Review of CP Violation in B Physics: Current Status, Belle II Expectations, and the $|V_{ub}|$ Puzzle

Indrayudh Das
Durba Ghosh

Indian Institute of Science

April 2, 2025

Contents

- Theoretical Framework
- CP Violation in B Sector
- Overview of experimental efforts (Belle II, BaBar, LHCb)
- References
- Acknowledgment

Theoretical Framework

The charged current weak interaction for quarks is given by

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}\,\overline{u}_L\,\gamma^\mu\,d_L\,W_\mu^+ + \text{h.c.}, \tag{1}$$

where the left-handed up-type and down-type quark fields are grouped as

$$u_L = \begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix}, \quad d_L = \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}.$$

After electroweak symmetry breaking, the quark mass matrices appear. Diagonalizing these mass matrices requires the unitary transformations:

$$u_{L,R} = U_{u,L,R}\,u_{L,R}^{(\text{mass})}, \tag{2}$$

$$d_{L,R} = U_{d,L,R}\,d_{L,R}^{(\text{mass})}. \tag{3}$$

Theoretical Framework

Expressing the charged current interaction in terms of the mass eigenstates leads to

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}\, \overline{u}_L^{(\text{mass})}\, \gamma^\mu\, V\, d_L^{(\text{mass})}\, W_\mu^+ + \text{h.c.}, \tag{4}$$

where the Cabibbo-Kobayashi-Maskawa (CKM) matrix is defined by

$$V = U_{u,L}^\dagger\, U_{d,L}. \tag{5}$$

Since $U_{u,L}$ and $U_{d,L}$ are unitary, it follows that V is also unitary:

$$VV^\dagger = V^\dagger V = I. \tag{6}$$

Theoretical Framework

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \tag{7}$$

The CKM matrix is a complex unitary matrix, and thus has nine real degrees of freedom. Using the $U(1)^6$ symmetry to set some phases to zero.

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \times$$

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{8}$$

Theoretical Framework

Now putting $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}, \tag{9}$$

The phase δ is the only source of CP violation in the Standard Model.

Theoretical Framework

Note that all the rotation angles are relatively small. Thus, the mass and flavor bases are fairly close and the CKM matrix is nearly diagonal. To a good approximation, θ_{23} and θ_{13} are negligible, and the biggest one, θ_{12}, gives all the flavor mixing. It is sometimes helpful to abbreviate this fact with an approximate parametrization in terms of $\lambda = \sin\theta_{12} \approx 0.22$

$$V \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4). \quad (10)$$

Here, the parameter η encodes the CP-violating effects.

Theoretical Framework

The Unitarity Triangle

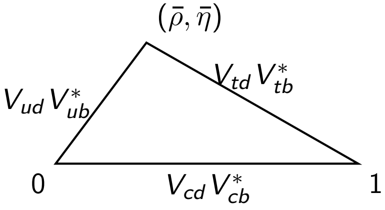
Unitarity of the CKM matrix imposes several relations. One of the most useful is derived from

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0. \tag{11}$$

In Wolfenstein parametrization the equation will be

$$-(\bar{\rho} + i\bar{\eta}) + 1 + (-1 + \bar{\rho} + i\bar{\eta}) = 0 \tag{12}$$

This relation can be represented as a triangle in the complex plane, known as the *unitarity triangle*.



The Jarlskog Invariant

The lengths of the sides of the unitarity triangle measure flavor mixing and the angles of the triangle are sensitive to CP violation. Indeed, if all the CKM elements were real, the triangle would collapse to a line. Thus, we define a quantity J as twice the area of the (non-rescaled) triangle

$$J = \mathrm{Im}\left(V_{ij} V_{kl} V_{il}^{*} V_{kj}^{*}\right) \approx (2.96 \pm 0.20) \times 10^{-5}, \qquad (13)$$

for any distinct indices $i \neq k$ and $j \neq l$.

Theoretical Framework

In the standard parameterization, this invariant is:

$$J = c_{12} c_{13}^2 c_{23} s_{12} s_{13} s_{23} \sin\delta. \tag{14}$$

A nonzero value of J is necessary for CP violation. Thus, the complex phase δ in the CKM matrix, along with nonzero mixing angles, gives rise to observable CP-violating effects both in decay processes (direct CP violation) and in meson mixing (indirect CP violation).

CP Violation in B Sector

CP violation is typically measured through asymmetries of the form

$$A_{\mathrm{CP}} \equiv \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})}$$

We need two amplitudes to interfere, either two decays, two mixings, or between a decay and a mixing.
Three options are

- CPV in decay. Also called direct CP violation.
- CPV in mixing.
- CPV in interference between decays with and without mixing

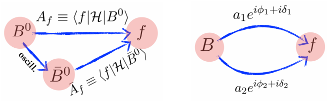


Figure: 1

Theoretical Framework

CP violation in the quark sector arises because the CKM matrix contains an irreducible complex phase. There are two primary mechanisms by which CP violation is manifested in meson decays:

Direct CP Violation

Direct CP violation occurs when the decay amplitudes of a particle and its CP-conjugate process have different magnitudes or phases. Suppose a decay amplitude can be written as a sum of two interfering contributions:

$$A = A_1 e^{i\delta_1} e^{i\phi_1} + A_2 e^{i\delta_2} e^{i\phi_2}, \tag{15}$$

where A_i are the magnitudes, δ_i are the strong (CP-even) phases from QCD interactions, and ϕ_i are the weak (CP-odd) phases from the CKM matrix.

Theoretical Framework

The CP-conjugate amplitude is

$$\bar{A} = A_1 e^{i\delta_1} e^{-i\phi_1} + A_2 e^{i\delta_2} e^{-i\phi_2}. \tag{16}$$

The CP asymmetry is then defined as:

$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2}. \tag{17}$$

$$A_{CP} = \frac{A_2}{A_1} \sin(\phi_2 - \phi_1) \sin(\delta_2 - \delta_1) \tag{18}$$

Non-zero A_{CP} requires non zero contribution in both the amplitudes and both a difference in weak phases ($\phi_1 \neq \phi_2$) and a non-zero difference in strong phases ($\delta_1 \neq \delta_2$). This type of CP violation is directly observable in decay rates.

Theoretical Framework

Mixing-Induced (Indirect) CP Violation
Mixing-induced CP violation arises from the interference between decays with and without mixing. For neutral B mesons, which can oscillate between B^0 and $\bar{B}^0$.
Time Dependent CP Asymmetry: Time-dependent decay rates into a common CP eigenstate f_{CP} can be written as

$$\Gamma(B^0(t) \to f_{CP}) \propto e^{-\Gamma t} \left[1 + S_{CP} \sin(\Delta m\, t) - C_{CP} \cos(\Delta m\, t)\right], \tag{19}$$

and

$$A_{CP}(t) = S_{CP} \sin \Delta m t - C_{CP} \cos \Delta m t \tag{20}$$

where:

- C_{CP} measures direct CP violation in the decay,
- S_{CP} measures mixing-induced CP violation and is related to the interference between decays with and without mixing.

Constraints on Unitarity Triangle

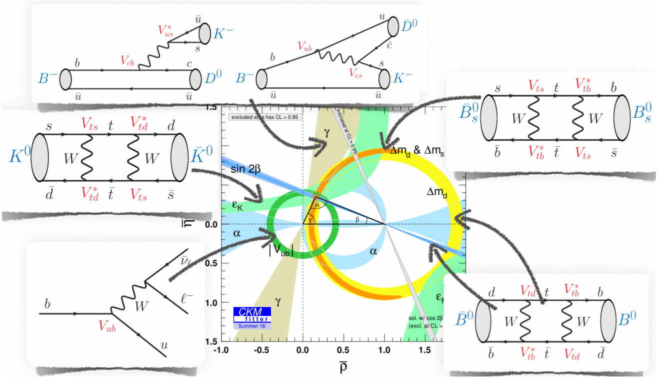


Figure: 2

Contraints on Unitarity Triangle

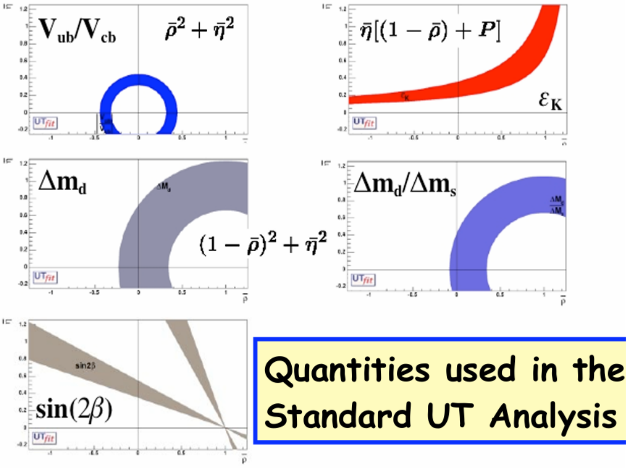


Figure: 3

Time Evolution of Constraints

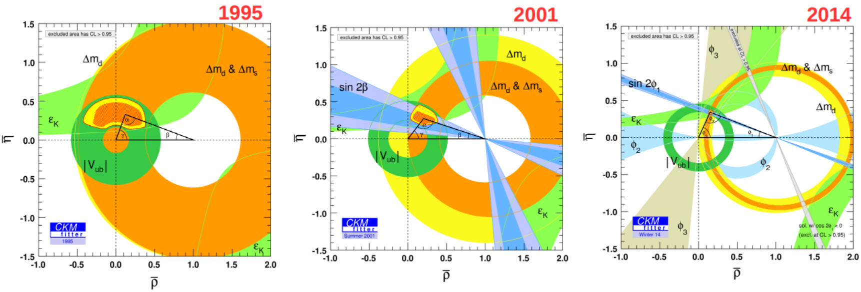


Figure: 4

We see that there was a big qualitative jump after the start of the B factories,and a very impressive set of improvements in the constraints since then.

Measuring CKM Phase γ

- CKM unitarity triangle angle use the decays in which there is interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transitions.
- The $B^- \to D^0 K^-$ decay is due to the transition $b \to c\bar{u}s$.
- The $B^- \to \overline{D^0} K^-$ decay is mediated by $b \to u\bar{c}s$ transitions which is proportional to $V_{ub} \propto e^{-i\gamma}$

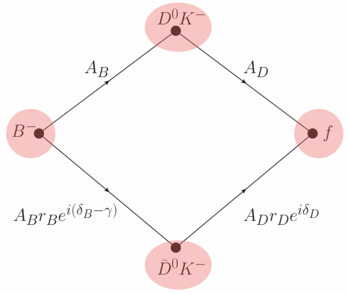


Figure: 5

Measuring CKM Phase γ

- The interference term in $B^- \to [D \to f]K^- \propto (\delta_B + \delta_D - \gamma)$ and the interference term in $B^+ \to [D \to \overline{f}]K^+ \propto (\delta_B + \delta_D + \gamma)$.
- The difference of the two thus gives the quantity we are after γ.
- $A_{CP} = r_B r_D \sin(\delta_B + \delta_D) \sin\gamma$. If the hadronic parameters are known we can calculate γ. The experimental value is $(65.4 \pm 1.1)^\circ$

Measuring β

- The decay $B^0 \to J/\psi K_S^0$ is used to extract β.
- The time-dependent CP asymmetry is given by:

$$A_{\mathrm{CP}}(t) = S_f \sin(\Delta m_d\, t) - C_f \cos(\Delta m_d\, t),$$

  where:

$$S_f = \sin(2\beta) \quad \text{and} \quad C_f \approx 0.$$

- The oscillation frequency Δm_d and decay time distribution are key experimental inputs.

Measuring β

- Both Belle II and LHCb perform flavor tagging and measure the decay-time distributions.
- The world average (PDG 2023) reports:

$$\sin(2\beta) = 0.691 \pm 0.017.$$

Measuring Sides of Unitarity Triangle

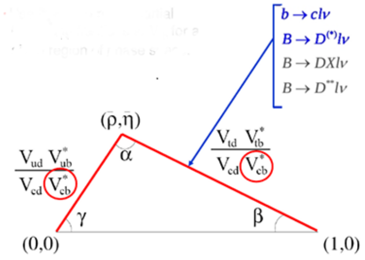
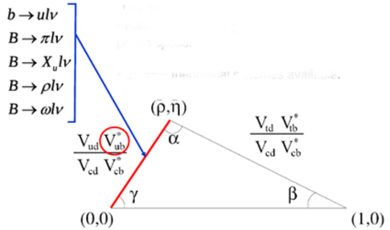


Figure: 6



Measuring Sides of Unitarity Triangle

- Sides are combinations of magnitudes of CKM matrix elements
- Heavy avor decays one way to measure these.
  - V_{cd} from $D_s \to Kl\nu$, $D \to \pi l\nu$.
  - V_{cs} from $D_s^+ \to \mu^+\nu$,$D \to Kl\nu$.
  - V_{cb} from $B \to X_c l\nu$,(X_c:D,D^* etc).
  - V_{ub} from $B \to X_c l\nu$,(X_d:D,D^* etc)

Current values:

$$|V| = \begin{pmatrix} 0.97 \pm 0.0001 & 0.22 \pm 0.001 & 0.0039 \pm 0.0004 \\ 0.23 \pm 0.01 & 1.02 \pm 0.04 & 0.0041 \pm 0.001 \\ 0.0084 \pm 0.0006 & 0.039 \pm 0.002 & 0.88 \pm 0.07 \end{pmatrix} \tag{21}$$

Experimental Landscape

- **Overview of key experiments: Belle II,Babar, LHCb:** The constraints on the CKM Unitarity Triangle is coming from the B_0, B_d^+ mesons from measurements at Belle , BaBar and LHCb, B_s meson and λ_b baryon from measurement at LHCb. The upshot of these results is that the KM mechanism is the dominant origin of CPV.
- **Complementary roles of Belle II and LHCb:**
  - Belle II operates as an electron-positron collider tuned to the $\gamma(4S)$ resonance (around 10.58 GeV). This resonance has just enough energy to decay into a pair of B^+B^- and $B^0\overline{B^0}$ mesons.Belle II contributes with high-precision measurements in a controlled environment.
  - LHCb operates in the environment of the Large Hadron Collider (LHC), where high-energy proton-proton collisions produce a wide variety of B mesons and b baryons(e.g. B_s, λ_b).LHCb adds complementary information from a richer b-hadron spectrum.

Belle II Experiment

KEKB:

- KEKB was the asymmetric e^- (8 GeV), e^+ (3.5 GeV) collider located at the High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan,produces large numbers of B mesons to study CP violation.
- It is operated from 1999 to 2010 .
- KEKB collided electrons and positrons at a center-of-mass energy near the $\Upsilon(4S)$ resonance (about 10.58 GeV), which decays into B^+,B^- pairs.
- Luminosity $= 2.11\ cm^-2\ s^-2$

Belle II Experiment

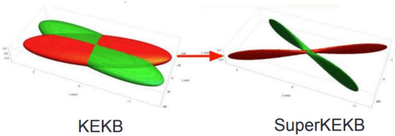
SuperKEKB:

- After KEKB shut down in 2010, it was upgraded to SuperKEKB. It has higher luminosity.
- It has Luminosity $= 80\ cm^{-2}\ s^{-2}$ (40 x KEKB).
- Asymmetric e^-(7 GeV), e^-(4 GeV) beam.
- It started operating in 2018.
- It uses nano beam scheme.

Belle II Experiment

	KEKB	SuperKEKB
$\mathcal{L}\ (10^{34} \frac{1}{s \cdot cm^2})$	2.11	80 (x40)
$\int \mathcal{L} dt$ (ab^{-1})	0.8	50
e^-/e^+ E (GeV)	8/3.5	7/4
e^-/e^+ I (A)	1.6/1.9	2.6/3.6 (x2)
$\beta\gamma$	0.45	0.28
$\langle \Delta z \rangle$ (μm)	$\sim$ 200	$\sim$ 130

Figure: 8



Nano Beam scheme:

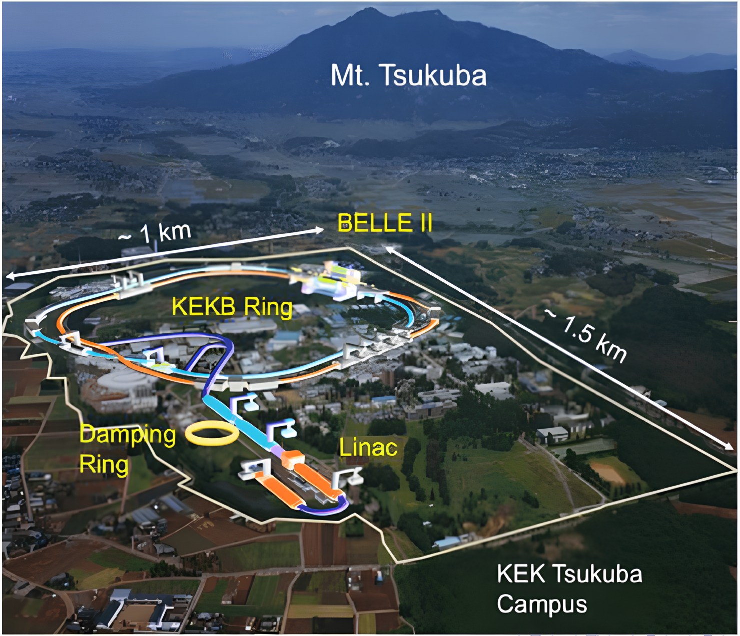
Figure: 9

Belle II Experiment

Belle II Detector:

- Belle II is the upgraded detector at SuperKEKB.
- Hermite Detector: Full event reconstruction.
- Excellent Tracking, PID, Vertex Performance.
- Belle II aims to collect about 8 x 10^{10} B mesons by about 2025, roughly 50 more than Belle did
- **Improvement:**
  - New, extended vertex detector 2 pixel layers: DEPFET technology 4 layers of double sided Si microstrip sensors.
  - Smaller cell size and longer lever arm in CDC.
  - Improved electronic and light yield for EM calorimeter.
  - New PID detector for K/ Π separation
  - Better ^0_s reconstruction
  - Improved KLM electronics.

KEK B Factory



SuperKEKB, Belle II

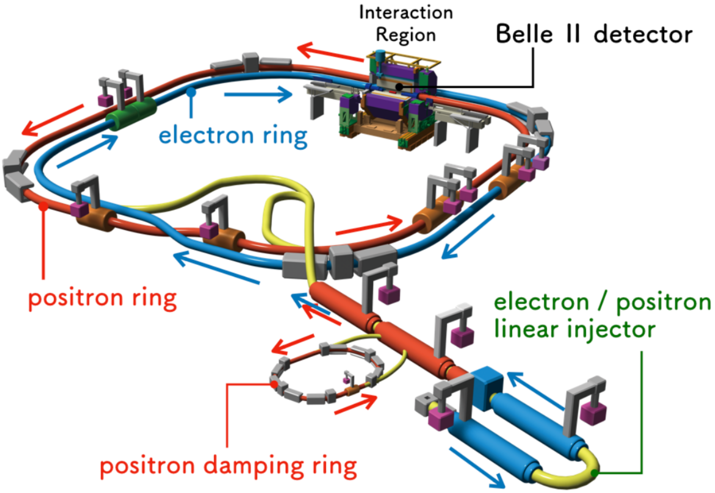


Figure: 11

Belle II Detector

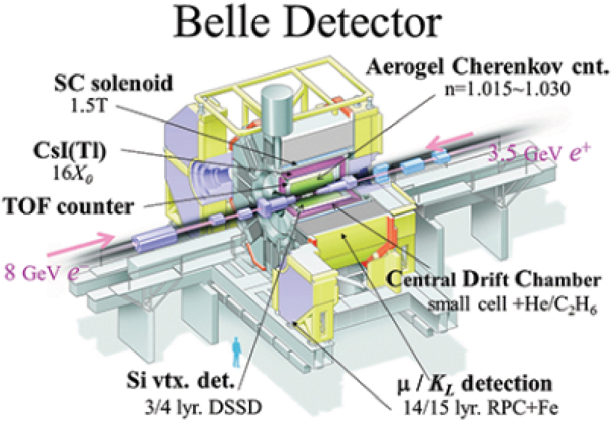


Figure: 12

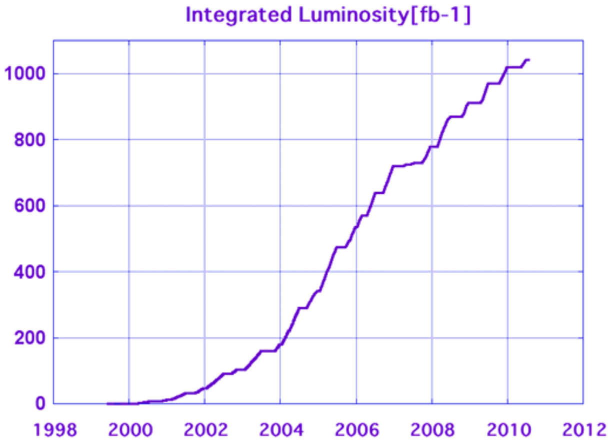

Integrated Luminosity[fb-1]
1000
800
600
400
200
0
1998
2000
2002
2004
2006
2008
2010
2012

Figure: 13

Sources of B Hadrons

CP violating effects are small. Need large number of B mesons to study decay rates with high accuracy.

$$e^+e^- \to \Upsilon(4s) \to B\overline{B}$$

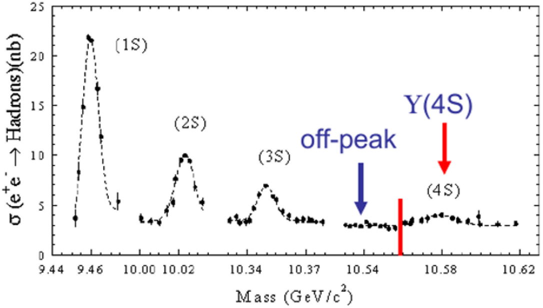


Figure: 14

After production, each meson oscillates in time, but in phase so that at any time there is only one B and one $\overline{B}$ until one particle decays. In center-of-mass, B hadrons have almost no momentum. It is difficult to distinguish which tracks come from B and which from $\overline{B}$.

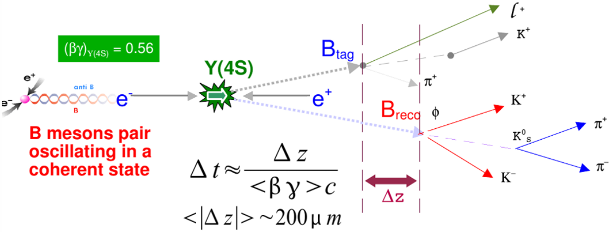


Figure: 15

LHCb Experiment

$p\overline{p} \rightarrow b\overline{b} + X$

- The LHCb detector is a forward spectrometer, and is installed at Intersection Point 8 of the LHC.
- Its primary aim is to investigate the decays of B-particles (particles containing b-quarks) and so provide insight into the phenomenon of matter-antimatter asymmetries.
- This results in a detector length of approximately 20 m, and with maximum transverse dimensions about 6 5 m3. The angular acceptance ranges from approximately 10 mrad to 300 mrad

LHCb Experiment

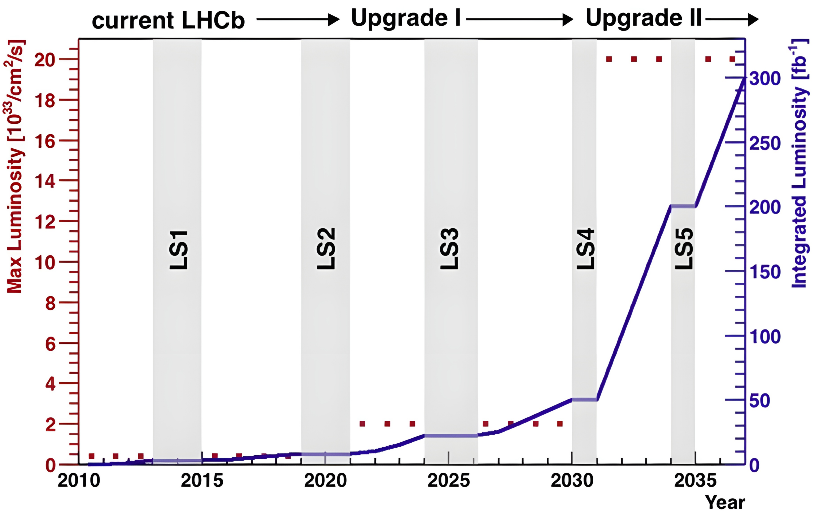


Figure: 16

LHCb Experiment

- LHCb started taking data in 2010. Run 1 commenced at an initial centre of mass energy of s =7 TeV which was then increased to s = 8 TeV, collecting an integrated luminosity of 323 $fb^{-}1$ until the end of 2012.
- LHC operation continued from 2015 to 2018 (Run 2), when the experiment took data at s = 13 TeV, recording an integrated luminosity of 6 fb 1
- The collaboration comprises almost 1000 physicists and engineers from more than 65 institutes from all over the world.

Experimental Results

TD CPV Measurement: 1) $B^0 \to J/\psi K_s^0$
SM gives A=0 B=$\sin 2\beta$

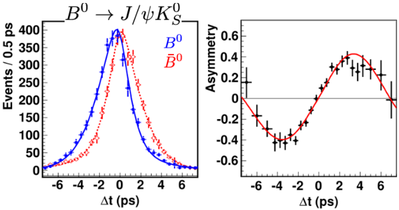


Figure: 17

Experimentally very clean determination of !
$S_f = \sin 2\beta = 0.667 \pm 0.023 \pm 0.012$ $A_f = 0.006 \pm 0.016 \pm 0.012$.

Experimental Results

2) $B^0 \to \eta' K_0$

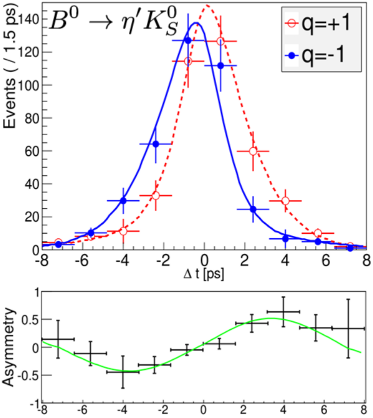


Figure: 18

$S = 0.68 \pm 0.07 \pm 0.03 \;\; A = 0.03 \pm 0.05 \pm 0.04$

Determination of V_{ub}

The CKM matrix element V_{ub} is one of the least precisely determined parameters due to its small magnitude and challenging experimental extraction. It is measured using:

- **Exclusive decays**: $B \to \pi \ell \nu$, $B \to \rho \ell \nu$
- **Inclusive decays**: $B \to X_u \ell \nu$

Exclusive Determination of V_{ub}

The exclusive method uses the decay $B \to \pi \ell \nu$, where the differential decay rate is:

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} p_\pi^3 |f_+(q^2)|^2, \tag{22}$$

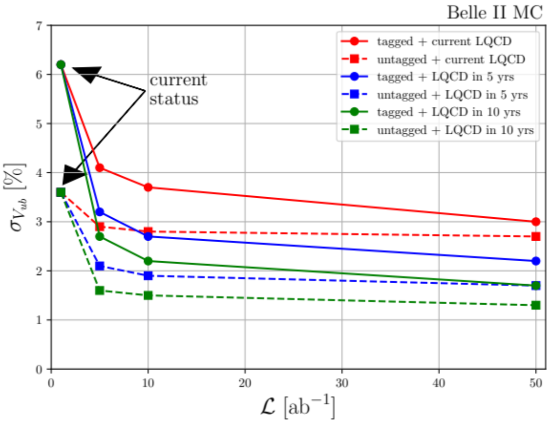
where:

- $f_+(q^2)$ is the hadronic form factor, obtained from Lattice QCD or Light-Cone Sum Rules.
- q^2 is the lepton-neutrino invariant mass squared.

Challenges:

- Dependence on theoretical form factors.
- Limited phase-space coverage in experiments.

Exclusive Determination of V_{ub}



Inclusive Determination of V_{ub}

The inclusive method relies on the process $B \to X_u \ell \nu$, where X_u represents all charmless hadronic system.

Differential decay width in the heavy quark expansion:

$$\Gamma(B \to X_u \ell \nu) = \frac{G_F^2 |V_{ub}|^2 m_b^5}{192\pi^3} \left[1 + \mathcal{O}(\alpha_s, \Lambda_{\mathrm{QCD}}/m_b)\right]. \tag{23}$$

Challenges:

- Large backgrounds from $B \to X_c \ell \nu$ decays.
- Dependence on the b-quark mass and nonperturbative effects.

Comparison of Exclusive and Inclusive Methods

- **Exclusive:** Relies on lattice QCD inputs for form factors.
- **Inclusive:** Uses heavy quark expansion but suffers from large theoretical uncertainties.

Current status: There is a discrepancy between the two methods:

$$|V_{ub}|_{\text{excl}} \approx 3.7 \times 10^{-3}, \quad |V_{ub}|_{\text{incl}} \approx 4.2 \times 10^{-3}. \tag{24}$$

Resolving this discrepancy is crucial for precision tests of the CKM paradigm.

B_s-$\bar{B}_s$ Oscillations & Quantum Entanglement in B Systems

B_s-$\bar{B}_s$ Oscillations:

- Neutral B_s mesons oscillate between particle and antiparticle states via second-order weak interactions.
- The oscillation frequency is governed by the mass difference Δm_s between the heavy (B_H) and light (B_L) eigenstates:

$$P(B_s \to \bar{B}_s)(t) \propto \sin^2\left(\frac{\Delta m_s\, t}{2}\right)$$

- The decay width difference, $\Delta\Gamma_s$, further modifies the time evolution of the decays:

$$\Gamma(B_s \to f)(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s\, t}{2}\right) \pm \cos(\Delta m_s\, t)\right]$$

- Precision measurements of Δm_s and $\Delta\Gamma_s$ are essential for testing the CKM paradigm and probing for New Physics.

B_s-$\bar{B}_s$ Oscillations & Quantum Entanglement in B Systems

Quantum Entanglement in B Systems:

- At e^+e^- colliders operating at the $\Upsilon(4S)$ resonance, $B\bar{B}$ pairs are produced in an entangled state:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\Big(|B^0\rangle\,|\bar{B}^0\rangle - |\bar{B}^0\rangle\,|B^0\rangle\Big)$$

- Measurement of one meson's decay instantaneously determines the state of its partner, enabling stringent tests of quantum coherence.
- Although traditionally studied with B^0 mesons, similar entanglement effects can be investigated in B_s systems, particularly in correlated production at hadron colliders.

Combined Perspectives:

- The interplay between oscillations and entanglement allows time-dependent analyses that are sensitive to CP-violating phases.
- Interference between the direct decay amplitude and the decay after mixing (enhanced by entanglement correlations) yields mixing-induced CP asymmetries.
- Measurements from experiments such as LHCb and Belle II utilize these phenomena to extract CKM parameters and search for deviations from Standard Model predictions.

Overview of Major Conferences I

- **EPS-HEP 2023 (European Physical Society Conference on High Energy Physics):**
  - Latest results on CP violation, including new measurements from Belle II and LHCb.
  - Improved determinations of V_{ub} and V_{cb} from exclusive and inclusive decays.
  - Discussions on flavor anomalies in B decays and potential new physics interpretations.
- **Lepton-Photon 2023:**
  - Theoretical advancements in CKM matrix fits and effective field theory approaches.
  - New results from lattice QCD on hadronic form factors relevant to flavor physics.
  - Developments in CP violation models and their implications for beyond Standard Model (BSM) physics.
- **FPCP 2023 (Flavor Physics CP Violation Conference):**
  - Recent LHCb measurements on B_s-$\bar{B}_s$ oscillations and CP asymmetries.

Overview of Major Conferences II

- Updates on rare B and K decays, including searches for lepton flavor universality violation.
- Experimental constraints on new physics contributions from kaon and charm decays.

- **CKM 2023 (International Workshop on the CKM Unitarity Triangle):**
  - Status of global unitarity triangle fits, highlighting tensions in CKM matrix elements.
  - Discussions on theoretical uncertainties in hadronic matrix elements.
  - Constraints on new physics models from precision flavor observables.

Key Results from Recent Talks

Belle II Collaboration (EPS-HEP, CKM 2023)

- First CP violation results in $B^0 \to K_S^0\pi^0$ and $B^0 \to J/\psi K^0$.
- Sensitivity to CP asymmetries surpassing BaBar/Belle expected by 2027.

LHCb Collaboration (Lepton-Photon, FPCP 2023)

- Best precision measurement of CP-violating phase ϕ_s in $B_s \to J/\psi\phi$.
- First CP violation measurements in charmless B_s decays ($B_s \to K^+K^-$).

Theoretical Developments

- Advances in lattice QCD for V_{ub} exclusive determinations.
- Effective field theory (EFT) approach to new physics in B decays.
- Long-distance effects in CP violation and their impact on Standard Model tests.

Future Directions and Open Questions

- **Resolving the V_{ub} puzzle:** Addressing the inclusive vs. exclusive tension.
- **Testing CKM unitarity:** Belle II and LHCb refining angles of the unitarity triangle.
- **New physics sensitivity:** Probing beyond Standard Model effects in rare B decays.
- **Entanglement and CP violation:** Quantum coherence tests in B meson pairs.

Conclusion

Major Takeaways:

- The CKM matrix framework and its unitarity triangle remain central to understanding CP violation.
- Precise measurements, such as those of the CKM phase β in $B^0 \to J/\psi K^0_S$, validate the Standard Model.
- Complementary experimental approaches from Belle II and LHCb are essential for cross-checking and improving the precision of CP violation measurements.

Conclusion

Future of CP Violation Studies:

- Ongoing and future data from Belle II and LHCb will reduce uncertainties in CKM parameters and provide deeper insights into CP asymmetries.
- Advances in detector technologies, flavor tagging, and vertex reconstruction are expected to push the precision of CP violation measurements to new levels.
- Precision studies in rare decays and mixing-induced CP asymmetries offer promising avenues for probing physics beyond the Standard Model.

Conclusion

Open Questions and Research Directions:

- How can the discrepancy between exclusive and inclusive determinations of $|V_{ub}|$ be resolved?
- What potential New Physics contributions could modify the expected CP asymmetries in B meson decays?
- Can studies of quantum entanglement in B systems provide additional tests of fundamental symmetries in particle physics?
- How will future experiments refine our understanding of the unitarity triangle and the overall CKM paradigm?

Acknowledgements and References I

Aggarwal, L., Banerjee, S., Bansal, S., Bernlochner, F., Bertemes, M., Bhardwaj, V., Bondar, A., Browder, T. E., Cao, L., Campajola, M., Casarosa, G., Cecchi, C., Cheaib, R., Pietro, G. D., Canto, A. D., Dorigo, M., Feichtinger, P., Ferber, T., Fulsom, B., . . . Zani, L. (2022). Snowmass white paper: Belle ii physics reach and plans for the next decade and beyond.

BA. (2021).Fermilab, $B_s - \bar{B}_s$ oscillation and quantum entanglement in b physics [Review article on oscillation measurements and quantum aspects in B physics]. *Current Science*, *120*(10), 1234–1240.

BA, Mandal, K., & Wyler, D. (2023). Recent advances in b physics: Cp violation and V_{ub} determination [Conference proceedings covering experimental and theoretical developments]. In BA, K. Mandal, & D. Wyler (Eds.), *Proceedings of the eps topical conference on b physics*. EPS.

Acknowledgements and References II

Beringer, J., Arguin, J. .-., Barnett, R. M., Copic, K., Dahl, O., Groom, D. E., Lin, C. .-., Lys, J., Murayama, H., Wohl, C. G., Yao, W. .-., Zyla, P. A., Amsler, C., Antonelli, M., Asner, D. M., Baer, H., Band, H. R., Basaglia, T., Bauer, C. W., . . . Schaffner, P. (2012).Review of particle physics. *Phys. Rev. D*, *86*, 010001. https://doi.org/10.1103/PhysRevD.86.010001

Collaboration, B. I. (2023).Observation of cp violation in $B^0 \to J/\psi\pi^0$ decays [Key CP violation measurement by Belle II]. *Phys. Rev. Lett.*, *131*(10), XXXX–XXXX. https://doi.org/10.1103/PhysRevLett.xxxxx

Acknowledgements and References III

Collaboration, B. I., Adachi, I., Aggarwal, L., Ahmed, H., Aihara, H., Akopov, N., Aloisio, A., Ky, N. A., Asner, D. M., Atmacan, H., Aushev, T., Aushev, V., Aversano, M., Babu, V., Bae, H., Bahinipati, S., Bambade, P., Banerjee, S., Barrett, M., . . . Zhukova, V. I. (2024).Measurement of CP asymmetries in $B^0 \to' K_s^0$ decays at belle ii. Phys. Rev. D 110, 112002, Published 2 December, 2024. https://doi.org/10.1103/PhysRevD.110.112002

Collaboration, L. (2022).Measurement of cp violation in $B^0 \to \eta' K_S^0$ decays [CP asymmetry studies in B decays]. *JHEP*, *2022*, XX–XX. https://doi.org/10.1007/JHEPxxxx

Group, P. D. (2024).Review of particle physics [Global averages and theoretical overview]. *Prog. Theor. Exp. Phys.*, *2024*, 1–1234.

Acknowledgements and References IV

Jarlskog, C. (1985). Commutator of the quark mass matrices in the standard electroweak model and a measure of maximal cp violation [Defines the Jarlskog invariant as a measure of CP violation]. *Phys. Rev. Lett.*, *55*, 1039–1042. https://doi.org/10.1103/PhysRevLett.55.1039

Licata, C. L. (2018). Belle ii prospects for cp-violation measurements. https://doi.org/10.5506/APhysPolB.49.1229

Schwartz, M. D. (2014, March). *Quantum Field Theory and the Standard Model*. Cambridge University Press.

Wolfenstein, L. (1983). Parametrization of the kobayashi-maskawa matrix [Introduces the Wolfenstein parameterization for the CKM matrix]. *Phys. Rev. Lett.*, *51*, 1945–1947. https://doi.org/10.1103/PhysRevLett.51.1945