CP violation within the Standard Model and Beyond at Belle II and LHCb

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IPHC - CNRS, Strasbourg

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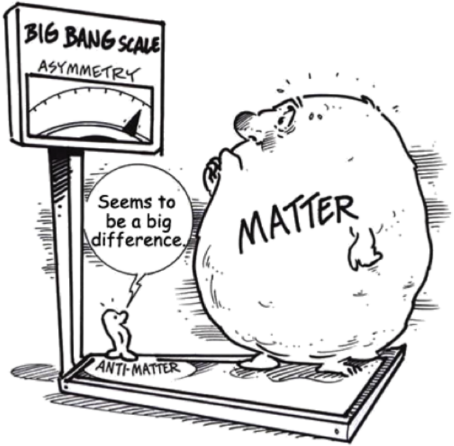
26ème Congrès Général de la SFP

The need for CP violation

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

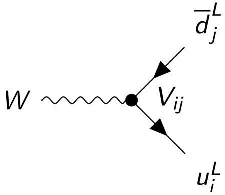
- CP violation is one of the Sakharov conditions needed to explain the matter-antimatter asymmetry in our universe
- In the Standard model the only currently known source of CP violation comes from the Kobayashi-Maskawa mechanism in the quark sector
- Orders of magnitude inferior to what is needed to explain observed matter-antimatter asymmetry
  - What about CPV in neutrino sector? See other talks
  - Room for New Physics!



CP violation in the quark sector of the Standard Model

- In the Standard Model the Higgs mechanism gives mass to quarks and fermions through the Yukawa couplings
- Eigenstates of the mass and weak interactions are not the same: after all possible field redefinition a 3x3 unitary matrix remains in the charged current interactions

$$\mathcal{L}_{cc}^{quarks} = \frac{g}{2\sqrt{2}} \sum_{ij} \bar{u}_i^L \gamma^\mu W_\mu^+ V_{ij}^{CKM} d_j^L + h.c.$$



CKM matrix

- 3 angles + 1 CP violating phase
- Tree-level coupling between up and down-type quarks

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

50 years since the Kobayashi-Maskawa paper

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

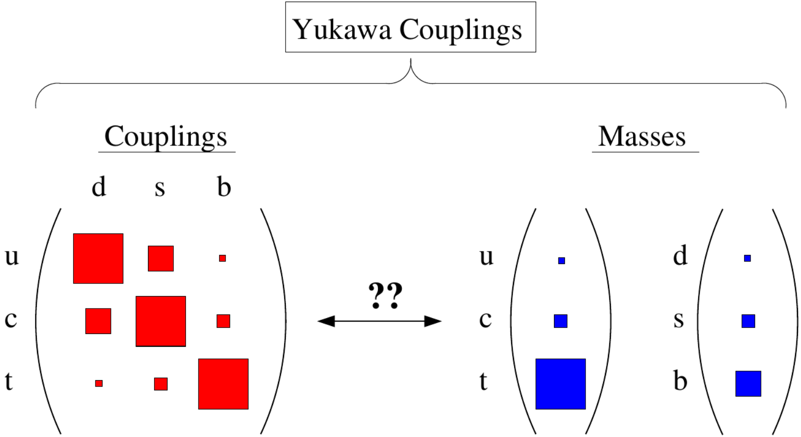
In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

Next we consider a 6-plet model, another interesting model of CP-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\text{weak}}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}.$$

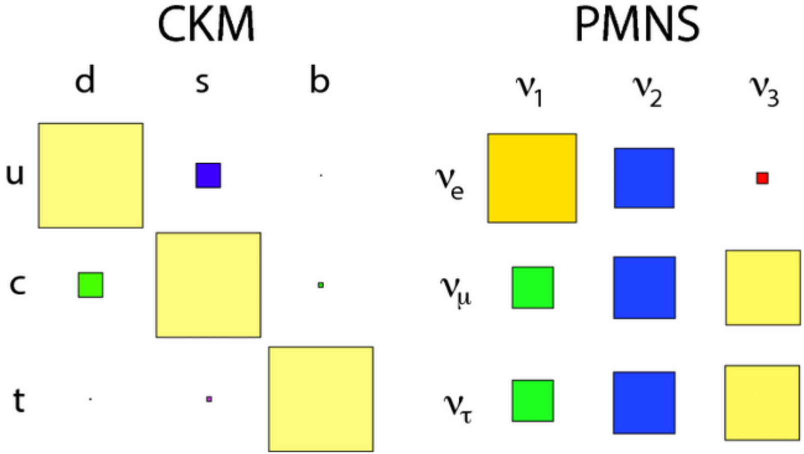
Predict third quark family one year before the discovery of the charm quark!

Strong hierarchy in couplings

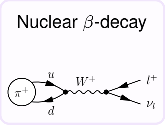


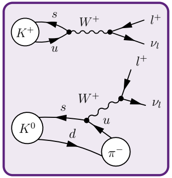
Sign of an underlying mechanism?

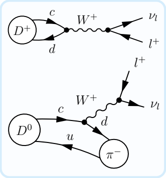
Quite different wrt neutrino sector

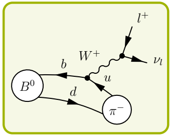


Determining the elements of the CMK matrix

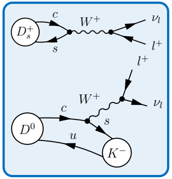


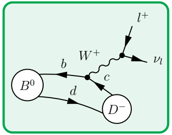


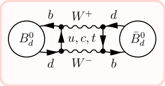


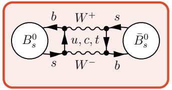


$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$





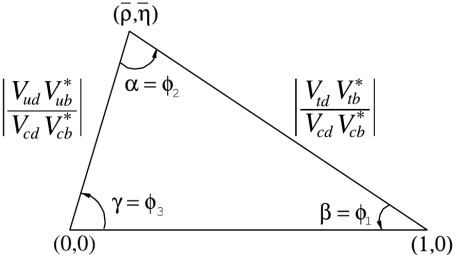


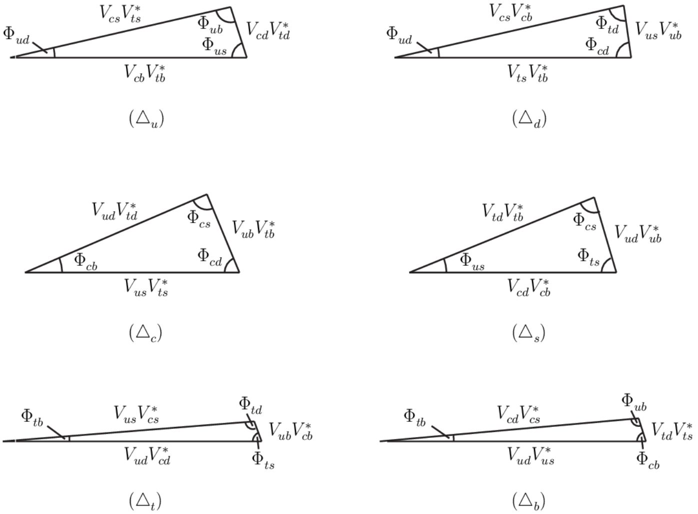


The unitarity triangles

From the unitaryty of the CKM matrix 6 null sums: triangles in complex planes

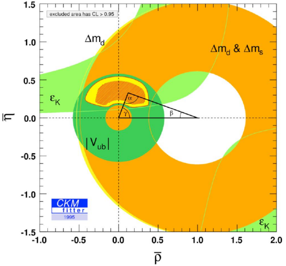
One particularly relevant for *B* decays:





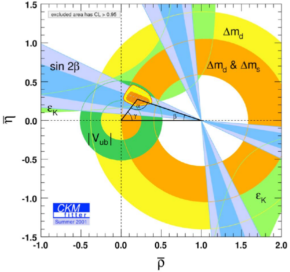
Evolution of the constraints on the unitarity triangle

1995



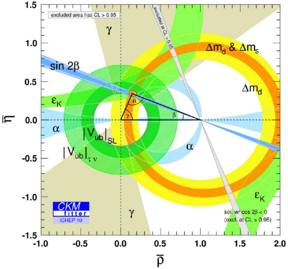
after LEP

2001



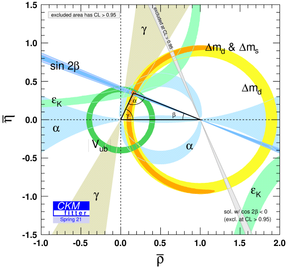
B-factories at work

2010



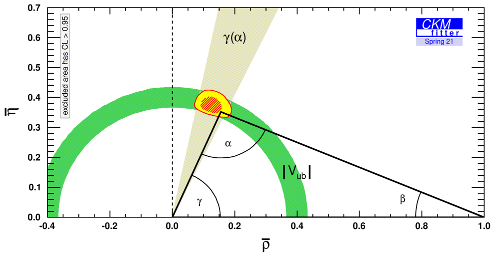
legacy B-factory + CDF@Tevatron

Today

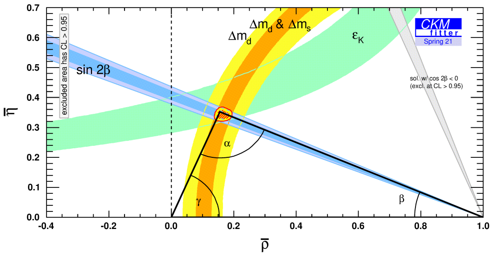


After 10 years of LHCb

Tree vs loop

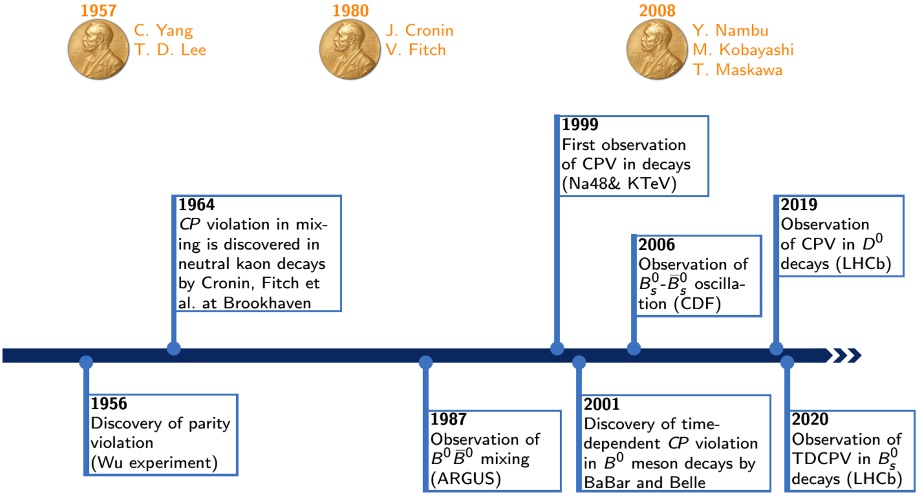


γ(α)
α
γ
β
|V_ub|
excluded area has CL > 0.95
CKM fitter
Spring 21
$\bar{\eta}$
$\bar{\rho}$



Δm_d & Δm_s
Δm_d
ε_K
sin 2β
α
γ
β
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
excluded area has CL > 0.95
CKM fitter
Spring 21
$\bar{\eta}$
$\bar{\rho}$

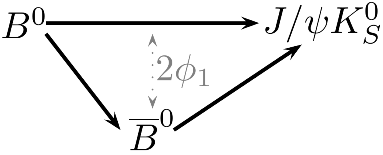
History of CP violation in the quark sector



Where to observe CP violation

CP violation caused by a complex phase: quantum interference needed to observe it

- Interference between different diagrams (e.g. tree and loop)
- For neutral mesons possible interference between direct decay and mixing



Types of CP violation

CP violation in mixing

Unequal transition probabilities between flavour eigenstates

$$P(B \to \overline{B}) \neq P(\overline{B} \to B)$$

CP violation in decay

Unequal CP-conjugate decay rates

$$\Gamma(B \to f) \neq \Gamma(\overline{B} \to \bar{f})$$

CP violation in interference between mixing and decay

Time-dependent or time-integrated difference of decay rates of initial flavour eigenstates

$$\Gamma(B_{(\rightsquigarrow \overline{B})} \to f) \neq \Gamma(\overline{B}_{(\rightsquigarrow B)} \to f)$$

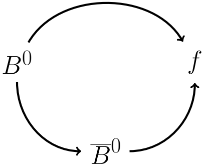
Extract CP violation parameters

CP violation parameters enter the decay rate to specific final states

$$\Gamma_{B^0\to f} = \frac{1}{2} e^{-\Gamma t} |A_f|^2 (1 + |\lambda_f|^2) \left\{ \cosh\left(\frac{\Delta\Gamma}{2} t\right) + A_{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma}{2} t\right) + C \cos(\Delta m\, t) - S \sin(\Delta m\, t) \right\}$$

They can be extracted by measuring asymmetries (time integrated or time dependent)

$$\mathcal{A}_{CP}(t) = \frac{\Gamma_{B^0\to f} - \Gamma_{\overline{B}^0\to f}}{\Gamma_{B^0\to f} + \Gamma_{\overline{B}^0\to f}} \propto S \sin(\Delta m\, t) - C \cos(\Delta m\, t)$$



Typical performance drivers

[I. Ripp-Baudot Moriond QCD '23]

- Large integrated luminosity
- Large σ(bb)
- Good detector acceptance
- Good trigger efficiency
- Good reconstruction efficiency

- Different B species: B^0, B_s^0, baryons

- Good flavour tagging (B or anti-B)

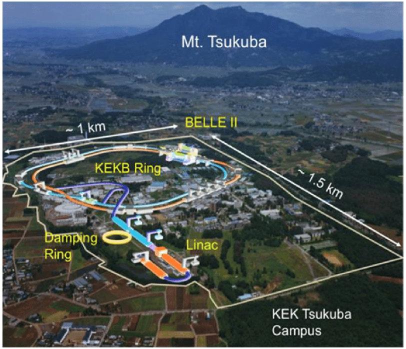
$$\mathcal{A}_{CP}(t) = \frac{N(B^0(t) \to f_{CP}) - N(\bar{B}^0(t) \to f_{CP})}{N(B^0(t) \to f_{CP}) + N(\bar{B}^0(t) \to f_{CP})}$$

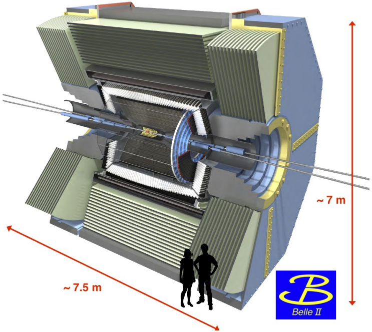
- Large B boost
- Good vertex resolution

- Good particle identification, K/π separation.
- Reconstruction of γ, π^0, η, K_S^0
- Presence of ν: good hermeticity
- Good S/N (physics, combinatorial, pile-up, beam bkg)

Belle II @ SuperKEKB

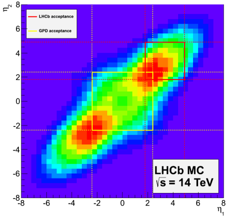
- General-purpose detector successor of Belle @ KEKB
- Beams of electrons and positrons with asymmetric energy (7 and 4 GeV): boost $\beta\gamma = 0.28$
- Collisions at the $\Upsilon(4S)$ mass (10.58 GeV)

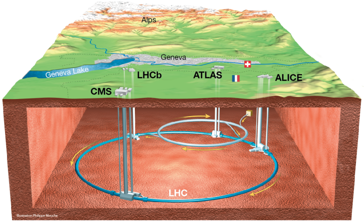


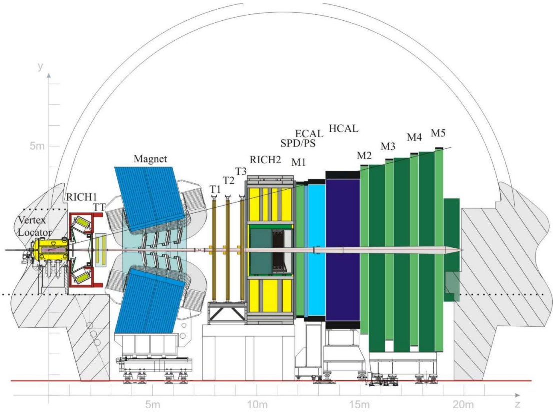


LHCb @ LHC

- General purpose detector in the forward region
- proton-proton collisions at $\sqrt{s} = 7 - 14$ TeV

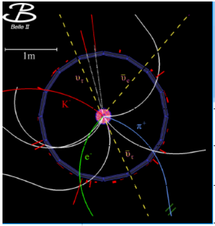


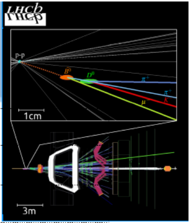




Belle II vs LHCb

[I. Ripp-Baudot Moriond QCD '23]



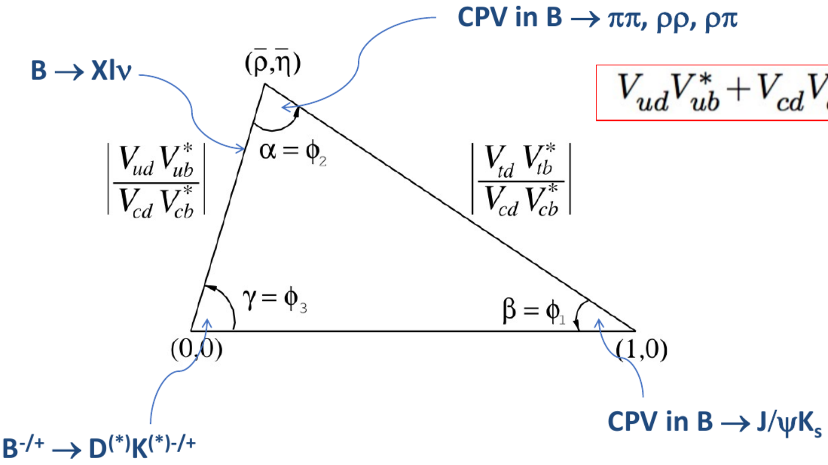


Belle II	&	LHCb
2019	Start	2011
428 (target: 50 000)	Current dataset (fb^{-1})	9 (target: 300)
4.7 (target: 60)	Instantaneous lumi. ($\times 10^{34}$ cm^{-2} s^{-1})	0.04 (target: 1.5)
1	bb cross-section (nb)	500 000 (@13 TeV) 😀
Good 😀	Selection efficiency	0.3-acceptance & trigger & background
B^0, few B_s^0 in the future?	B species	all: B^0, B_s^0, B_c^+, B-baryons 😀
130	B boost (μm)	10 000 😀
> 33% 😀	B-flavour tagging power	typically 5%
• Unique measurements: D* polarisation, inclusive measurements, … 😀 • Excellent τ physics capability • Good reco of γ, π^0, η, K_S^0	Collision setup	Hadronisation and large occupancy

➛ **Good complementarity between Belle II and LHCb**

Recent results

CKM angles



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

Toward CKM angle α @ Belle II

$\alpha = arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$ less precisely known angle, may limit the global testing power of CKM fits.

$$\alpha[^\circ] = 85.2\ {}^{+\,4.8}_{-\,4.3}$$

HFLAV

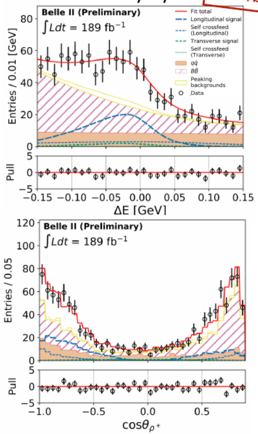
Determined using $B \to \rho\rho$ and $B \to \pi\pi$ isospin analyses: combine information from BF and A_{CP} to reduce impact of hadronic uncertainties — non-perturbative QCD.

Unique Belle II capability to study in consistent way all $B \to \rho\rho$ and $B \to \pi\pi$ channels.

$B \to \rho\rho$ measurements require angular analysis:

- Winter 2022 $B^+ \to \rho^+\rho^0$ result: arxiv.org/abs/2206.12362;
- result for $B^0 \to \rho^+\rho^-$.

$B^0 \to \rho^+\rho^-$ 189 fb-1



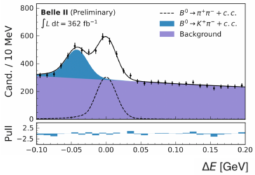
$\Delta E = E^* - E^*_{beam}$

$\mathscr{B} = (26.7 \pm 2.8 \pm 2.8) \times 10^{-6}$
$f_L = 0.956 \pm 0.035 \pm 0.033$

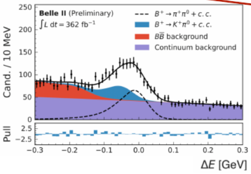
arxiv.org/abs/2208.03554

Toward CKM angle α @ Belle II

$B^0 \to \pi^+\pi^-$



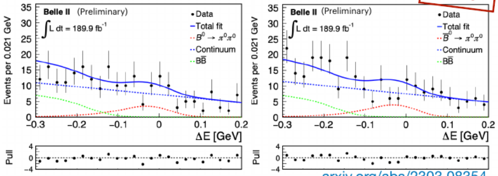
$B^+ \to \pi^+\pi^0$ 362 fb-1



$$\mathcal{B}(\pi^+\pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$$
$$\mathcal{B}(\pi^+\pi^0) = (5.10 \pm 0.29 \pm 0.32) \times 10^{-6}$$
$$\mathcal{A}(\pi^+\pi^0) = -0.081 \pm 0.54 \pm 0.008$$

$B^0 \to \pi^0\pi^0$ 189 fb-1

First $B^0 \to \pi^0\pi^0$ measurement at Belle II:
- rare, small *BF* (10^{-6}),
- only photons in the final state — dominated by signal-like background,
- large theoretical uncertainties.



arxiv.org/abs/2303.08354

Achieved Belle *BF* precision using only 1/3 of data.

$$\mathcal{B}(\pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$$
$$\mathcal{A}(\pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07$$

Preliminary Belle II results on par with best performance from Belle/Babar.

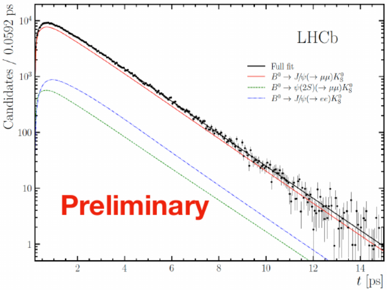
CKM angle β @ LHCb

$$B^0 \to \psi K^0_S$$

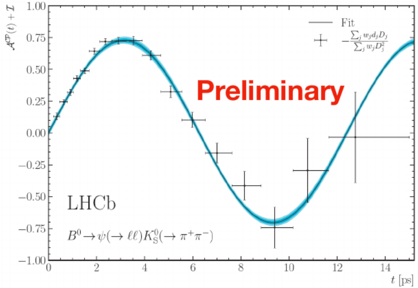
NEW!!

LHCb-PAPER-2023-013
HFLAV

- Γ_d, Δm_d & Spline coefficients constrained to their know values.
- FT calibration parameters + $\mathcal{A}_{prod}$ constrained to $B^0 \to J/\psi K^*$.



$\mathcal{I}$: Small offset from 0, due to production and FT asymmetries



☑ Precision higher than current average
☑ In agreement with current average.

Full Run2 Results

$$S_{\psi K^0_S} = 0.716 \pm 0.013 \pm 0.008$$
$$C_{\psi K^0_S} = 0.012 \pm 0.012 \pm 0.003$$

Previous HFLAV

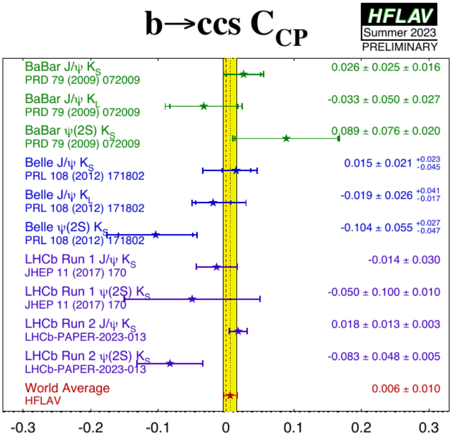
$$S = 0.699 \pm 0.017$$
$$C = -0.005 \pm 0.015$$

[R.A.R. Fernandez FPCP ’23]

$$B^0 \to \psi K^0_S$$

Preliminary !!!

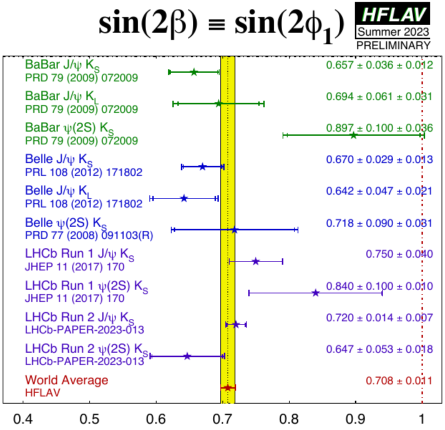
HFLAV



NEW!!

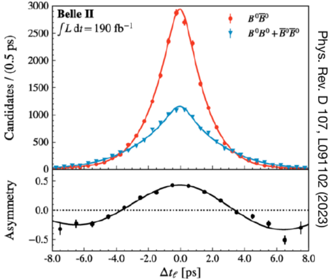
NEW!!

NEW!!



- SM measurement, but important analysis to refine all our tools for future measurement sensitive to NP (e.g. $B^0 \to K_S^0 K_S^0 K_S^0$ - see following): we are ready!
- Essential to validate Δt resolution (~1 ps) & flavor tagger (ϵ_{tag} ~ 30%) performance for TDCPV analyses

33k events from $B^0 \to D^{(*)-}\pi^+$

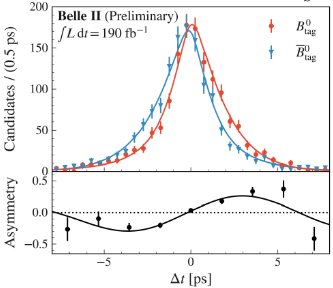


Phys. Rev. D 107, L091102 (2023)

$\tau_{B^0} = 1.499 \pm 0.013 \pm 0.008$ ps w.a. 1.519 ± 0.004 ps

$\Delta m_d = 0.516 \pm 0.008 \pm 0.005\ \text{ps}^{-1}$ w.a. $0.5065 \pm 0.0019\ \text{ps}^{-1}$

2.8k events from $B^0 \to J/\psi K_S^0$

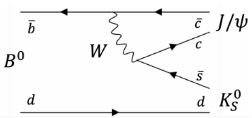


https://arxiv.org/abs/2302.12898

$S_{CP} = 0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$ w.a. 0.698 ± 0.017

$A_{CP} = 0.094 \pm 0.044(\text{stat})^{+0.042}_{-0.017}(\text{syst})$ w.a. -0.005 ± 0.015

Reference mode for measurement of β with gluonic penguins



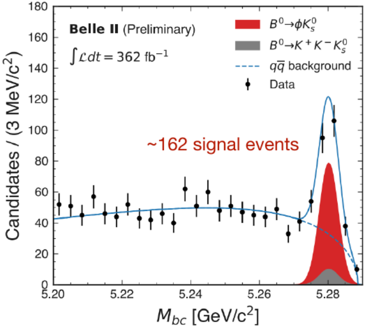
Other time dependent CPV measurements @ Belle II

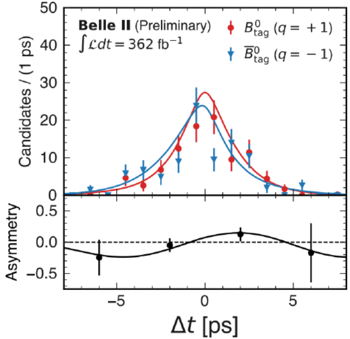
[J Bennet FPCP '23]

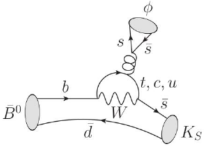
$B^0 \to \phi K_S^0$ on par with best measurements

- Clean experimental signature
- Calibration of resolution and tagging with $B \to D^*\pi$
- Validated with $B^+ \to \phi K^+$ (null asymmetry test)
- 4D fit: $(M_{bc}, O'_{CS}, \cos(\theta), \Delta t)$

Continuum suppression BDT output







$$A_{CP} = 0.31 \pm 0.20^{+0.05}_{-0.06} \qquad A_{CP}^{w.a.} = -0.01 \pm 0.14$$

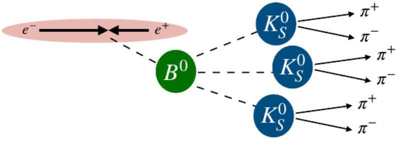
$$S_{CP} = 0.54 \pm 0.26^{+0.06}_{-0.08} \qquad S_{CP}^{w.a.} = 0.59 \pm 0.14$$

Other time dependent CPV measurements @ Belle II

[J Bennet FPCP '23]

$B^0 \to K_S^0 K_S^0 K_S^0$ on par with best measurements

- Complex vertexing (only displaced tracks!)
- 3D signal fit: (M_{bc}, M_B, O'_{CS}) simultaneous fit with
  - $B^+ \to K_S^0 K_S^0 K^+$ (background, Δt calibration)
  - time-ind $B^0 \to K_S^0 K_S^0 K_S^0$ for A_{CP} constraint
- Δt fit to extract A_{CP} and S_{CP}



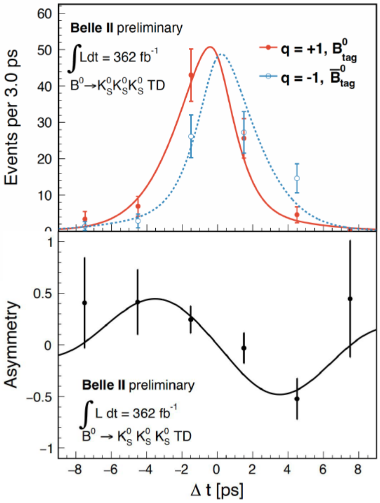
(K_S^0 flight distance ~10 cm)

$$A_{CP} = 0.07^{+0.15}_{-0.20} \pm 0.02$$

$$S_{CP} = -1.37^{+0.35}_{-0.45} \pm 0.03$$

$$A_{CP}^{w.a.} = 0.15 \pm 0.12$$

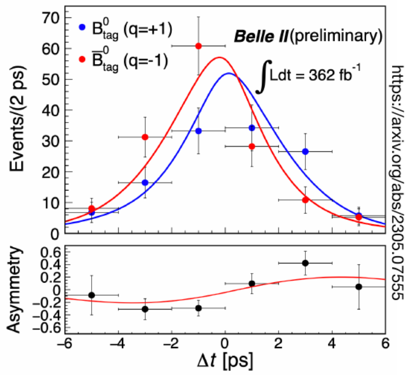
$$S_{CP}^{w.a.} = -0.83 \pm 0.17$$



Other time dependent CPV measurements @ Belle II

[J Bennet FPCP '23]

$B^0 \to K_S^0 \pi^0$ on par with best measurements



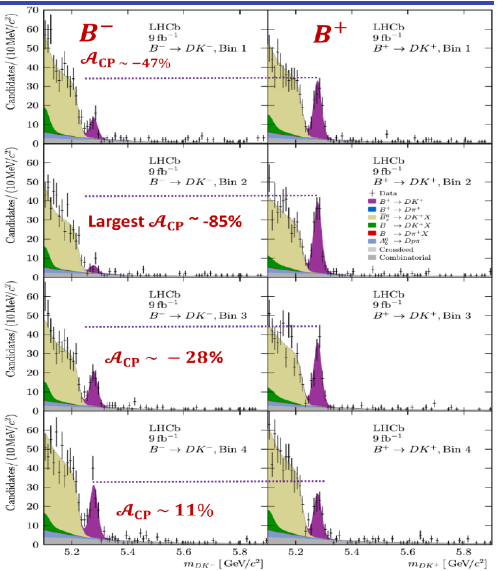
$$A_{CP} = 0.04 \pm 0.15 \pm 0.05 \qquad A_{CP}^{w.a.} = 0.00 \pm 0.13$$

$$S_{CP} = 0.75^{+0.20}_{-0.23} \pm 0.04 \qquad S_{CP}^{w.a.} = 0.58 \pm 0.17$$

$B^{\pm} \rightarrow D^0 K^{\pm}$ with $D^0 \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$

- Binned approach based on Improved sensitivity to phase γ through binning D decay phase space [T. Evans et al. PLB 802 (2020)]
- Maximise the sensitivity: on second bin largest CPV ever observed!
- D decay hadronic parameters from CLEO-C and BESIII

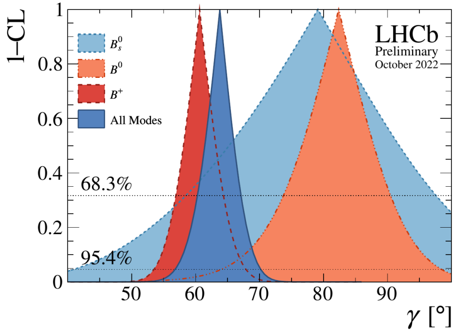
$$\gamma = \left(54.8^{+6.0+0.6+6.7}_{-5.8-0.6-4.3}\right)^{\circ}$$



Update γ combination from LHCb measurements

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

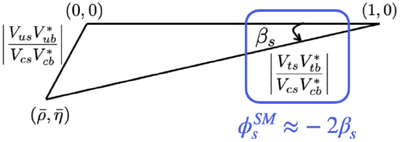
- Improvement of about 10%
- Good compatibility with unitarity fits
  $$\gamma_{CKMFitter} = \left(65.5^{+1.1}_{-2.7}\right)^\circ$$
- Tension between different *B* categories remains ($\sim 2\sigma$)

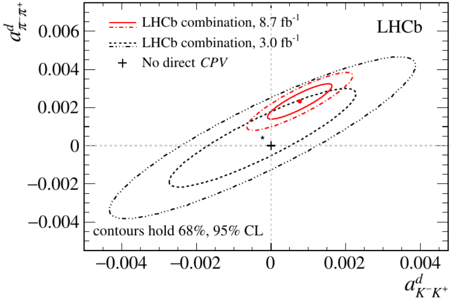


Other recent results I have not the time to cover

- ϕ_s in $B_s^0 \to J/\psi K^+K^-$ at LHCb [LHCb-Paper-2023-016]
  - Improves World average by 15%
- $\phi_s^{s\bar{s}s}$ in $B_s^0 \to \phi\phi$ at LHCb [LHCb-Paper-2023-001]
  - The most precise measurement of $\phi_s^{s\bar{s}s}$ in penguin dominated decays
- Combination of the measurement of CPV in $D^0 \to K^+K^-$ with the difference between $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$.
  - First charm CPV in a single channel $D^0 \to \pi^+\pi^-$
  - Moving from discovery to precision measurements
  - $a^d_{K^+K^-} = (7.7 \pm 5.7) \times 10^{-4}$
  - $a^d_{\pi^+\pi^-} = (23.2 \pm 6.1) \times 10^{-4}$
- ...

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$





Conclusions

- Study of CP violation and over-constraining of unitary triangle formidable way to look for New Physics
- Abundant flux of new results by Belle II and LHCb
- The future looks bright