \pm 0.069$ rad**





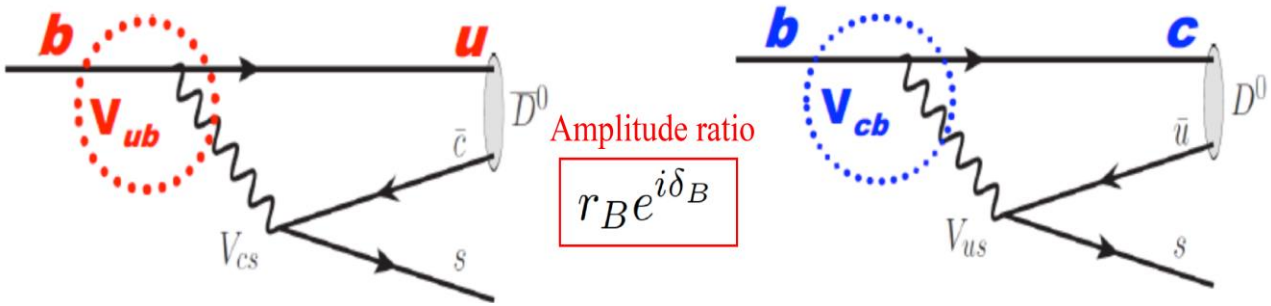
No sign of CP violation

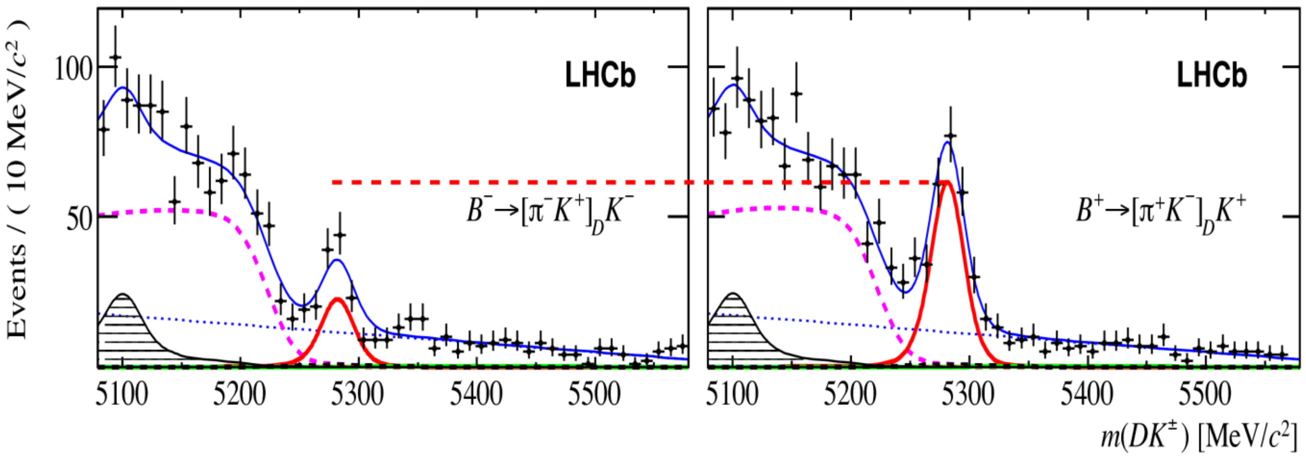
CKM angle γ



γ measurement methods

- **Measure γ through b → u and b → c interference in $B \to Dh$ decays, which leads to direct CP violation.**





- **Can use many B decay modes**
  - $B^+ \to Dh^+, B^+ \to D^*h^+, B^+ \to DK^{*+}, B^+ \to Dh^+\pi^+\pi^-$
  - $B^0 \to DK^{*0}, B^0 \to D^\mp\pi^\pm$
  - $B_s^+ \to D_s^\mp K^\pm, B_s^+ \to D_s^\mp K^\pm\pi^+\pi^-$

- **And many D^0 decay modes**
  - 2-body: $D^0 \to K^+\pi^-$, $D^0 \to h^+h^-$
  - 3-body: $D^0 \to K_S^0 h^+h^-$
  - 4-body: $D^0 \to K^-\pi^+\pi^-\pi^+$, $D^0 \to K^-K^+\pi^-\pi^+$

$$\frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)} = A_{CP+} = \frac{1}{R_{CP+}} 2r_B(2F_+ - 1)\sin(\delta_B)\sin(\gamma)$$

Previous status

- **B factories each: $\sigma_\gamma \approx 15°$**

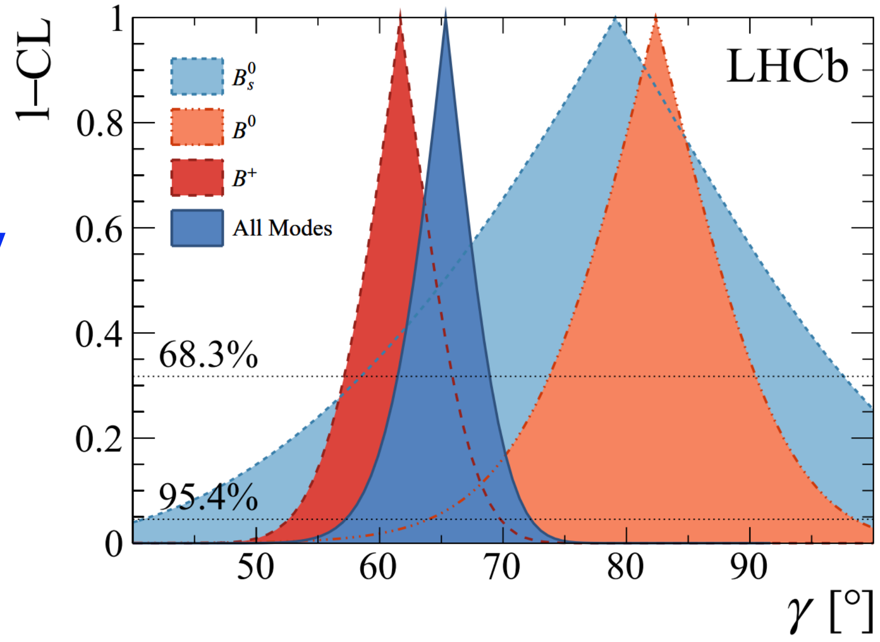
BaBar: $\gamma = (70 \pm 18)°$ PRD 87 (2015) 052 015

BELLE: $\gamma = \left(73^{+13}_{-15}\right)°$ arXiv: 1301.2033

- **LHCb previous combination of many decay modes: $\sigma_\gamma \approx 4°$**

LHCb: $\gamma = \left(65.4^{+3.8}_{-4.2}\right)^{\circ}$ JHEP 12 (2021) 141

An updated combination recently performed to include several new measurements



New γ results with $B \to Dh$ decays

γ in $B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$ arXiv:2209.03692

$$\Gamma_{B^{\pm}\to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]K^{\pm}} \propto r_{K3\pi}^2 + (r_B^K)^2 + 2r_{K3\pi}r_B^K R_{K3\pi}\cos(\delta_B^K + \delta_{K3\pi} \pm \gamma)$$
$$\Gamma_{B^{\pm}\to D[K^{\pm}\pi^{\mp}\pi^{\mp}\pi^{\pm}]K^{\pm}} \propto 1 + (r_{K3\pi}^2 r_B^K)^2 + 2r_{K3\pi}r_B^K R_{K3\pi}\cos(\delta_B^K - \delta_{K3\pi} \pm \gamma),$$

- Decay rates measured in bins of $K3\pi$ phase space
- Bin-by-bin strong-phase difference $\delta_{K3\pi}$ and coherence factor $R_{K3\pi}$ are measured by CLEO-c and BESIII in quantum-correlated $D\overline{D}$ decays

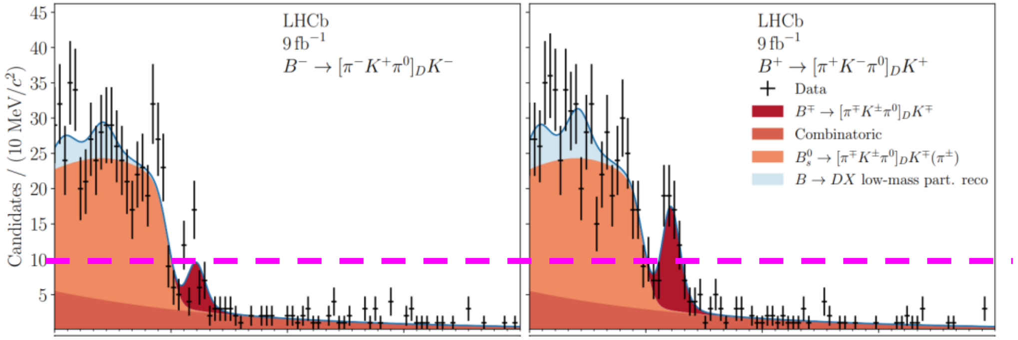
$$\gamma = (54.8^{+3.8}_{-5.8}{}^{+0.6}_{-0.6}{}^{+6.7}_{-4.3})^{\circ}$$

Uncertainty of external inputs dominates!

γ in $B^{\pm} \to D[h^{\pm}h'^{\mp}\pi^0]h^{\pm}$ JHEP 07 (2022) 099

- Evidence for CPV in $B^{\pm} \to [\pi^{\pm}K^{\mp}\pi^0]_D K^{\pm}$

$$\gamma = (56^{+24}_{-19})^{\circ}$$



γ in $B^{\pm} \to D[K^+K^-\pi^+\pi^-]h^{\pm}$

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

arXiv:2301.10328 **new!**

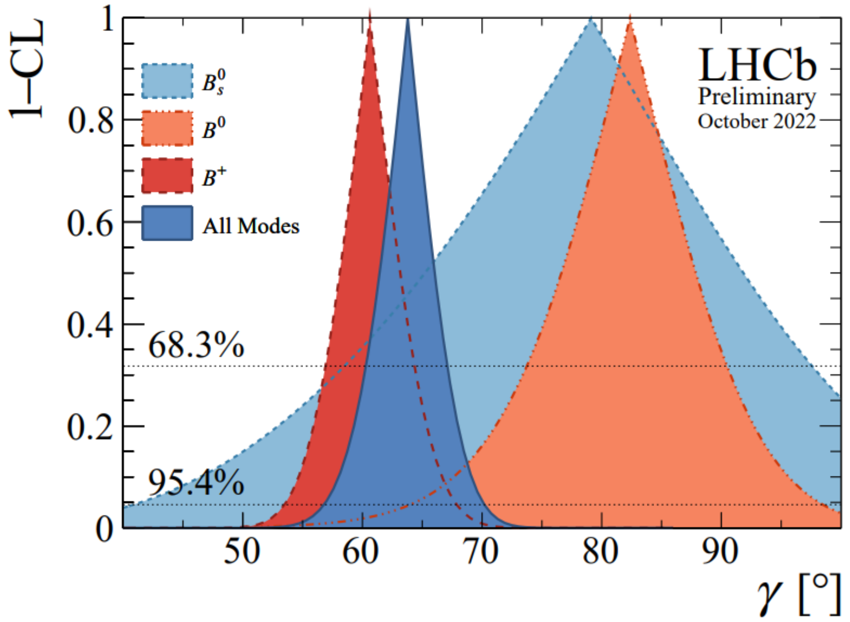
New γ combination

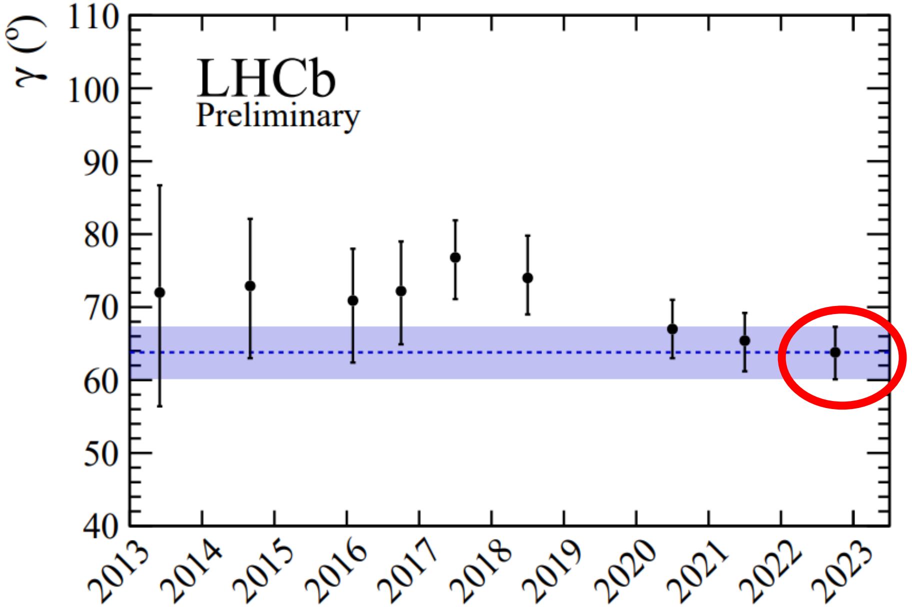
LHCb-CONF-2022-002 **new!**

Determine γ from CP violation measurements in $B \to Dh$

- Many B and D decay modes
- D decay amplitudes and strong phases from CLEO-c and BESIII

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





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

10% improvement

CKMFitter prediction: $\gamma = \left(65.5^{+1.1}_{-2.7}\right)^\circ$

γ measurement at Belle II

Model-independent analysis of $B^{\pm} \to D[K_S^0 h^+ h^-]h^{\pm}$

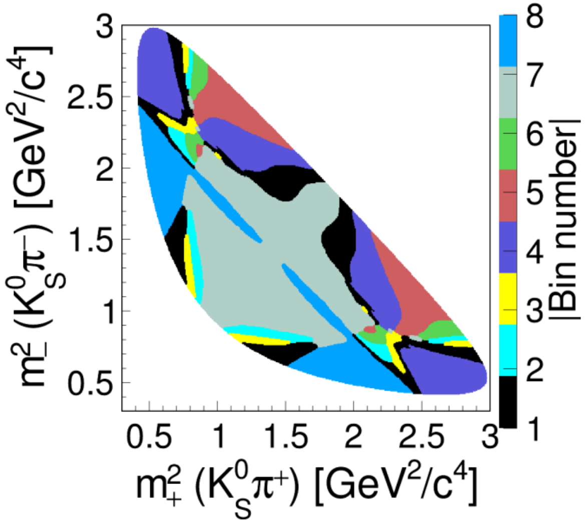
- Data from Belle (711 fb^{-1}) and Belle II (128 fb^{-1})
- Bin-by-bin D^0 strong-phase parameter c_i and s_i from CLEO-c and BESIII

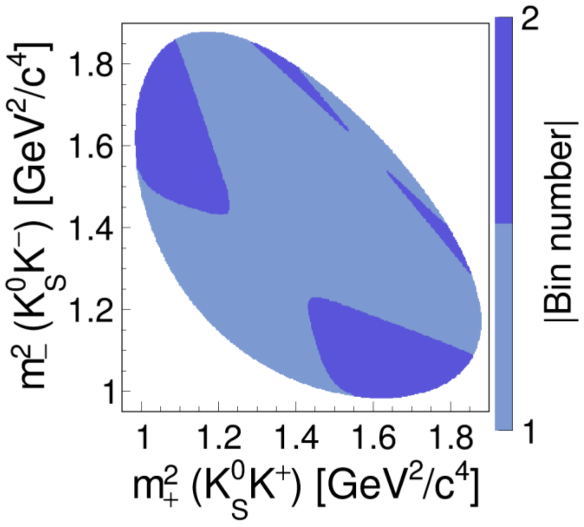
$$N_i(B^0) = h^{B^0}\left[F_{-i} + (x_+^2 + y_+^2)F_i + 2\kappa\sqrt{F_i F_{-i}}(x_+ c_i - y_+ s_i)\right],$$
$$N_i(\overline{B}^0) = h^{\overline{B}^0}\left[F_i + (x_-^2 + y_-^2)F_{-i} + 2\kappa\sqrt{F_i F_{-i}}(x_- c_i + y_- s_i)\right],$$

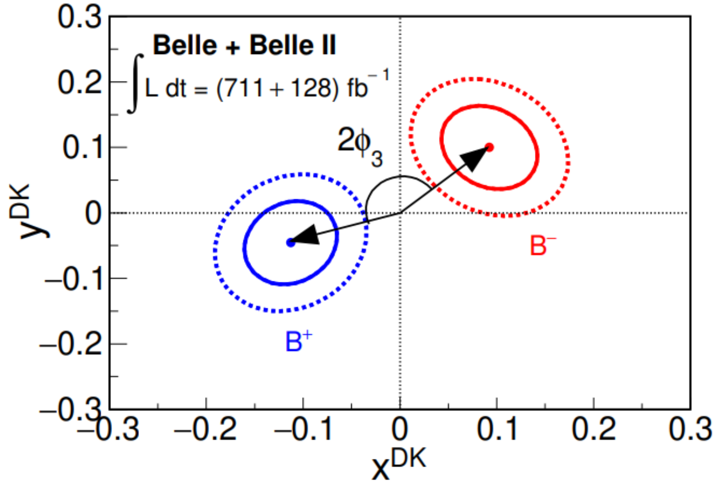
$$x_{\pm} \equiv r_{B^0}\cos(\delta_{B^0} \pm \gamma),$$
$$y_{\pm} \equiv r_{B^0}\sin(\delta_{B^0} \pm \gamma).$$

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

JHEP 02 (2022) 063





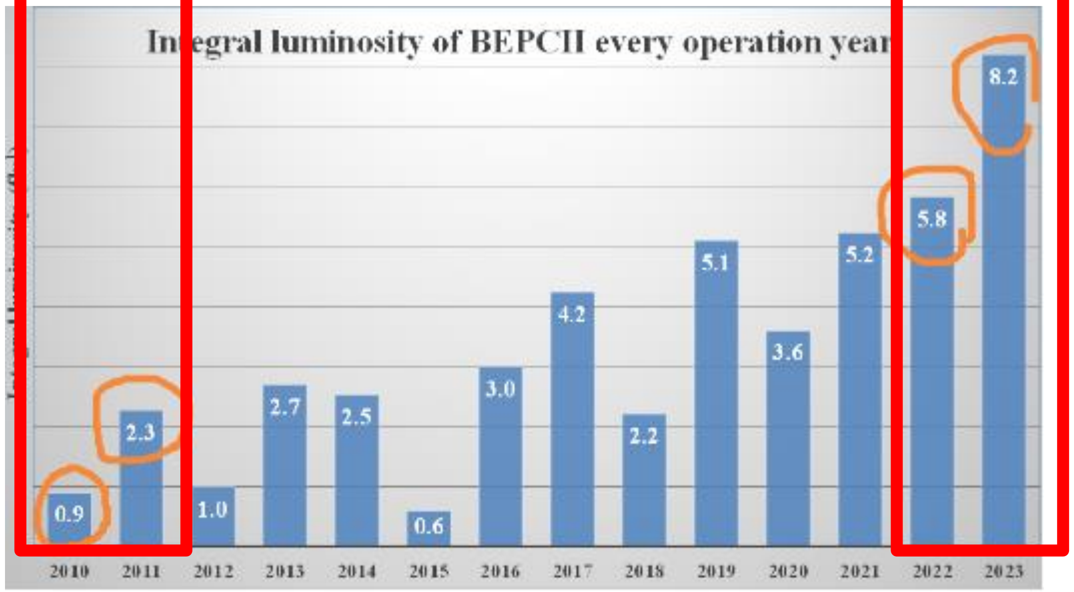


D^0 parameters from BESIII

mode	Para.	Ref.
$D^0 \to K_S^0\pi^+\pi^-$	Strong phase	PRD 101 (2020) 112002
$D^0 \to K_S^0K^+K^-$	Strong phase	PRD 102 (2020) 052008
$D^0 \to K^+\pi^-$	Strong phase	EPJC 82 (2022) 1009
$D^0 \to K^-\pi^+\pi^+\pi^-$	Strong phase	arXiv:2103.05988
$D^0 \to K^+K^-\pi^+\pi^-$	Strong phase	arXiv:2212.06489
$D^0 \to K^+K^-\pi^+\pi^-$	CP-even fraction	arXiv:2305.03975
$D^0 \to \pi^+\pi^-\pi^+\pi^-$	CP-even fraction	arXiv:2208.10098

Used for D parameters

To be used



- Current BESIII measurements of D^0 strong-phase parameters used 3 fb^{-1} of $\psi(3770) \to D\bar{D}$ data
- BESIII will accumulate 20 fb^{-1} of $\psi(3770) \to D\bar{D}$ data this year
- Significant improvements in D^0 decay parameters are expected

Summary

- LHCb has achieved unprecedented precision in study of beauty CP violation, pushing flavour physics into a new era

- Belle II is ramping up and producing interesting physics results