Heavy Flavour Decays: CKM & CP

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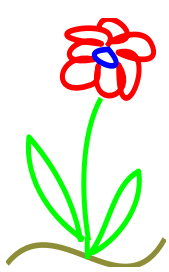
Three lectures covering:

- **The Fundamentals**
  - The weak interaction
  - CP violation in K system
  - The CKM matrix
- **Experimental environment**
  - Compare B hadron producers
  - Experimental requirements and techniques
- **B Lifetimes**
- **B Oscillations**
- **CP Violation**
- **Conclusions**



Visible universe is made of matter!

Discovery of CP Violation in K_L^0 Decays

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EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

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(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, K_2^0 mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a $1\frac{1}{2}$-in.$\times 1\frac{1}{2}$-in.$\times$ 48-in. collimator at an average distance of 14.5 ft. from the internal target. This collimator was followed by a sweeping magnet of 512 kG-in. at ~20 ft. and a 6-in.$\times$6-in.$\times$48-in. collimator at 55 ft. A $1\frac{1}{2}$-in. thickness of Pb was placed in front of the first collimator to attenuate the gamma rays in the beam.

The experimental layout is shown in relation to the beam in Fig. 1. The detector for the decay products consisted of two spectrometers each composed of two spark chambers for track delineation separated by a magnetic field of 178 kG-in. The axis of each spectrometer was in the horizontal plane and each subtended an average solid angle of 0.7×10^{-2} steradians. The spark chambers were triggered on a coincidence between water Cherenkov and scintillation counters positioned immediately behind the spectrometers. When coherent K_1^0 regeneration in solid materials was being studied, an anticoincidence counter was placed immediately behind the regenerator. To minimize interactions K_2^0 decays were observed from a volume of He gas at nearly STP.

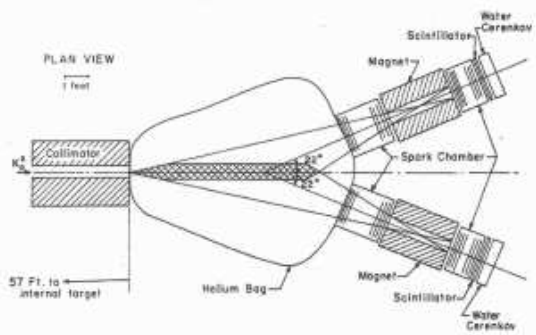


FIG. 1. Plan view of the detector arrangement.

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion. In this detector the K_{e3} decay leads to a distribution in m^* ranging from 280 MeV to ~536 MeV; the $K_{\mu 3}$, from 280 to ~516; and the $K_{\pi 3}$, from 280 to 363 MeV. We emphasize that m^* equal to the K^0 mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, θ, between it and the direction of the K_2^0 beam were determined. This angle should be zero for two-body decay and is, in general, different from zero for three-body decays.

An important calibration of the apparatus and data reduction system was afforded by observing the decays of K_1^0 mesons produced by coherent regeneration in 43 gm/cm^2 of tungsten. Since the K_1^0 mesons produced by coherent regeneration have the same momentum and direction as the K_2^0 beam, the K_1^0 decay simulates the direct decay of the K_2^0 into two pions. The regenerator was successively placed at intervals of 11 in. along the region of the beam sensed by the detector to approximate the spatial distribution of the K_2^0's. The K_1^0 vector momenta peaked about the forward direction with a standard deviation of 3.4 ± 0.3 milliradians. The mass distribution of these events was fitted to a Gaussian with an average mass 498.1 ± 0.4 MeV and standard deviation of 3.6 ± 0.2 MeV. The mean momentum of the K_1^0 decays was found to be 1100 MeV/c. At this momentum the beam region sensed by the detector was 300 K_1^0 decay lengths from the target.

For the K_2^0 decays in He gas, the experimental distribution in m^* is shown in Fig. 2(a). It is compared in the figure with the results of a Monte Carlo calculation which takes into account the nature of the interaction and the form factors involved in the decay, coupled with the detection efficiency of the apparatus. The computed curve shown in Fig. 2(a) is for a vector interaction, form-factor ratio $f^-/f^+=0.5$, and relative abundance 0.47, 0.37, and 0.16 for the K_{e3}, $K_{\mu 3}$, and $K_{\pi 3}$, respectively.[3] The scalar interaction has been computed as well as the vector interaction

Current Understanding of Matter

3 Generations of Fermions:

Quarks $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$ $\begin{matrix} Q = +2/3 \\ Q = -1/3 \end{matrix}$

Leptons $\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$ $\begin{matrix} Q = -1 \\ Q = 0 \end{matrix}$

4 Carriers of Force (Bosons):

γ	EM (QED)	Electroweak
Z	Weak	
W		
g	Strong (QCD)	
H	Higgs particles, responsible for mass	

Standard Model:

Successful description of world of particle physics!

The 5th Quark: Beauty or Bottom

- 1977: Discovery of b quark in hadronic collisions at FNAL (Lee-on)

  Υ resonances = bound $b\,\bar{b}$ state

- Today: well established B states:

  $B^0 = |\bar{b}d\rangle,\ B^+ = |\bar{b}u\rangle,\ B_S^0 = |\bar{b}s\rangle,\ B_c^+ = |\bar{b}c\rangle$ (mesons)

  $\Lambda_b^0 = |bdu\rangle$ (baryon)

- Rest mases: 5.3 - 6.5 GeV (~ 6 x mass of proton)

- Recall: quarks are not free but bound in mesons $(|q\bar{q}'\rangle)$ and baryons $(|qqq\rangle)$

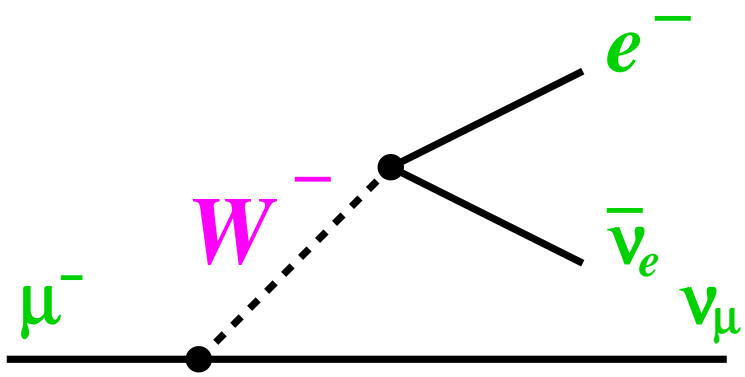
- K mesons: $K^0 = |\bar{s}d\rangle,\ K^+ = |\bar{s}u\rangle$

- All B hadrons decay weakly

The Weak Interaction

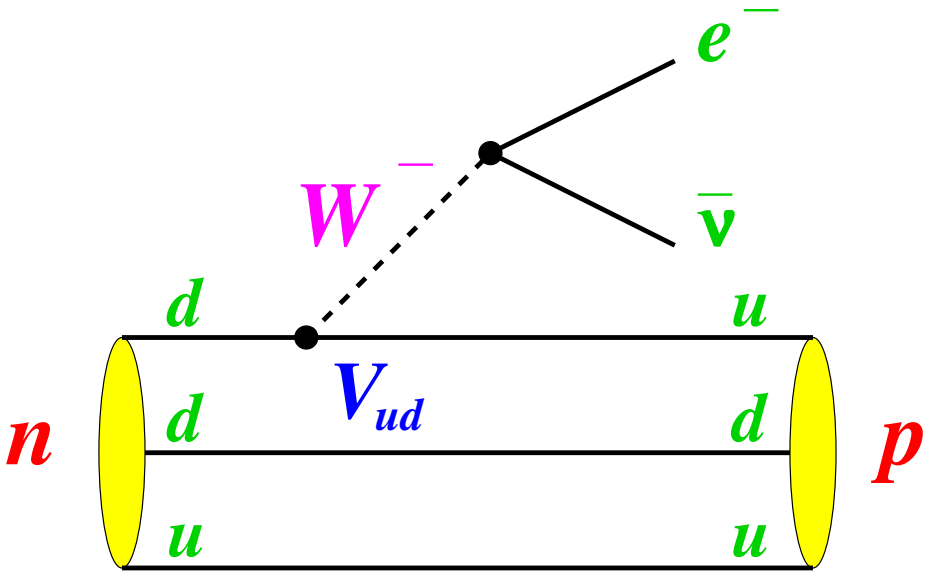
- Particles interact or decay by absorbing or emitting a W boson ('weak' because m_W large)

Muon decay: $\mu^- \to e^- \bar{\nu}_e \nu_\mu$



$$\Gamma_\mu = \frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}$$

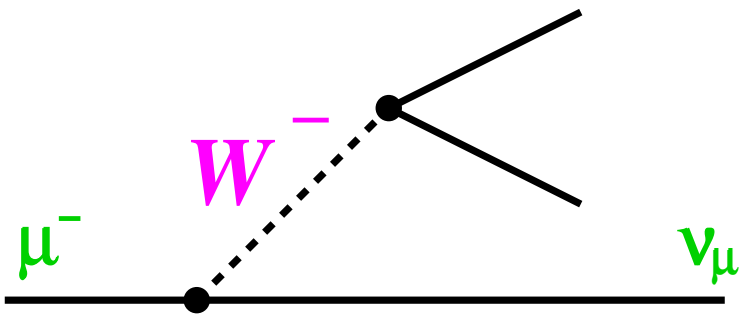
Neutron (beta) decay: $n \to p\, e^- \bar{\nu}_e$



To explain rate compared to muon decay
⟶ need extra factor 0.97

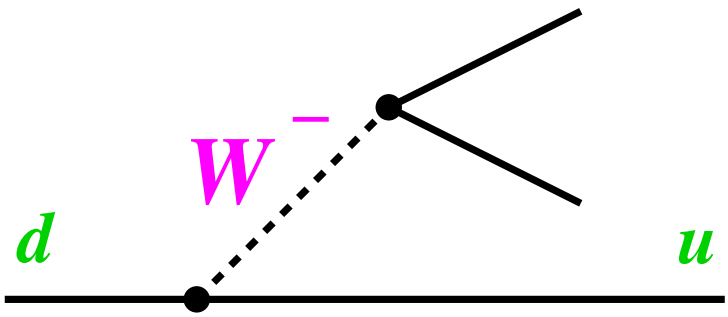
The Weak Interaction

Leptons:

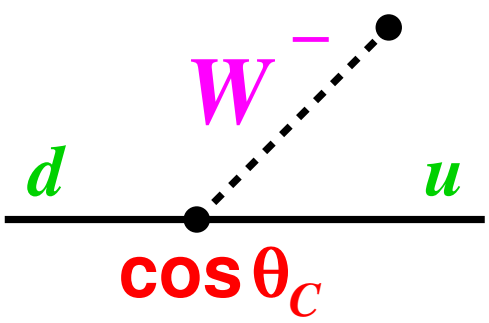


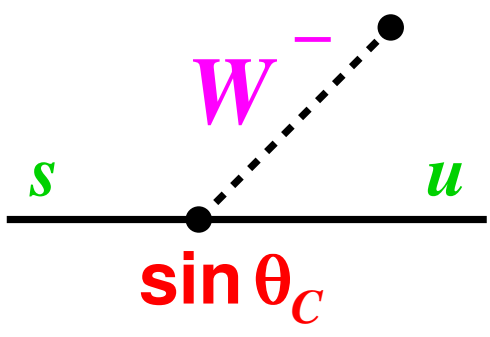
- No cross talk between generations
- Coupling is the same for each generation

Quarks:



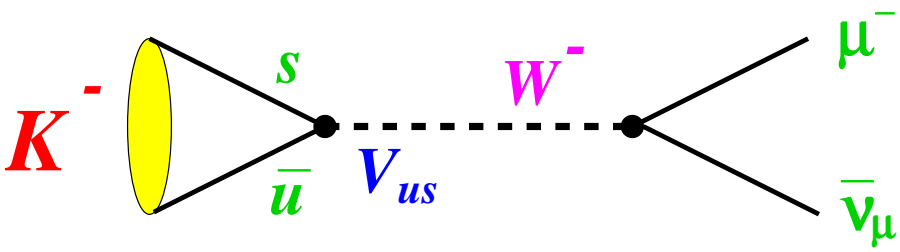
- There is cross talk between generations
- Coupling depends on which quark is involved



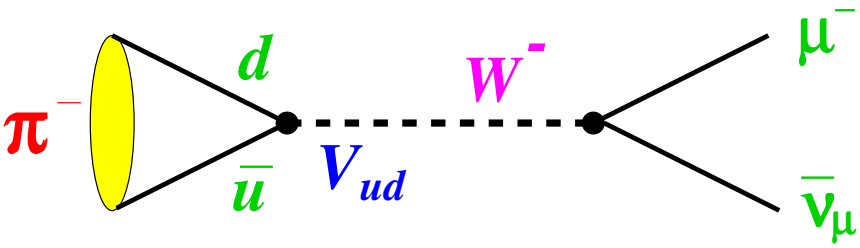


The Cabibbo Angle θ_C

Experimental rate difference between:



$$K^- \rightarrow \mu^- \bar{\nu}_\mu$$



$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

Different coulings explained by Cabibbo angle:

$V_{us} = \sin\theta_C \qquad V_{ud} = \cos\theta_C$

Actual reason:

Quark mass eigenstate ≠ Weak eigenstate

Instead:

$$\begin{pmatrix} d_w \\ s_w \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

Unitarity $V^t V = 1$ → matrix described by

$(n-1)^2 = 1$ parameter: Cabibbo angle θ_C

What is CP Violation?

- C: **Charge conjugation**
- P: **Parity (left-right symmetry)**

$$P\,\Psi(\vec{p}) \rightarrow \Psi(-\vec{p})$$

1957: Parity violation in weak decays

$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$$

emitted e preferentially along nuclear spin

- **Today: there exist left handed neutrinos but no left handed antineutrinos**

$$\pi^+ \rightarrow \mu^+ \nu_L \quad \stackrel{P}{\Longrightarrow} \quad \cancel{\pi^+ \rightarrow \mu^+ \nu_R}$$

ν_L ok — can't have ν_R

P flips $\vec{p}$ but not spin

- **Parity maximally violated in weak decays**

What is CP Violation?

- C: **Charge conjugation**

  transform particle into antiparticle

$$C|\pi^+\rangle = |\pi^-\rangle$$

- **Weak interaction violates C**

$$\pi^- \to \mu^- \, \bar{\nu}_R \quad \stackrel{C}{\Longrightarrow} \quad \cancel{\pi^+ \to \mu^+ \, \nu_R}$$

$\bar{\nu}_R$ ok — can't have ν_R

- **But: combination of C and P is ok**

$$\pi^+ \to \mu^+ \, \nu_L \quad \stackrel{CP}{\Longrightarrow} \quad \pi^- \to \mu^- \, \bar{\nu}_R$$

ν_L ok — $\bar{\nu}_R$ ok

CP Violation in the Kaon System

Neutral kaons: $|K^0\rangle = |\bar{s}d\rangle \quad |\bar{K}^0\rangle = |s\bar{d}\rangle$

Produced in strong interaction: e.g. $\pi^- p \to \Lambda K^0$

But decay through weak interaction

CP operation: $CP\,|K^0\rangle = -|\bar{K}^0\rangle$

$CP\,|\bar{K}^0\rangle = -|K^0\rangle$

(phase convention)

Physical states: well defined mass and lifetime Γ:

$\Psi(t) = \mathrm{e}^{-(im+\Gamma/2)t}$

Linear combination of $|K^0\rangle$ and $|\bar{K}^0\rangle$:

$|K^0_\ell\rangle = 1/\sqrt{2}(|K^0\rangle + |\bar{K}^0\rangle)$ (ℓ = light, $\Delta m = m_h - m_\ell$)

$|K^0_h\rangle = 1/\sqrt{2}(|K^0\rangle - |\bar{K}^0\rangle)$ (h = heavy, $\Delta\Gamma = \Gamma_\ell - \Gamma_h$)

If CP is conserved, the physical K eigenstates are CP eigenstates:

$$CP|K^0_\ell\rangle = CP[\tfrac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)] = \tfrac{1}{\sqrt{2}}(-|\bar{K}^0\rangle - |K^0\rangle) = -|K^0_\ell\rangle$$

("CP odd")

$$CP|K^0_h\rangle = CP[\tfrac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)] = \tfrac{1}{\sqrt{2}}(-|\bar{K}^0\rangle + |K^0\rangle) = +|K^0_h\rangle$$

("CP even")

CP Violation in the Kaon System

- $CP|K_\ell^0\rangle = -|K_\ell^0\rangle \quad CP|K_h^0\rangle = +|K_h^0\rangle$

- Neutral kaons decay into $\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$

  $CP|\pi^+\pi^-\rangle = +1$

  $[L = 0$ for $\pi^+\pi^-$: $P = (-1)^L = +1,\ C = (-1)^L = +1]$

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

  identify $|K_h^0\rangle$ with $K_S^0 \to \pi^+\pi^-$
  $|K_\ell^0\rangle$ with $K_L^0 \to \pi^+\pi^-\pi^0$

- Since $\mathrm{m}(\pi^+\pi^-\pi^0) \sim \mathrm{m}(K^0) \Rightarrow \tau(K_S^0) \ll \tau(K_L^0)$

  $(\tau(K_S^0) \sim 0.9 \cdot 10^{-10}$ s, $c\tau \sim 2.7$ cm)
  $(\tau(K_L^0) \sim 5.2 \cdot 10^{-8}$ s, $c\tau \sim 15.5$ m)

- If CP is conserved: $K_L^0 \not\to \pi^+\pi^-$
- But 1964: Christenson, Cronin, Fitch, Turlay

  $K_L^0 \to \pi^+\pi^-$ about $2 \cdot 10^{-3}$ of the time
- Very small effect (parity violation 'maximal')

CP Violation in the Kaon System

* How to Explain CP Violation in K Decays?

- $|K_L^0\rangle$ must have small component of $|K_h^0\rangle$:

  CPT: only one small complex parameter ϵ necessary

$$|K_L^0\rangle = |K_\ell^0\rangle + \epsilon\, |K_h^0\rangle$$
$$|K_S^0\rangle = |K_h^0\rangle + \epsilon\, |K_\ell^0\rangle$$

- How to implement into Standard Model?
- With 2 generations:

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$\Rightarrow$ matrix described by $(n-1)^2 = 1$ parameters

1973: Kobayashi & Maskawa: with 3 generations:

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

- Unitarity $V^\dagger V = 1$: $(n-1)^2 = 4$ parameters

  Three angles plus one complex phase $\rightarrow$
  $\rightarrow$ responsible for CP violation

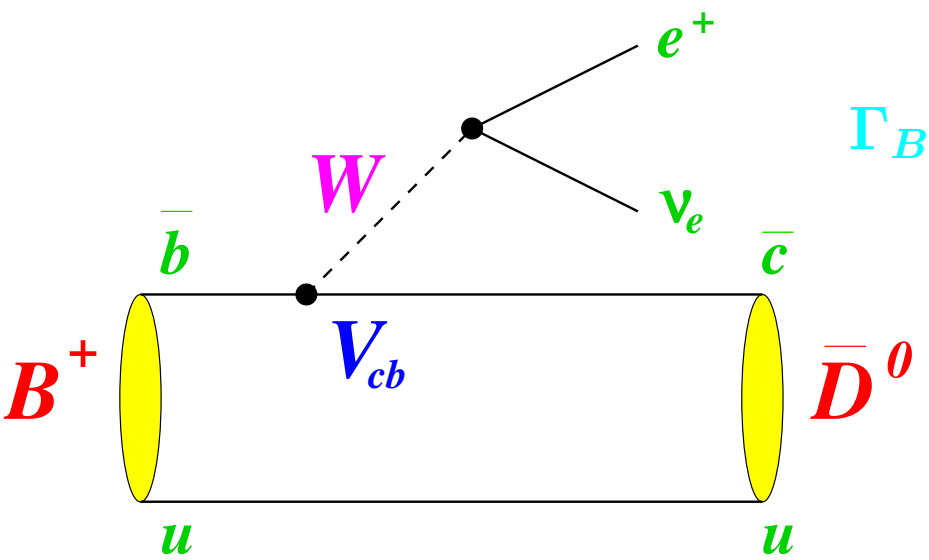
- Other explanations: new superweak force (Wolfenstein 1964)

ruled out 1999 by KTeV + NA48

The CKM Matrix

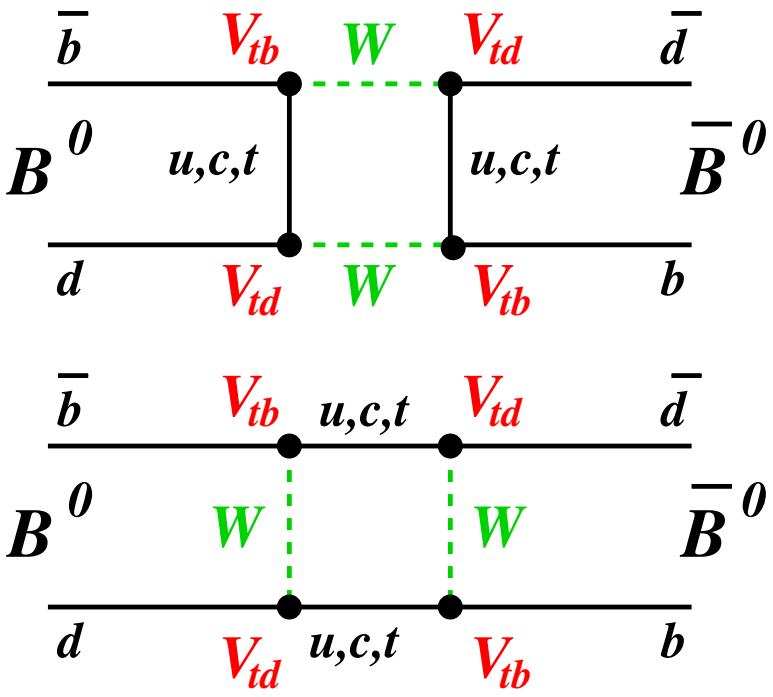
- **Individual matrix elements not predicted by SM**
  ⟶ must be measured from weak decays

Example: Semileptonic decay $B^+ \to \bar{D}^0 e^+ \nu_e$



$$\Gamma_B = \frac{1}{\tau_B} = \frac{|V_{cb}|^2 m_b^5}{192\,\pi^3}$$

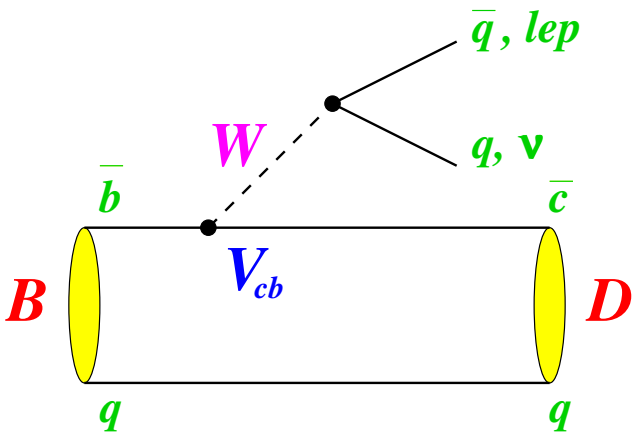
Example: $B^0 \bar{B}^0$ **Oscillations**



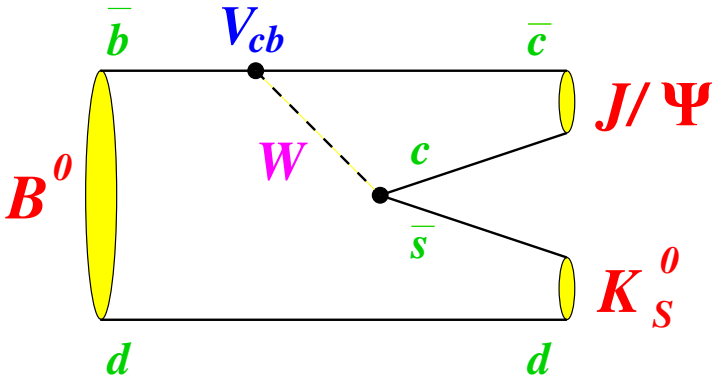
Mixing frequency

$\Delta m_d \sim |V_{td} V_{tb}|^2$

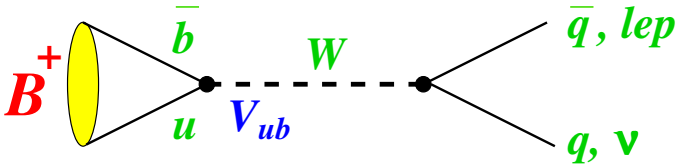
Overview of B Decay Diagrams



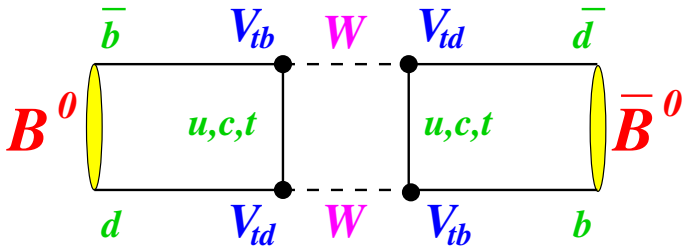
External spectator
(semileptonic, hadronic)



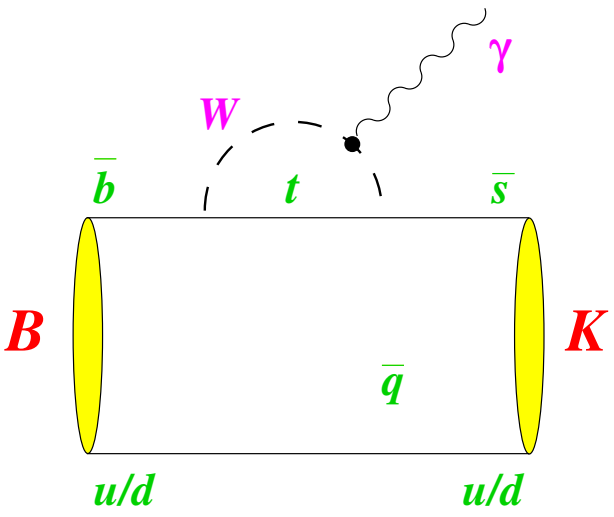
Internal spectator



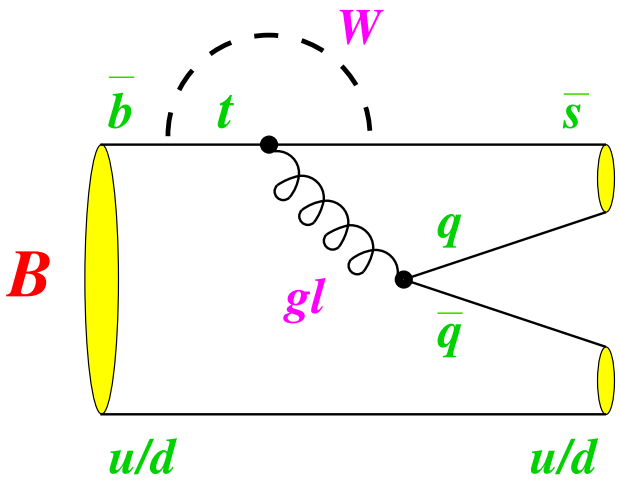
Annihilation



Oscillation



Penguin (radiative)



Penguin (gluonic)

The CKM Matrix

★ The CKM matrix

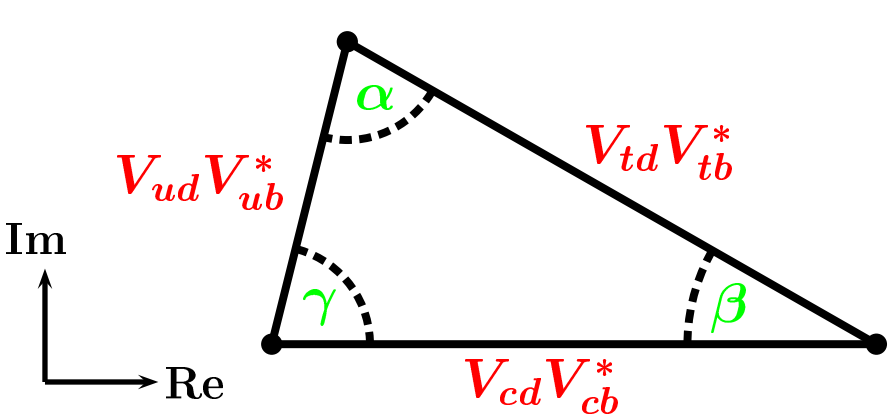
$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

★ B decays measure 5 CKM matrix elements: V_{cb}, V_{ub}, V_{td}, V_{ts} and V_{tb}

★ Unitarity of $V_{\rm CKM}$:

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

★ Triangle relation in complex plane



$$\alpha = arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta = arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

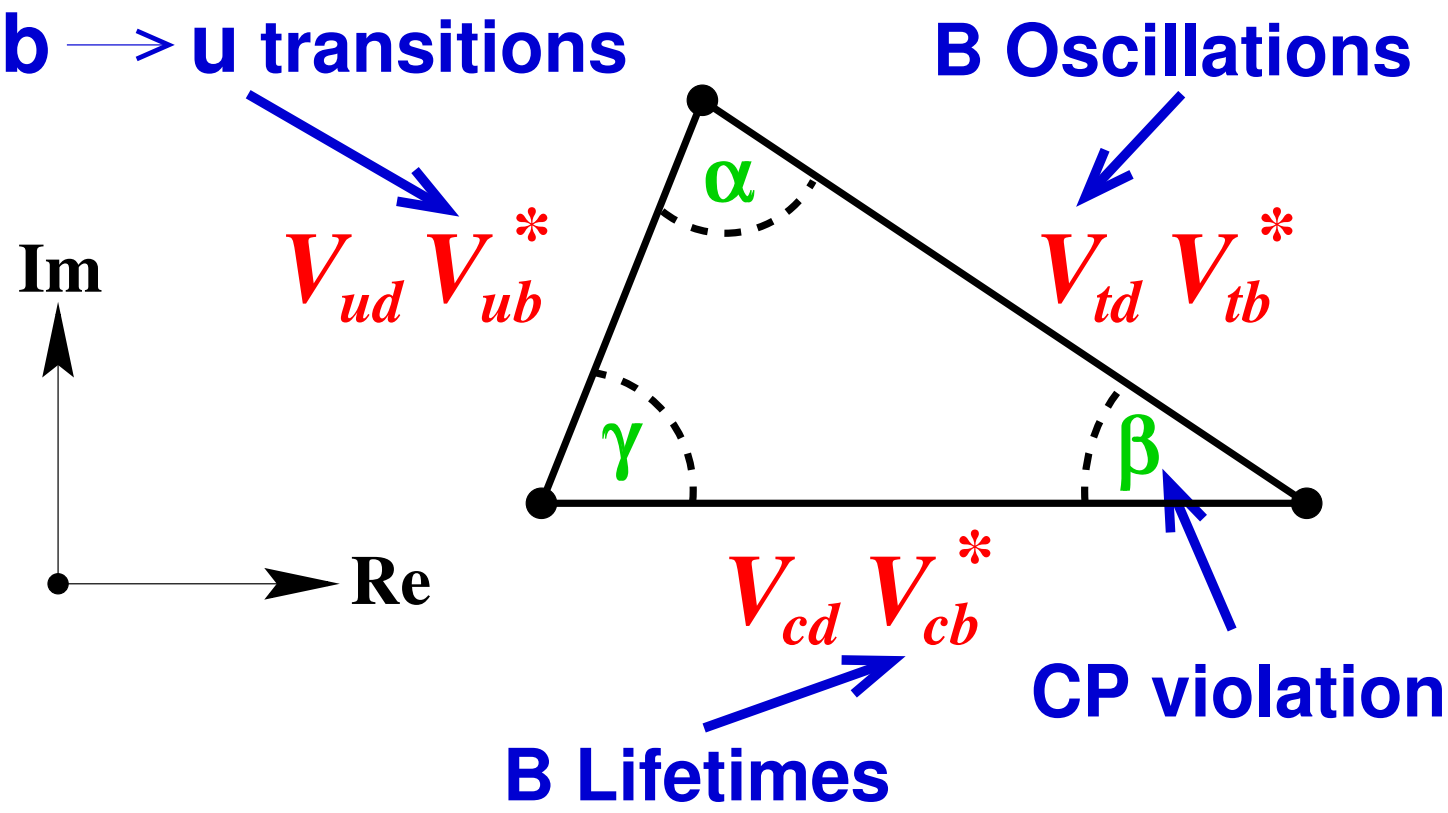
$$\gamma = arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

★ B decays measure sides of unitarity triangle

★ CP asymmetries measure angles

Heavy Flavour Decays: CKM and CP

The CKM Unitarity Triangle



Our Program:

- Experimental environment
- B Lifetimes: V_{cb}
- B Oscillations: V_{td}
- CP violation: sin 2β