CP VIOLATION

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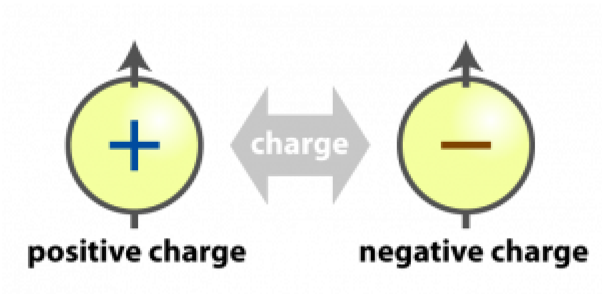
Outlines:

1. Introduction
2. Observation of parity violation
3. CP violation in K-system
4. CP violation in standard model
5. Discussion
6. Experiments on Unitary triangle

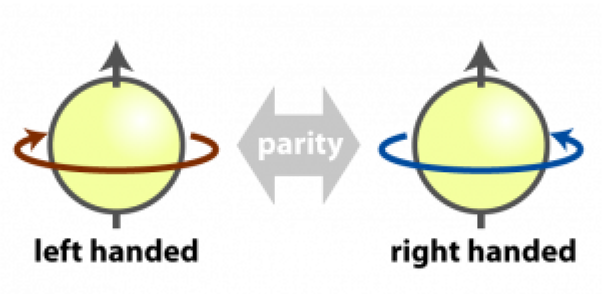
Studies of CP violation may help us understand the matter-antimatter asymmetry and may lead to new physics

1.Introduction

C Symmetry



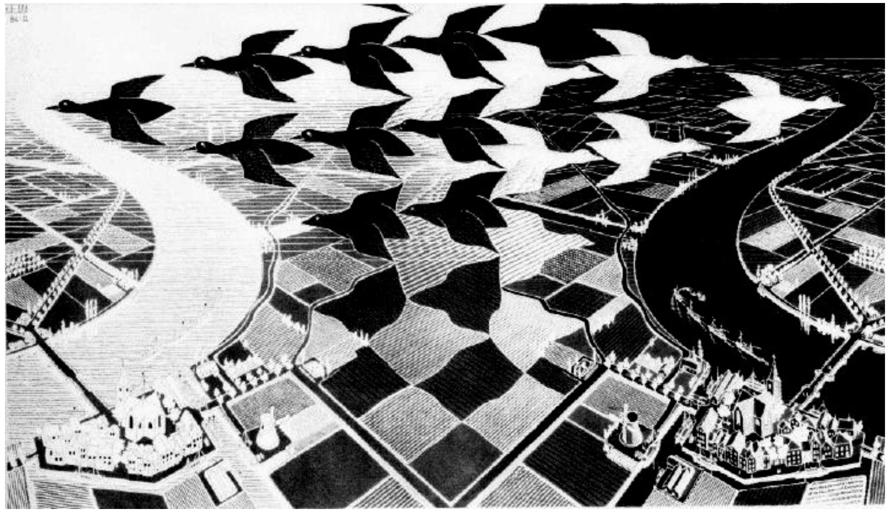
P Symmetry

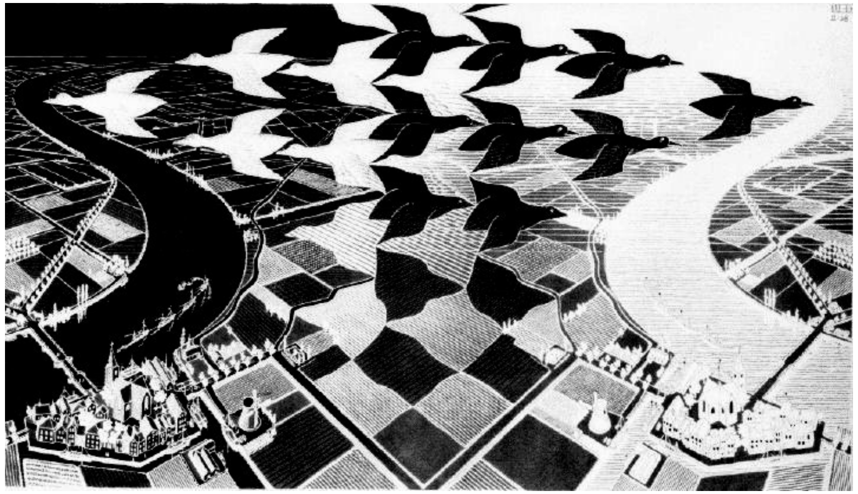


CP Symmetry:
Product of charge and parity symmetries.

Strong Interaction
Electromagnetic Interaction } CP Symmetry

Weak Interaction : CP Violation





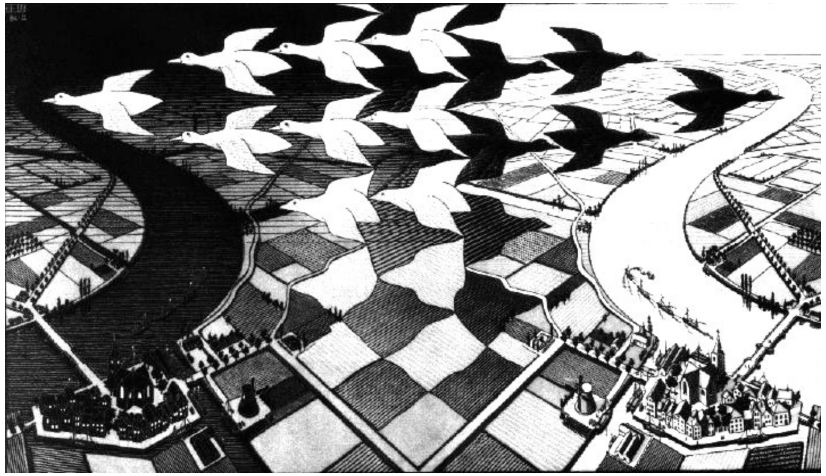
Charge Inversion
Particle-antiparticle
mirror

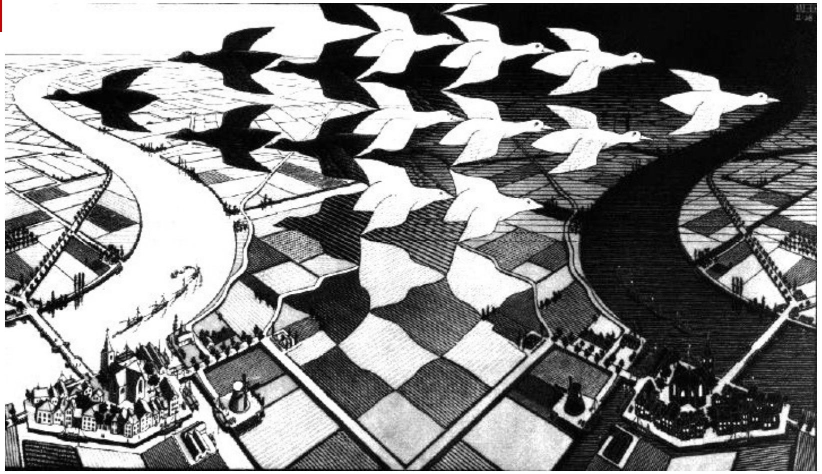
C

P

Parity
Inversion
Spatial
mirror

CP



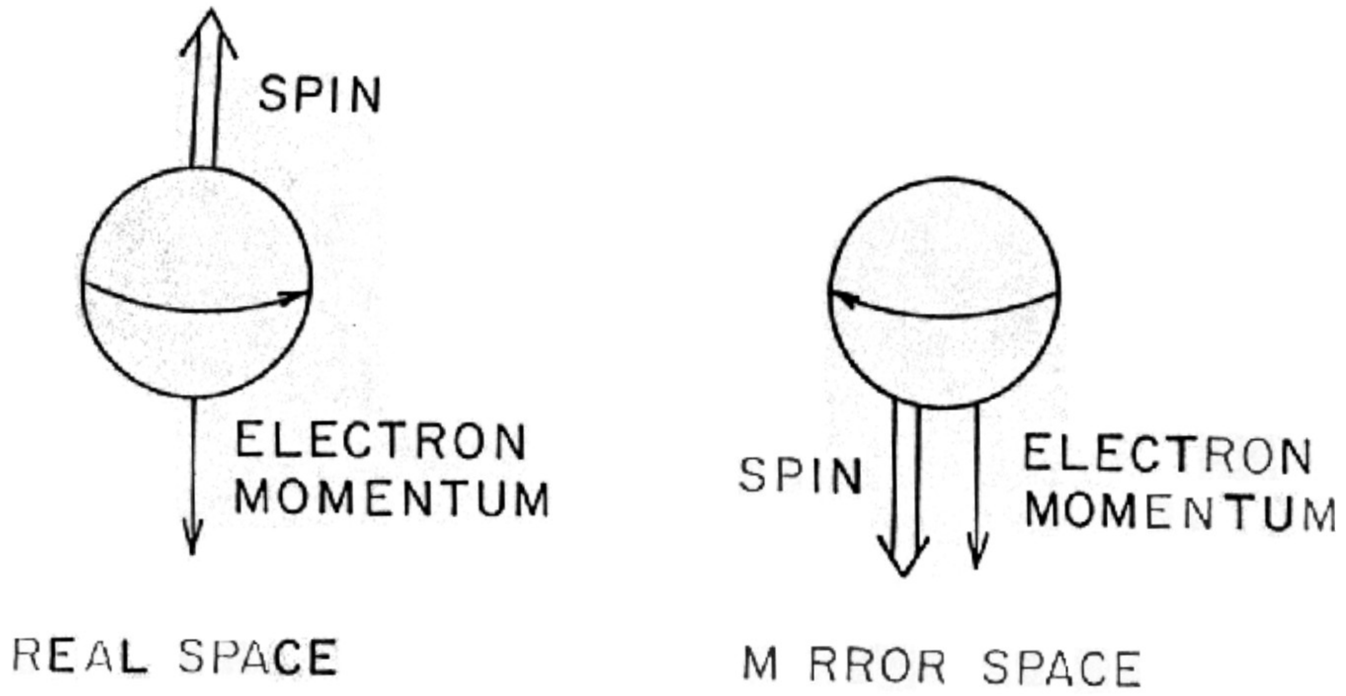


2. Observation of parity violation

Search for parity violation in b-decay

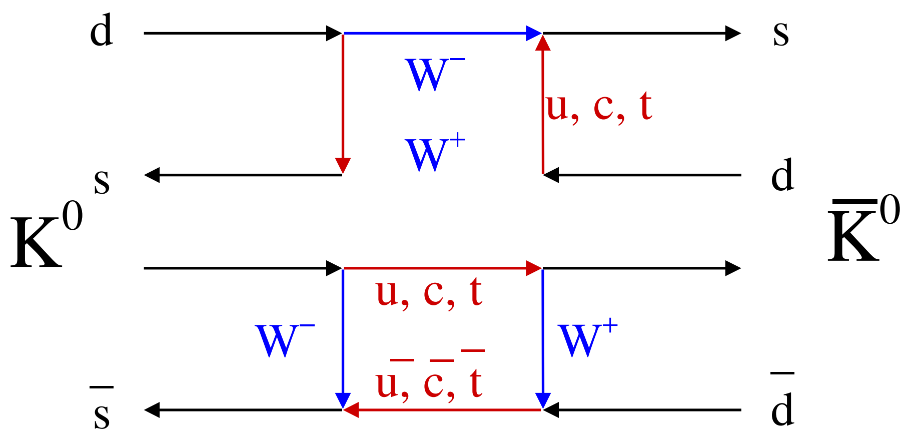
1956 – C. Wu

$^{60}Co \rightarrow {}^{60}Ni^{*} + e^{-} + \nu_e$



3. CP violation in the K-system

π^0 is a pseudoscalar meson consisting of a quark and antiquark.



$$C|\pi^0\rangle = |\pi^0\rangle$$

$$\boxed{CP|\pi^0\rangle = -1\ |\pi^0\rangle}$$

$$CP|\pi^0\pi^0\rangle = (-1)^2\ |\pi^0\pi^0\rangle = +1\ |\pi^0\pi^0\rangle$$

$$CP|\pi^+\pi^-\rangle = \mathbb{1}|\pi^+\pi^-\rangle = +1\ |\pi^+\pi^-\rangle$$

$$CP|\pi^0\pi^0\pi^0\rangle = (-1)^3\ |\pi^0\pi^0\pi^0\rangle = -1\ |\pi^0\pi^0\pi^0\rangle$$

Pion state	CP eigenvalue	
π^0	-1	
$\pi^+\pi^-$	+1	
$\pi^0\pi^0$	+1	
$\pi^0\pi^0\pi^0$	-1	
$\pi^+\pi^-\pi^0$	-1	$(L_{(\pi^+\pi^-)\leftrightarrow\pi^0} = 0, 2, ..)$
	+1	$(L_{(\pi^+\pi^-)\leftrightarrow\pi^0} = 1, 3, ..)$

CP Eigen states

$$|K^0_+\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\bar{K}^0\rangle\right]$$

$$|K^0_-\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle - |\bar{K}^0\rangle\right]$$

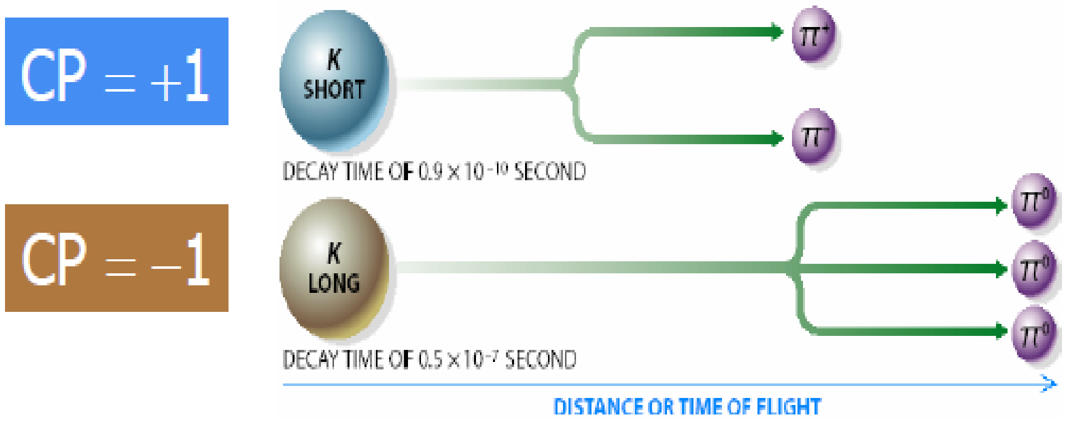
$$\begin{aligned} CP|K^0_+\rangle &= +1\,|K^0_+\rangle \\ CP|K^0_-\rangle &= -1\,|K^0_-\rangle \end{aligned}$$

If CP is conserved, the state $|K^0+\rangle$ will only decay into $\pi^+\pi^-$ or $\pi^0\pi^0$ whereas the state $|K^0-\rangle$ is strictly forbidden to decay into a two pion final state.

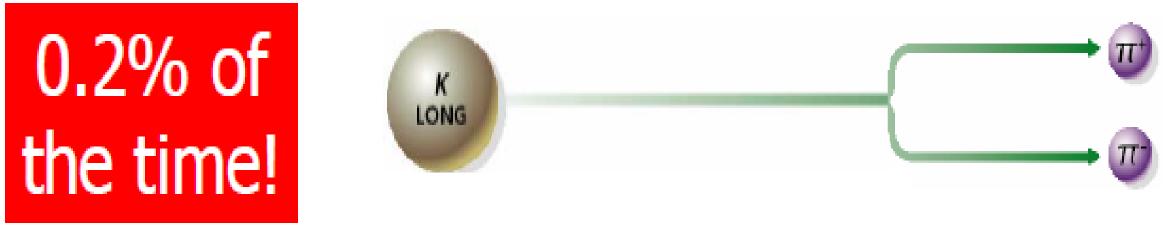
$$|K^0_S\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\bar{K}^0\rangle\right]$$

$$|K^0_L\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle - |\bar{K}^0\rangle\right]$$

- CP conservation implies



- CP violation in kaons observed in 1964



- No theoretical explanation!

The Cronin-Fitch experiment

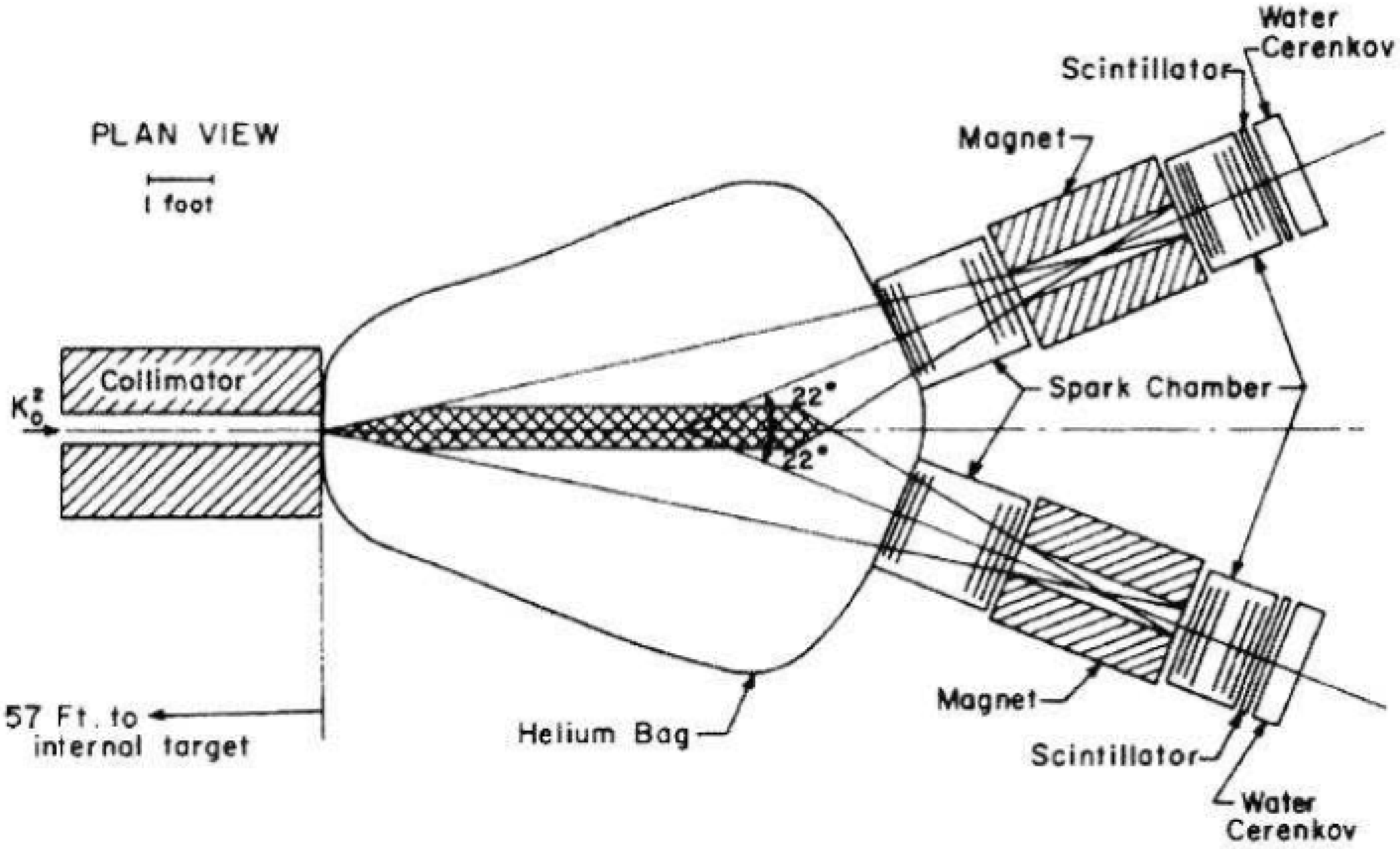
Cronin, Fitch and Turlay in 1964.

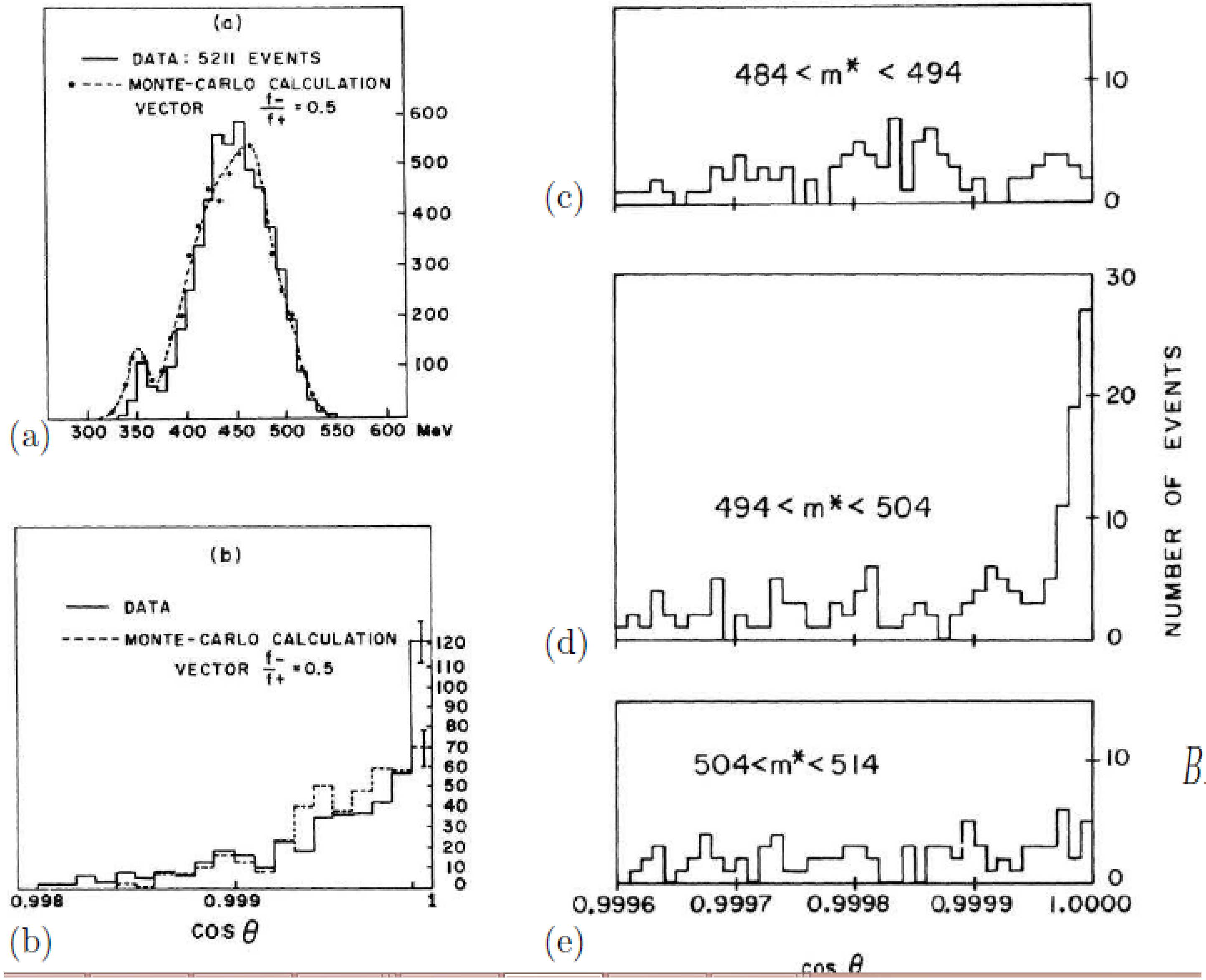
1. Be-target placed in [illegible]- beam.
2. K^0 were allowed to decay in low pressure He tank.
3. 20 m magnetic spectrometer dis which corresponds to 300 lifetime of K^0_s.

$$K_L^0 \rightarrow \pi^+\pi^-\pi^0$$

$$K_L^0 \rightarrow \pi\mu\nu \text{ and } K_L^0 \rightarrow \pi e\nu$$

μ and the e are misidentified as pions





(a) The measured two "pion" mass spectrum. (b) The distribution of the cosine of the angle between the summed momentum vector of the two pions and the direction of the K^0 beam. (c-e) The angular distribution for different ranges in the invariant mass.

The forward peak is only present for 494 < M(π+π−) < 504 MeV. Outside this mass interval there is no indication for a forward enhancement. The enhancement contains 49±9 events.

$$K_L^0 \rightarrow \pi^+\pi^-$$

$$BR(K_L^0 \rightarrow \pi^+\pi^-) = \frac{\Gamma(K_L^0 \rightarrow \pi^+\pi^-)}{\Gamma(K_L^0 \rightarrow \text{all charged decay modes})} = 2.0 \pm 0.4 \times 10^{-3}$$

CP-symmetry is violated in weak interactions

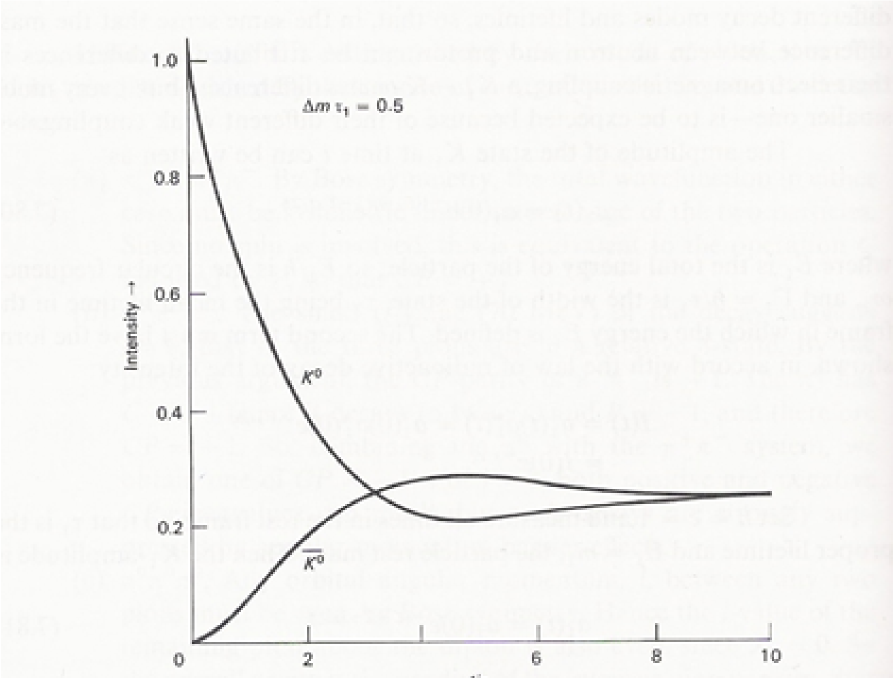
CP Violation in mixing (ༀ)

$$|K_S^0\rangle = p|K^0\rangle + q|\bar{K}^0\rangle$$
$$|K_L^0\rangle = p|K^0\rangle - q|\bar{K}^0\rangle$$

$$|K_L^0\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(|K_-^0\rangle + \epsilon|K_+^0\rangle\right)$$

$$|K_S^0\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(|K_+^0\rangle - \epsilon|K_-^0\rangle\right)$$

$$q/p = (1-\epsilon)/(1+\epsilon)$$



CP violation is found by determining corresponding branching ratio.

$$\eta_{+-} \equiv \frac{\langle\pi^+\pi^-|T|K_L^0\rangle}{\langle\pi^+\pi^-|T|K_S^0\rangle}$$

Measured Value

$$|\eta_{+-}| = (2.285 \pm 0.019) \times 10^{-3}$$
$$|\eta_{00}| = (2.275 \pm 0.019) \times 10^{-3}$$

The charge asymmetry in the decay of the K_L^0 will then be

$$\begin{aligned} A_{+-} &= \frac{\Gamma(K_L^0 \to e^+\pi^-\nu_e) - \Gamma(K_L^0 \to e^-\pi^+\bar{\nu}_e)}{\Gamma(K_L^0 \to e^+\pi^-\nu_e) + \Gamma(K_L^0 \to e^-\pi^+\bar{\nu}_e)} \\ &= \frac{|1+\epsilon|^2 - |1-\epsilon|^2}{|1+\epsilon|^2 + |1-\epsilon|^2} \\ &\sim 2\Re\,\epsilon \end{aligned}$$

$$A_{+-} = 3.32 \pm 0.06 \times 10^{-3}$$

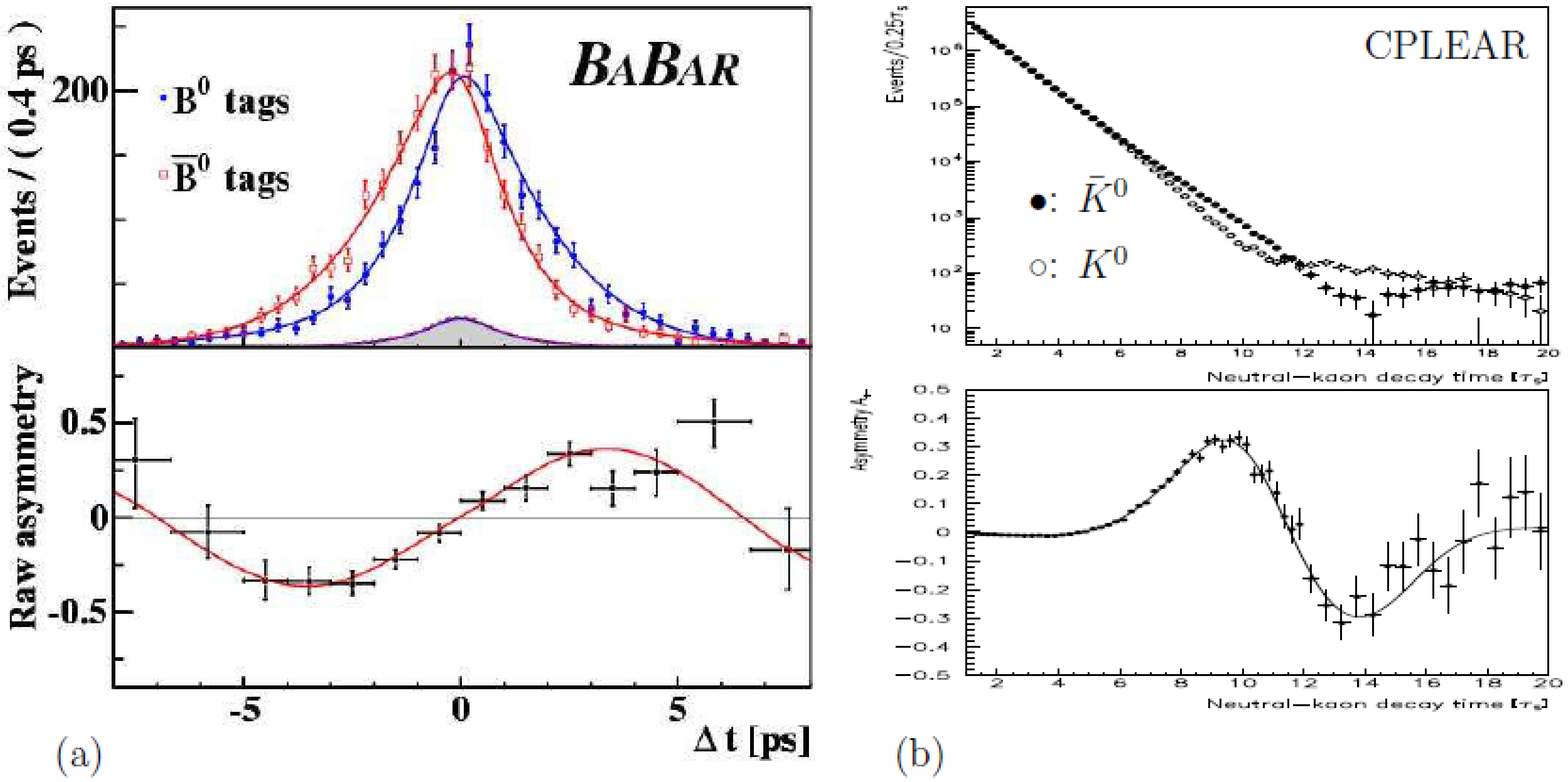
The size of the effect is consistent with two pion decay rate.

Direct CP violation

CP Violation in interference

- This depends on neutral meson meson mixing i.e. time dependent CP symmetries.
- Interference occur when we have two amplitudes.

$$K^0 \to \pi^+\pi^- \text{ and } \bar{K}^0 \to \pi^+\pi^-$$

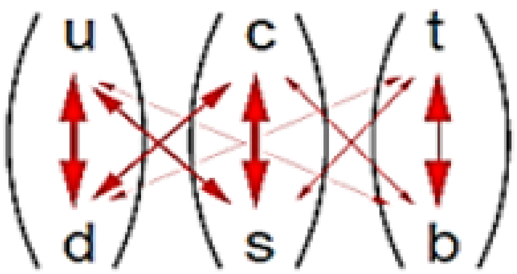


Compared to the time dependent CP asymmetry as measured in the B-system with $B^0 \to J/\psi K_S$

4. CP Violation in Standard Model

CKM-mechanism is the origin of CP violation

Nobel price in 2008, *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*



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

flavour CKM matrix mass

Quark families	# Angles	# Phases	# Irreducible Phases
n	n(n-1)/2	n(n+1)/2	n(n-1)/2-(2n-1)=(n-1)(n-2)/2
2	1	3	0
3	3	6	1
4	6	10	3

Only Source of CP Violation in SM

Historical excursion

1963- Mixing between d and s quarks , introducing Cabbibo mixing angle θ_c.

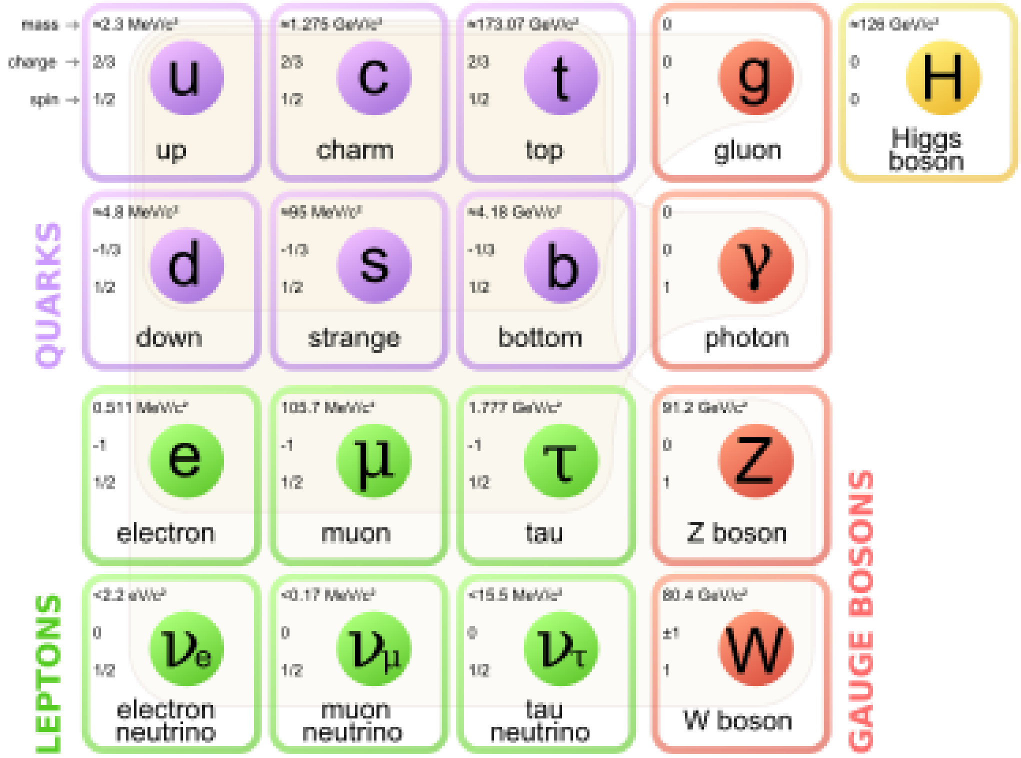
1964- Complex element in mixing matrix to get a CP violation. (Cronin and Fitch)

1973- Existence of 3rd family can explain CP violation. (Kobayasi and Maskawa)

1974- Charm quarks was discovered in the form of J/ψ resonance

1995- Top quark discovered

1977- Bottom quark discovered

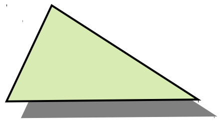


Unitary condition for CKM Matrix

$$V^\dagger V = V V^\dagger = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\left.\begin{aligned} V_{ud}V_{ud}^* + V_{us}V_{us}^* + V_{ub}V_{ub}^* &= 1 \\ V_{cd}V_{cd}^* + V_{cs}V_{cs}^* + V_{cb}V_{cb}^* &= 1 \\ V_{td}V_{td}^* + V_{ts}V_{ts}^* + V_{tb}V_{tb}^* &= 1 \end{aligned}\right\} \quad \textit{weak universality}$$

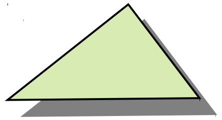
db: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$



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

ds: $V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$

ut: $V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0$



ct: $V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0$

uc: $V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$

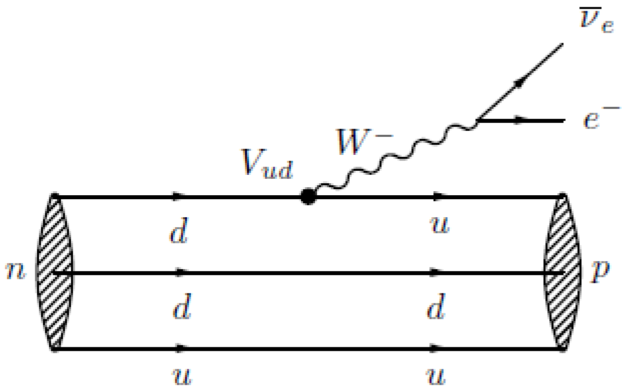
Orthogonality conditions

This parameterization was introduced by Chau and Keung, and has been adopted by the Particle Data Group

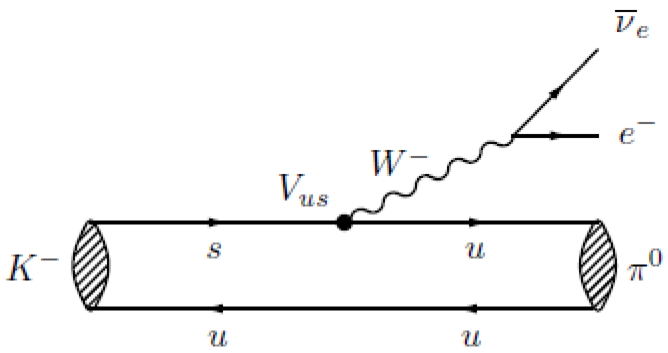
Euler angles (θ_{12}, θ_{23}, θ_{13}) and one CP-violating phase (δ_{13}). Couplings between quark generation i and j vanish if $\theta_{ij} = 0$. Cosines and sines of the angles are denoted c_{ij} and s_{ij}, respectively. θ_{12} is the Cabibbo angle

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

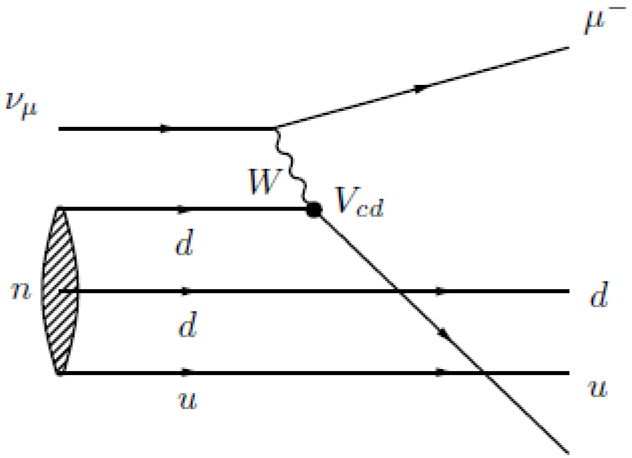
Experimental Evidence for size of matrix element



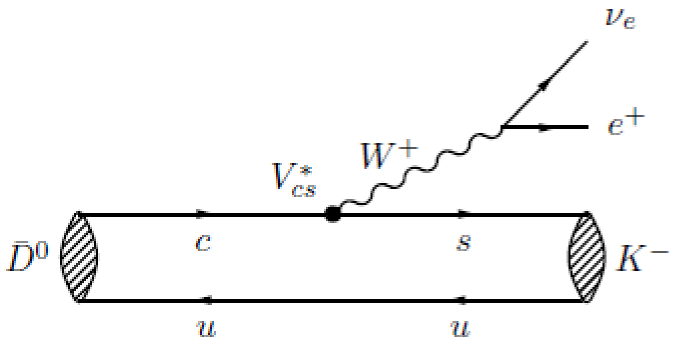
$|V_{ud}| = 0.97425 \pm 0.00022$



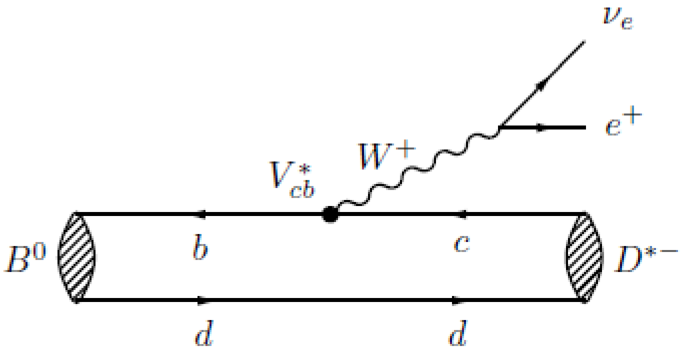
$|V_{us}| = 0.2252 \pm 0.0009$



$|V_{cd}| = 0.230 \pm 0.011$



$|V_{cs}| = 1.023 \pm 0.036$



$|V_{cb}| = 0.0406 \pm 0.0013$

$B \to \pi l^+ \nu_l$

$|V_{ub}| = 0.00389 \pm 0.00044$

$|V_{td}| = 0.0084 \pm 0.0006$

$|V_{ts}| = 0.0387 \pm 0.0021$

} Loop diagram

$|V_{tb}| = 0.88 \pm 0.07$ → D0 exp.

$$V_{CKM} = \begin{pmatrix} 0.97428 & 0.2253 & 0.00347 \\ 0.2252 & 0.97345 & 0.0410 \\ 0.00862 & 0.0403 & 0.999152 \end{pmatrix} \pm \begin{pmatrix} 0.00015 & 0.0007 & 0.00016 \\ 0.0007 & 0.00016 & 0.0011 \\ 0.00026 & 0.0011 & 0.000045 \end{pmatrix}$$

$$|V_{CKM}| \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

Wolfenstein parameterization

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

$$\begin{aligned} \sin\theta_{12} &= \lambda \\ \sin\theta_{23} &= A\lambda^2 \\ \sin\theta_{13} e^{-i\delta_{13}} &= A\lambda^3(\rho - i\eta) \end{aligned}$$

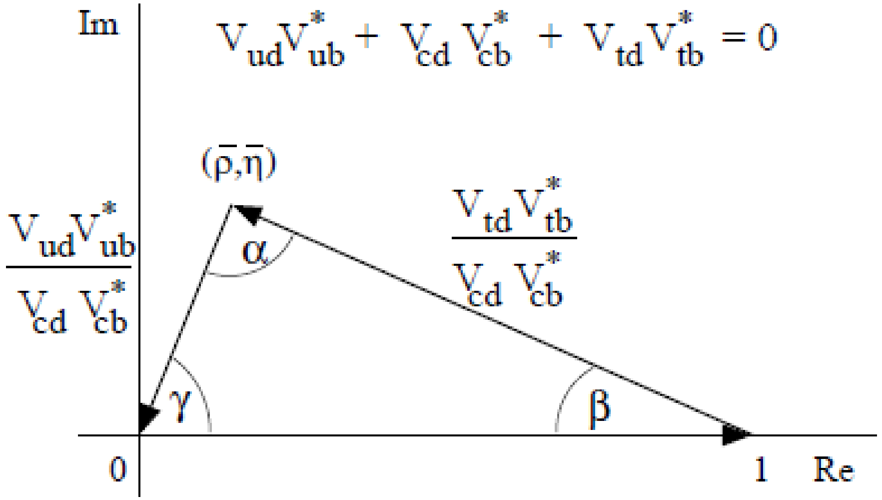
The higher order terms in the Wolfenstein parametrization are of particular importance for the Bs-system.

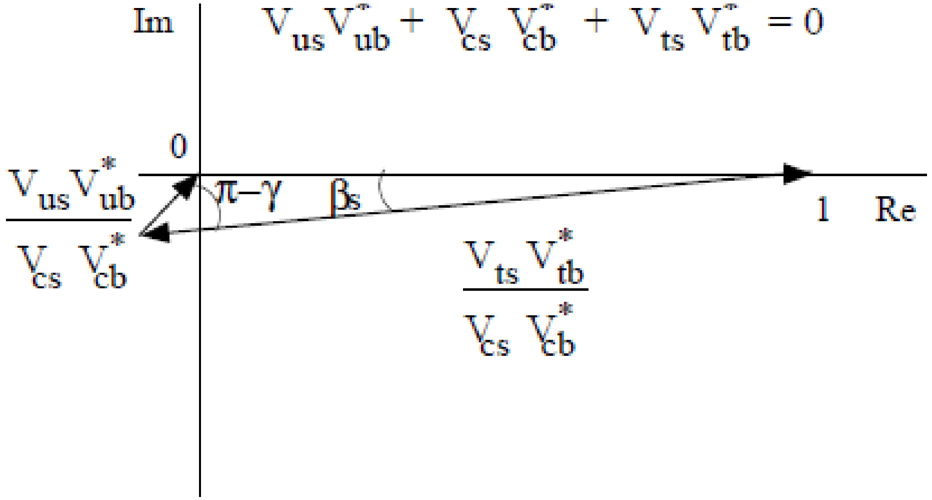
$\lambda = 0.22 =$
Sinθ_{12}

$$\begin{array}{ccccccc} V_{ud}V_{ub}^* & + & V_{cd}V_{cb}^* & + & V_{td}V_{tb}^* & = 0 \\ \mathcal{O}(\lambda^3) & & \mathcal{O}(\lambda^3) & & \mathcal{O}(\lambda^3) & \end{array}$$

$$\begin{array}{ccccccc} V_{td}V_{ud}^* & + & V_{ts}V_{us}^* & + & V_{tb}V_{ub}^* & = 0 \\ \mathcal{O}(\lambda^3) & & \mathcal{O}(\lambda^3) & & \mathcal{O}(\lambda^3) & \end{array}$$

Only these 2 have terms with equal power of □ i.e. triangles.



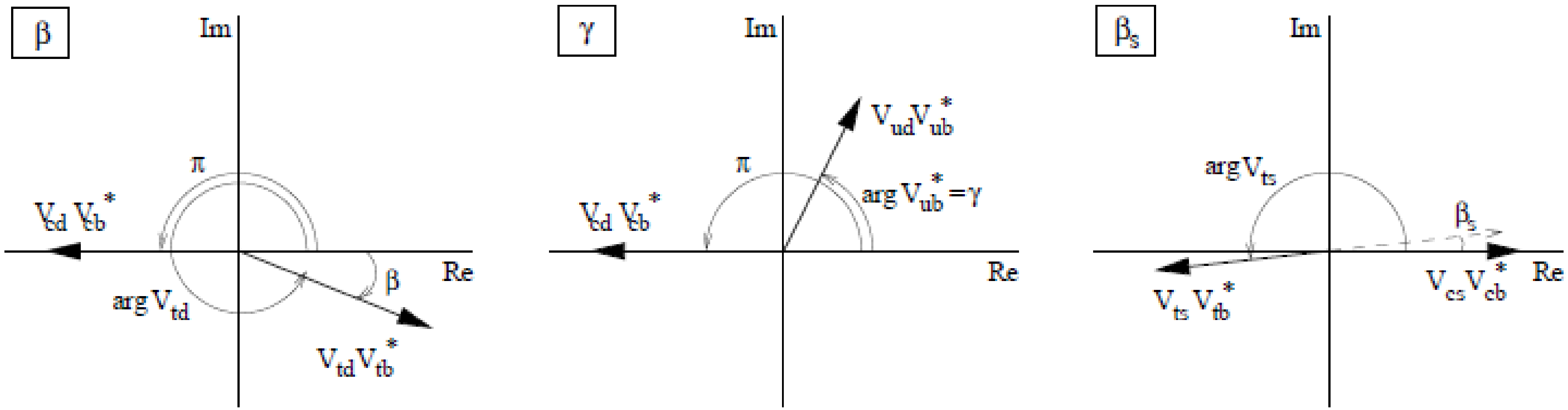


The apex of the triangle is located by definition at (ρ^{-}, η^{-})

$$\beta_s \equiv \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$$

$$\bar\rho + i\bar\eta \equiv \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \qquad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \qquad \gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



$$\beta \approx -\arg(V_{td})$$
$$\gamma \approx -\arg(V_{ub})$$
$$\beta_s \approx \arg(V_{ts}) + \pi$$

The angles β, γ and β_s using the phase convention as given by the Wolfenstein parameterization. (a) β (b) γ (c) β_s.

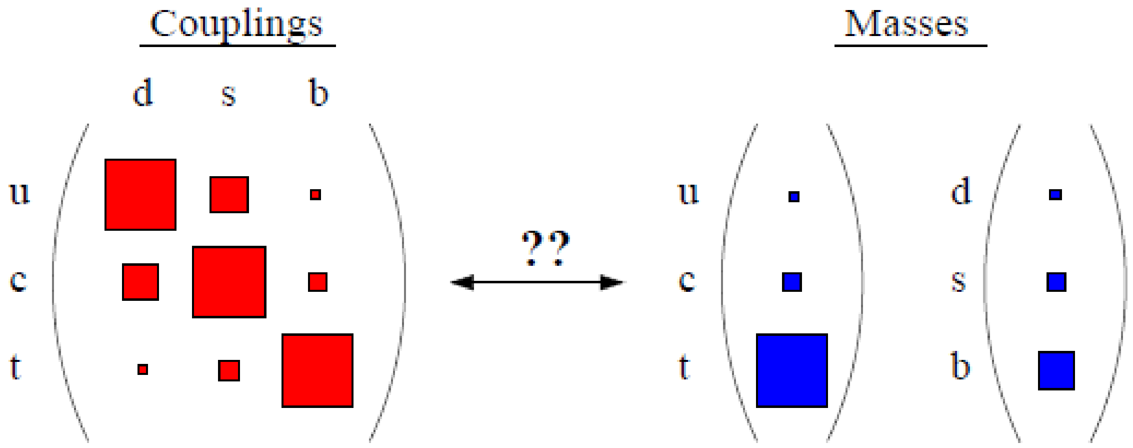
$$V_{CKM,\text{Wolfenstein}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5)$$

$$V_{ij} \neq V_{ij}^*$$

CP violation

Discussion

Yukawa coupling between Higgs's field and quark field is responsible for quark masses.



Both the charged current quark couplings and the quark masses originate from the Yukawa couplings and both the couplings and the masses show an intriguing hierarchy. Does this suggest an underlying connection between them?

All manifestation of CP violation can be explained??

Theoretical:
1. Supersymmetry
2. Increases the number of families

1. Verify the standard model.
2. Length of sides of unitary triangle can be extracted from measurable quantities.
3. How to measure different angles??
4. Disagreement between angle and length of side………
new physics

Experiments on unitary triangle

e^{-} e^{+} collider (B factory)

BaBaR (Stanford)

KEK (Belle)

β (accurately measured)

Uncertainty in ϒ is large

pp collider

LHC (aims to measure ϒ and β_s)


Thank you for your attention