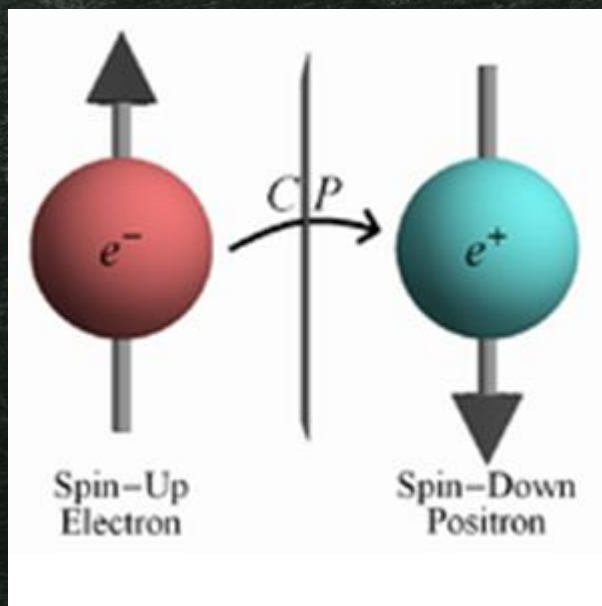


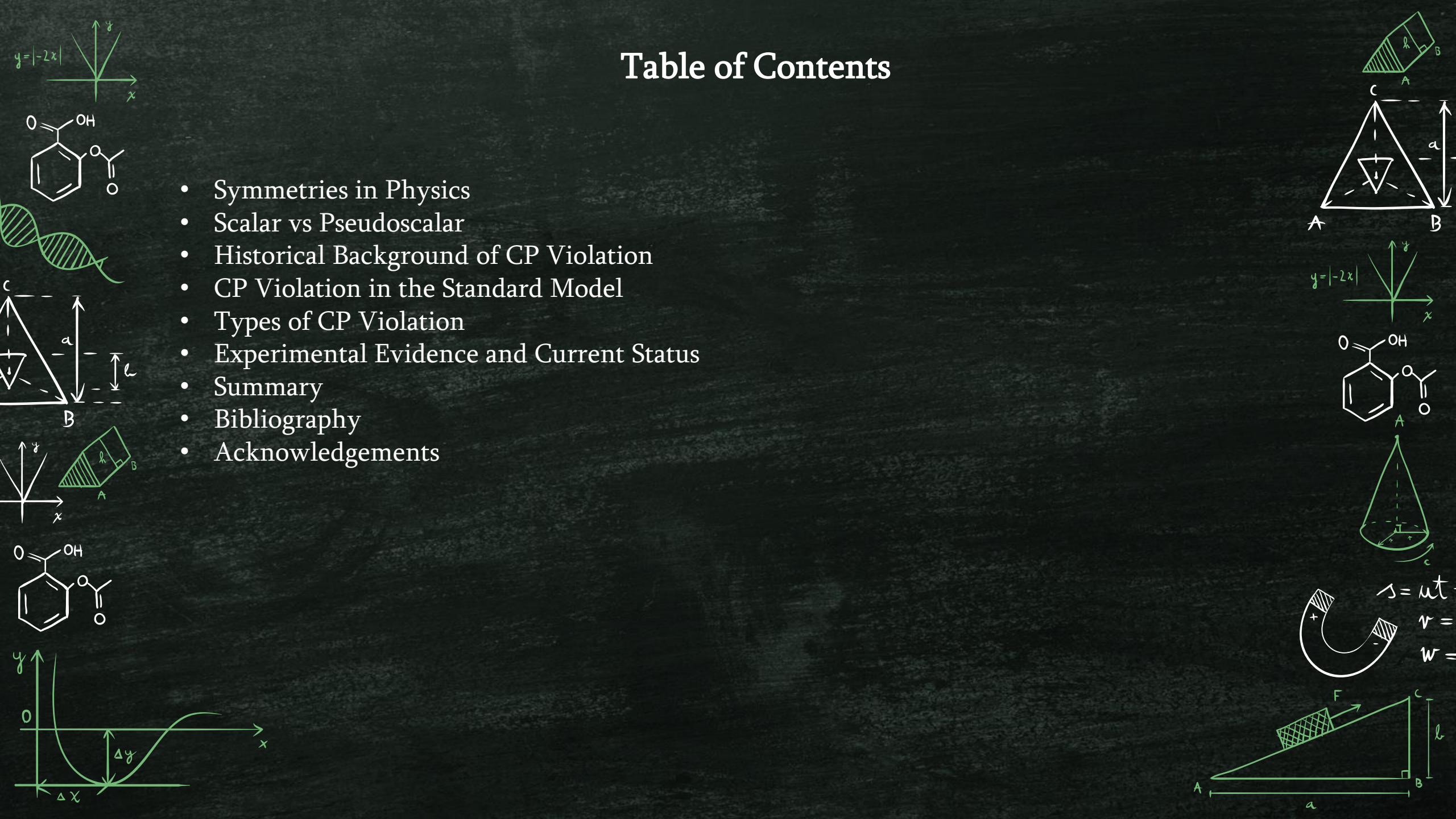
# CP Violation in Particle Physics



Author: Luka Kopadze

# Table of Contents

- Symmetries in Physics
- Scalar vs Pseudoscalar
- Historical Background of CP Violation
- CP Violation in the Standard Model
- Types of CP Violation
- Experimental Evidence and Current Status
- Summary
- Bibliography
- Acknowledgements

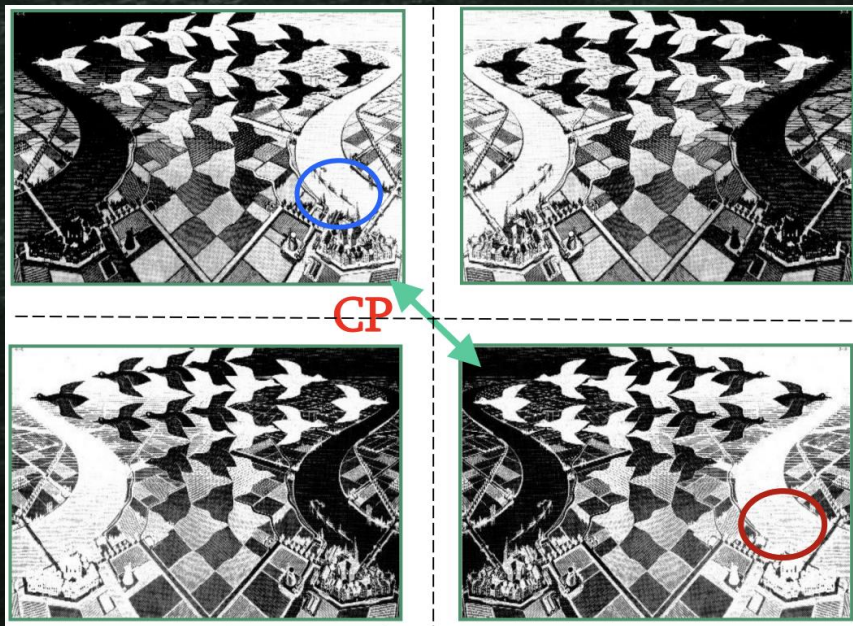


# Symmetries in Physics

## Core Concepts:

- Symmetries dictate conservation laws (Noether's theorem).
- Discrete symmetries: C (Charge Conjugation), P (Parity), T (Time Reversal)
- **CPT theorem:** Any Lorentz-invariant local quantum field theory must be invariant under the combined CPT operation.

$$\text{CPT: } (C \circ P \circ T)L = L$$



## Key Equations and Explanation:

- **Parity transformation:**  $\vec{r} \rightarrow -\vec{r}, t \rightarrow t$   
 $\rightarrow$  acts on wavefunctions:  $\mathcal{P}\psi(t, \vec{r}) = \gamma^0\psi(t, -\vec{r})$
- **Charge conjugation:**
  - $C\psi = C\bar{\psi}^T$  (particle  $\leftrightarrow$  antiparticle)
- **T violation** is difficult to measure directly; often inferred from CP violation (via CPT).

## What is CP-symmetry?

CP-symmetry states that the laws of physics should be the same if a particle is interchanged with its antiparticle (C-symmetry) while its spatial coordinates are inverted ("mirror" or P-symmetry).



# Scalar vs Pseudoscalar

## Scalar:

- A quantity that has magnitude only.
- **Does not change sign** under a parity inversion (P).
- **Does not change sign** under CP transformation (assuming the particle is its antiparticle, or we consider the CP transformation on the entire system).
- Examples: The Higgs Boson (H).

## Pseudoscalar:

- A quantity that has magnitude only.
- **Changes sign** under a parity inversion (P).
- Its behavior under CP depends on its behavior under charge conjugation (C).

The CP transformation will leave it unchanged for a pseudoscalar particle that transforms into its antiparticle with the opposite sign under C. However, if it transforms into its antiparticle with the same sign or its antiparticle, the CP transformation will flip its sign.

- Often arises from cross products or scalar triple products of polar vectors.

- Examples: Pions, kaons,  $\eta$ ,  $\eta'$  mesons.



# Historical Background

## Cronin–Fitch Experiment (1964):

- Observed decay:

$$K_L \rightarrow \pi^+ \pi^- \text{ (CP even)}$$

$K_L$  is mostly CP odd. This decay violates CP.

**Neutral Kaon System:**  $K^0 = |d\bar{s}\rangle, \bar{K}^0 = |\bar{d}s\rangle$   $CP|K^0\rangle = |\bar{K}^0\rangle, CP|\bar{K}^0\rangle = |K^0\rangle$

- CP eigenstates:  $K_1 = \frac{1}{\sqrt{2}}(K^0 + \bar{K}^0), CP = +1$  decays predominantly into two pions,  $\pi^+ \pi^-$   
 $K_2 = \frac{1}{\sqrt{2}}(K^0 - \bar{K}^0), CP = -1$  decays predominantly into three pions,  $\pi^+ \pi^- \pi^0$
- In the absence of CP violation:  $K_S \equiv K_1, K_L \equiv K_2$  Two different particles with the same mass and lifetime?

## Significance:

- First evidence that nature is not CP invariant → Nobel Prize in 1980.

$$P_{\text{total}} = P(\pi) \cdot P(\pi) \cdot (-1)^L = (-1)^2 \cdot (-1)^L = (+1) \cdot (-1)^L = +1, L = 0$$

$$C_{\text{total}} = +1$$

# CP Violation in the Standard Model (SM)

Why is CP violation not in gauge terms?:

The gauge part (electroweak + QCD) of the SM Lagrangian is CP invariant.

CP violation comes from the Higgs–Yukawa interaction, i.e., how quarks get mass.}

Yukawa interactions:

$$\mathcal{L}_{\text{Yukawa}} = -\bar{Q}_L Y_d \phi d_R - \bar{Q}_L Y_u \tilde{\phi} u_R + \text{h.c.} \quad Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}: \text{ left-handed quark doublet}$$

$\phi$ : Higgs doublet,  $\tilde{\phi} = i\sigma_2 \phi^*$

After spontaneous symmetry breaking, the Higgs field gets a vacuum expectation value (vev):

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \Rightarrow \text{quark mass matrices: } M_u = Y_u \frac{v}{\sqrt{2}}, \quad M_d = Y_d \frac{v}{\sqrt{2}}$$

Why complex phases matter:

These mass matrices are complex in general. We can diagonalize them by rotating quark fields:

$V_{uL}^\dagger M_u V_{uR} = \text{diag}(m_u, m_c, m_t)$ ,  $V_{dL}^\dagger M_d V_{dR} = \text{diag}(m_d, m_s, m_b)$  When rotating fields, the charged weak current picks up a mixing matrix:

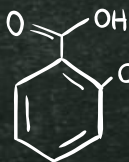
$$\mathcal{L}_{\text{CC}} = \frac{g}{\sqrt{2}} \bar{u}_L \gamma^\mu V_{\text{CKM}} d_L W_\mu^+ + \text{h.c.} \quad \text{where:}$$

$$V_{\text{CKM}} = V_{uL}^\dagger V_{dL}$$

So CP violation arises from complex, physical phases in the CKM matrix!

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}.$$

# Types of CP Violation



CP Violation in Mixing: This occurs when neutral particles (like  $K^0$  or  $B^0$ ) oscillate into their antiparticles at a different rate than the reverse oscillation.. This was the first type of CP violation observed in the neutral kaon system.

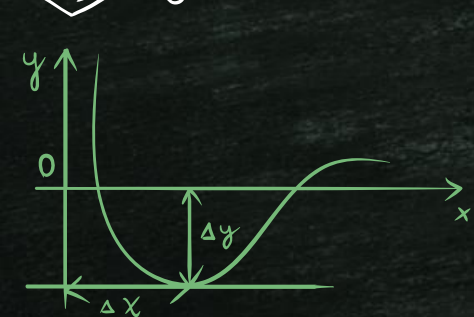
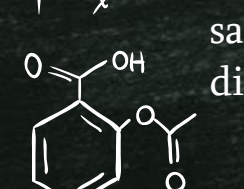
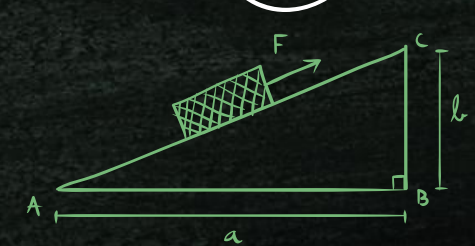
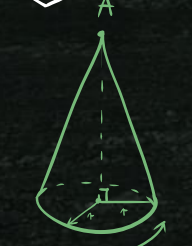
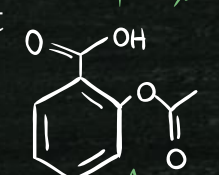
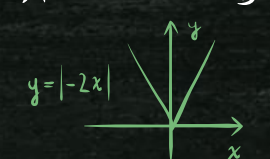
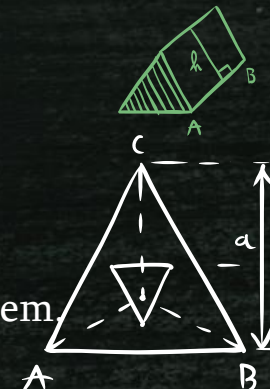
$$|K_L\rangle \neq |K_2\rangle \text{ Instead:}$$

$$|K_L\rangle \approx \frac{1}{\sqrt{1+|\varepsilon|^2}} (|K_2\rangle + \varepsilon|K_1\rangle)$$

Direct CP Violation: This happens when a particle and its antiparticle decay into different final states, or with different probabilities into the same final states. This type of CP violation requires the existence of at least two interfering amplitudes with different weak phases and different strong phases in the decay process.

$$|A(B^0 \rightarrow f)| \neq |A(\bar{B}^0 \rightarrow \bar{f})|$$

CP Violation in the Interference between Mixing and Decay: This arises when there are two pathways to reach the same final state: one through direct decay, and another through mixing followed by decay. If these two paths have different CP-violating phases, their interference can lead to an observable CP asymmetry.



# Experimental Evidence of CP Violation

1964 – Kaon Decays (Cronin & Fitch): Discovered that the long-lived neutral kaon  $K_L$  decays into two pions, violating CP symmetry.

First discovery of CP violation → Nobel Prize (1980)

1990s – Direct CP Violation in Kaons: Experiments (NA48, KTeV) showed CP violation also happens in the decay process itself. Confirms Standard Model predictions.

2001 – B-Meson Decays (BaBar & Belle): Observed time-dependent CP violation in  $B^0 \rightarrow J/\psi K_S$  decays. Validated the CKM mechanism of CP violation.

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

Recent – LHCb (CERN): Found CP violation in  $B_s$  mesons and rare decays. Matches Standard Model but also tests for new physics.

## Summary

- CP symmetry is broken in weak interactions.
- The CKM matrix includes a complex phase responsible for CP violation.
- Direct and indirect CP violation are measured in kaon and B-meson systems.
- Observed matter–antimatter asymmetry suggests CP violation beyond the Standard Model.

# Bibliography

- კოსმოლოგია და ელემენტარული ნაწილაკები, მერაბ გოგბერაშვილი, ლექცია 4
- Griffiths, D. *Introduction to Elementary Particles*
- Peskin & Schroeder, *An Introduction to Quantum Field Theory*
- PDG: Particle Data Group – <https://pdg.lbl.gov>
- LHCb Collaboration papers

[illegible]