Physics of Particle Flavors

Belle II Explorer

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Belle II

What is flavor?

Fermions

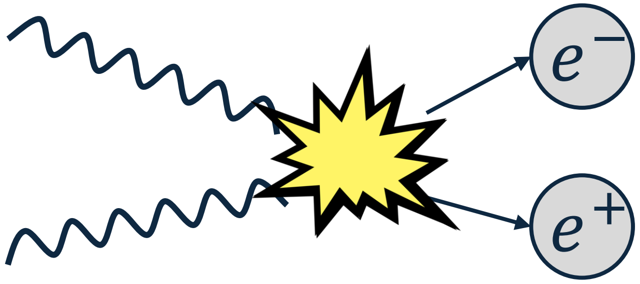
	I generation	II generation	III generation
Quarks	$\mathbf{u}$ up	$\mathbf{c}$ charm	$\mathbf{t}$ top
	$\mathbf{d}$ down	$\mathbf{s}$ strange	$\mathbf{b}$ bottom
Leptons	e^- electron	μ^- muon	τ^- tau
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

Flavor: The **type of quark or lepton**.

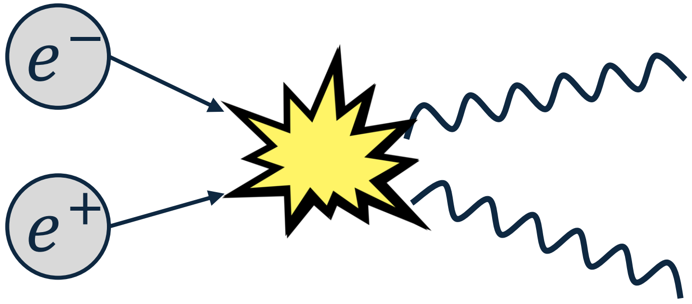
Why do we study flavor physics?

To answer open questions of the Standard Model, for example:

- The Big Bang should have produced the **same amount of matter and antimatter**



particle-antiparticle pair production
from energetic radiation

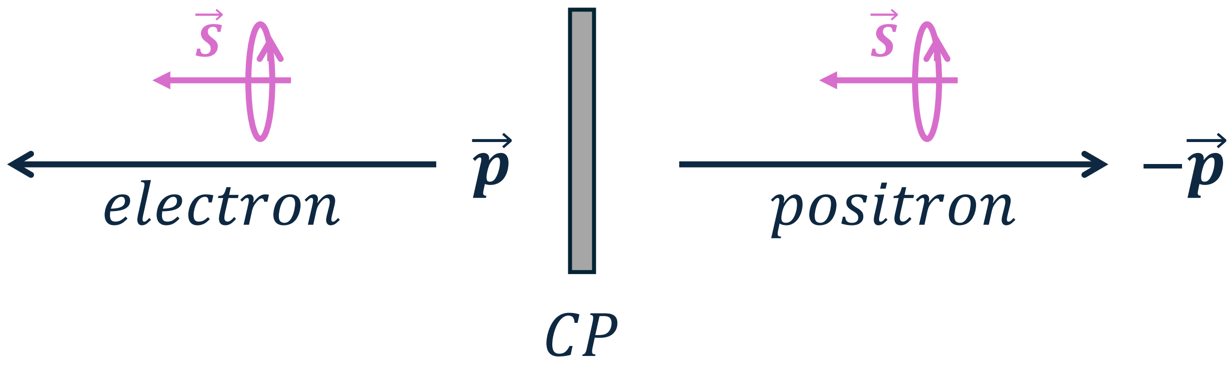


particle-antiparticle annihilation
into energy

- But the Universe is not empty, and everything we see is made mostly of **matter**:

Where did all the antimatter go?

One key ingredient: CP violation



<u>***CP* transforms a particle into its antiparticle**</u>

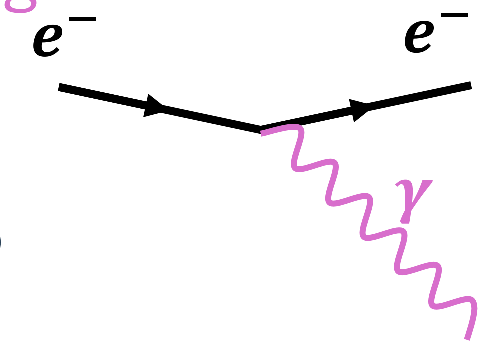
- **Charge Conjugation C**:
  - ➢ Changes the sign of a particle internal quantum numbers (charge, color, flavor, etc.), e.g. $e^- \to e^+, \ u \to \bar{u}$
- **Parity P**, or *spatial inversion*:
  - ➢ $\vec{x} \to -\vec{x}, \ \ \vec{p} \to -\vec{p}$ but $\vec{S} \to \vec{S}$
- If particles and antiparticles <u>behave differently</u>, ***CP* is violated**

Standard Model Interactions

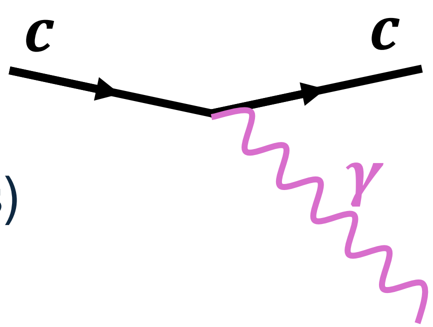
Interaction of gauge bosons with fermions:

- *Electromagnetic interaction* vertices:

Charged Leptons ($e^{\pm}, \mu^{\pm}, \tau^{\pm}$)

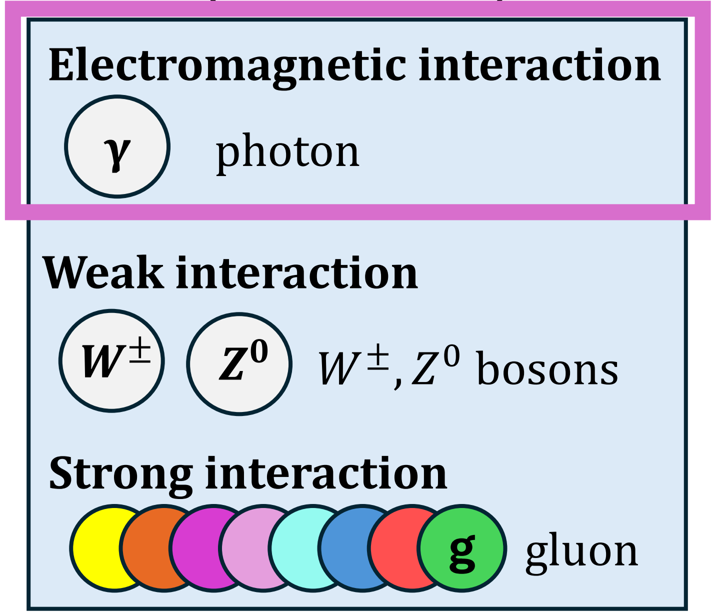


Quarks (and anti-quarks)



➢ <u>No flavor change</u>

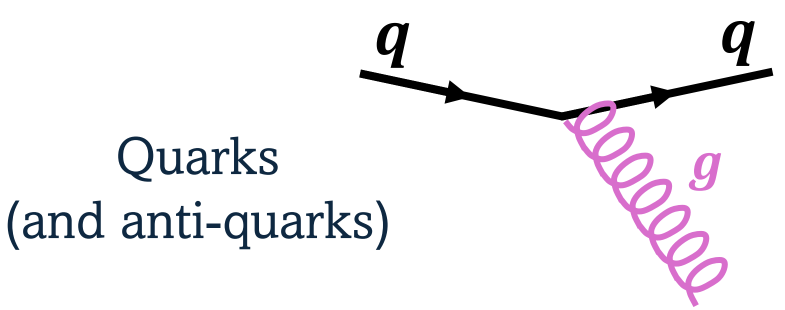
Gauge Bosons
(force mediators)



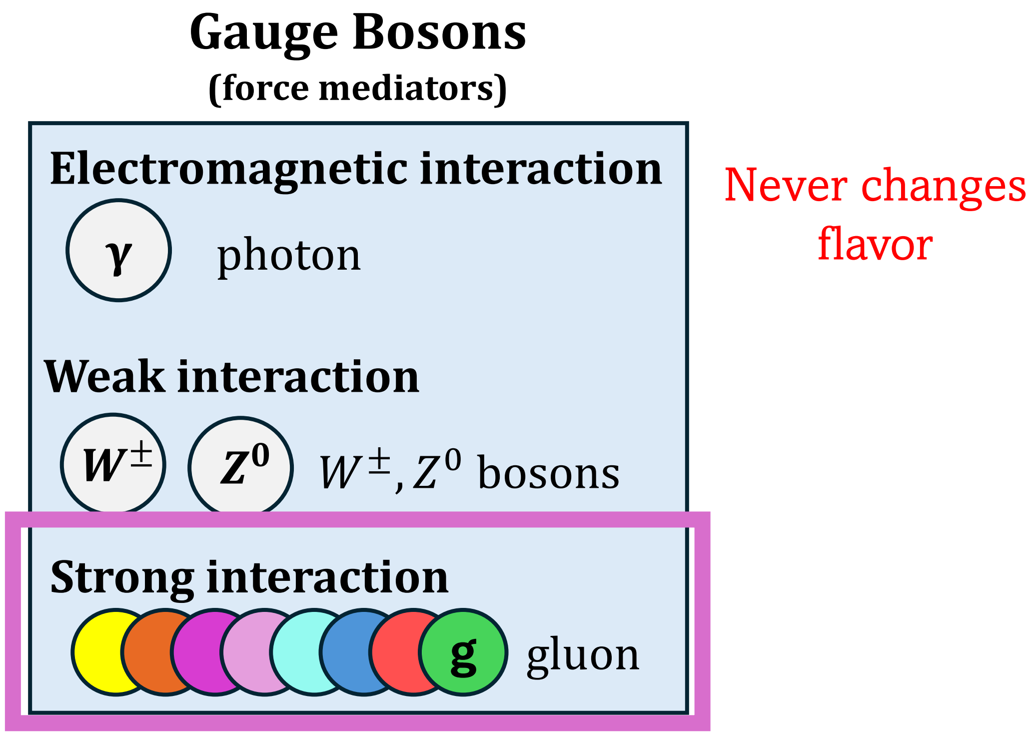
Standard Model Interactions

Interaction of gauge bosons with fermions:

- *Strong interaction* vertex:



➢ <u>No flavor change</u>

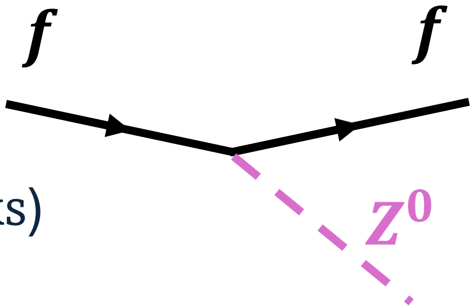


Standard Model Interactions

Interaction of gauge bosons with fermions:

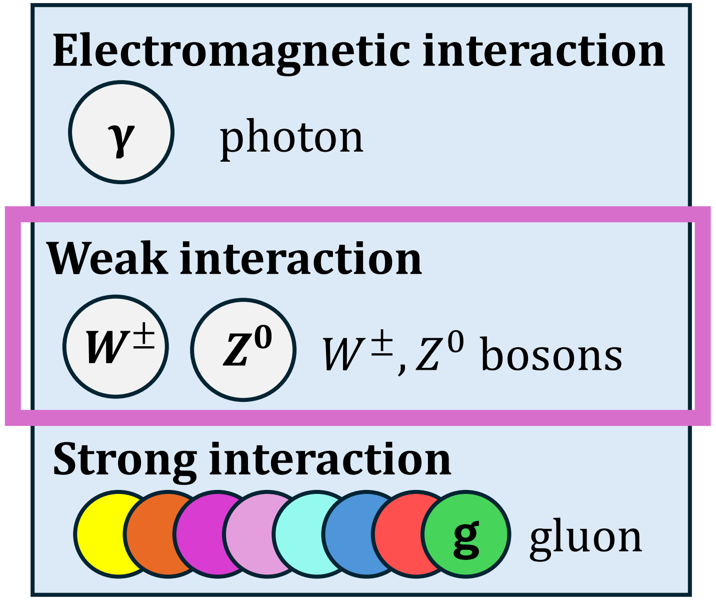
- *Z^0 weak interaction* vertices:

All fermions
(leptons and quarks)



➢ No flavor change

Gauge Bosons
(force mediators)



Never changes flavor

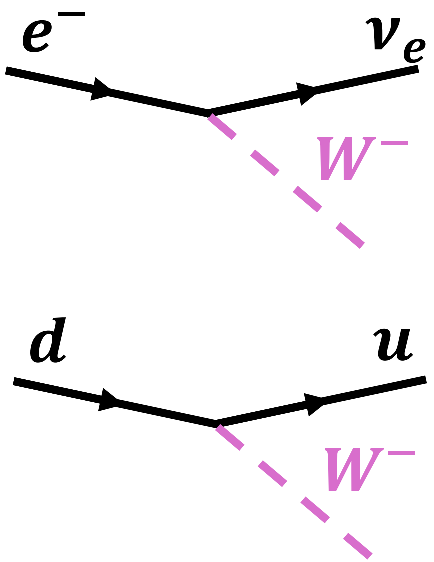
Never changes flavor

Standard Model Interactions

Interaction of gauge bosons with fermions:

- $W^{\pm}$ *weak interaction* vertices:

All fermions (leptons and quarks)



➢ Always changes flavor
➢ Violates *CP*

Gauge Bosons
(force mediators)

Electromagnetic interaction
γ photon
Never changes flavor

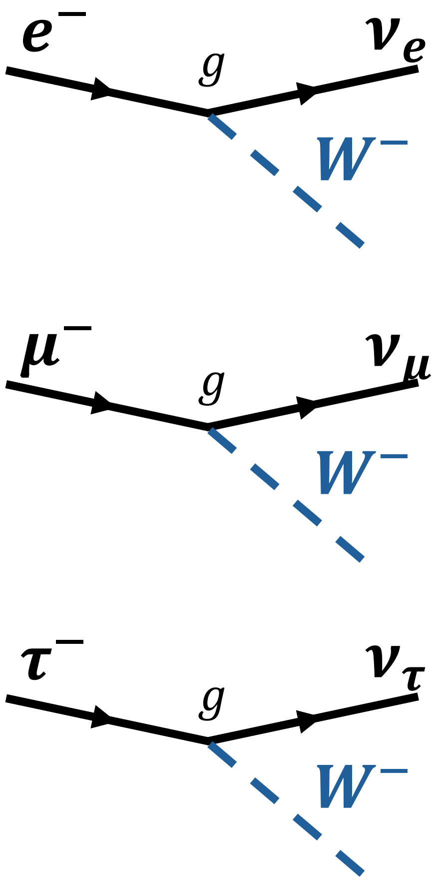
Weak interaction
$W^{\pm}$ Z^0 $W^{\pm}, Z^0$ bosons
Can change flavor

Strong interaction
g gluon
Never changes flavor

We will focus on these
Flavor Changing Interactions

Flavor Changing Interactions

- <u>Lepton vertices</u>



- Flavor changing processes within the **same generation***

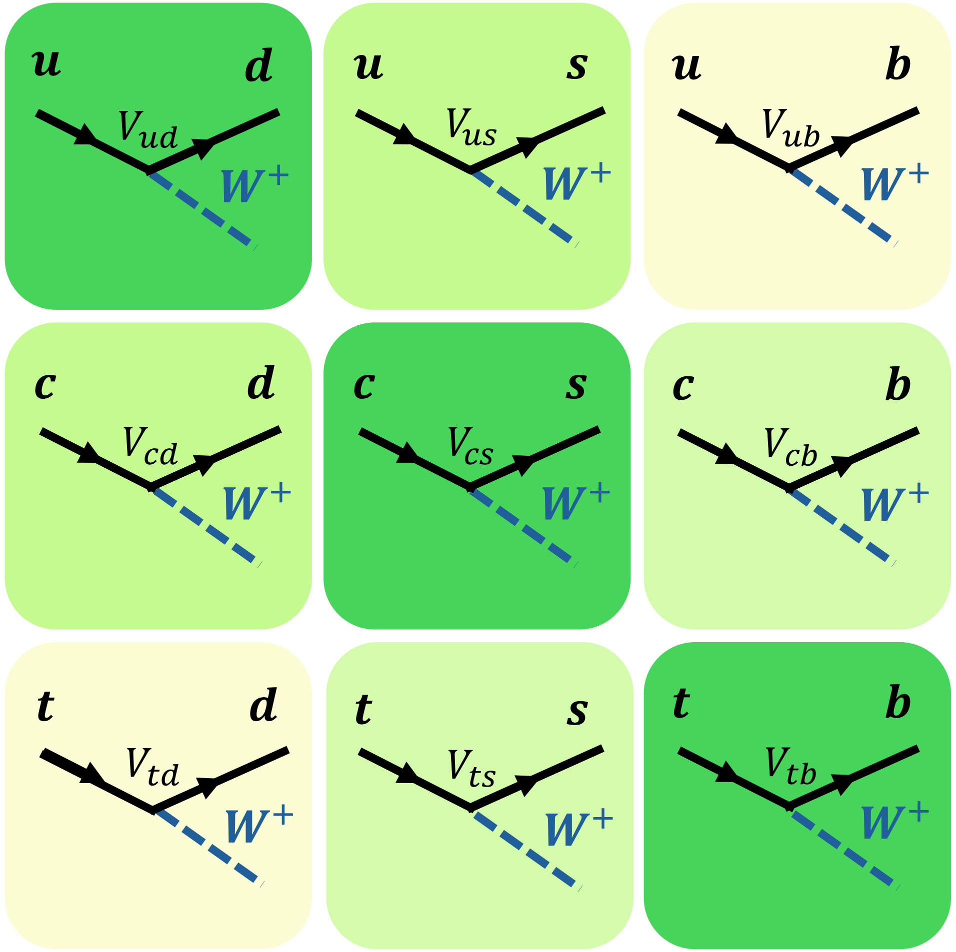
- **Same strength** for all generations

$$e^- \leftrightarrow \nu_e \qquad \mu^- \leftrightarrow \nu_\mu \qquad \tau^- \leftrightarrow \nu_\tau$$

*but neutrino oscillations have been observed:
[Discovery of Atmospheric Neutrino Oscillations](#)
2015 Nobel Prize

Flavor Changing Interactions

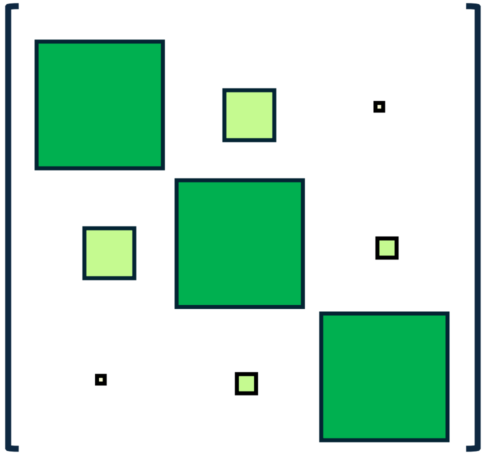
- <u>Quark vertices</u>:



- Flavor changing processes **across generations**, between up-type quarks (u,c,t) and down-type quarks (d,s,b)

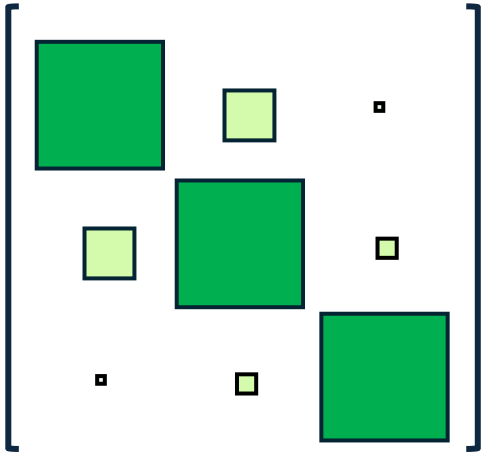
- Strength of the interaction proportional to V_{ij}, elements of the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix V

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



CKM Matrix

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



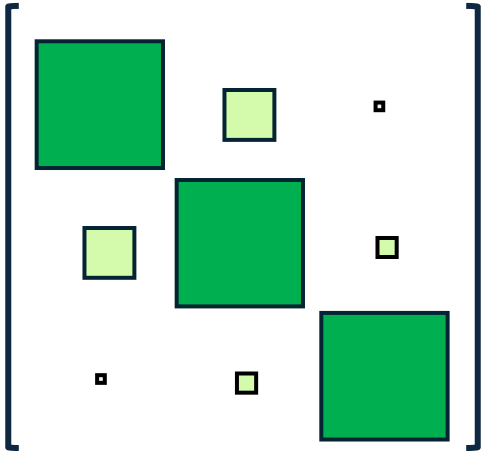
- The CKM matrix V is non-diagonal, and describes mixing between the generations of quarks

    - 1963: Cabibbo introduced the idea of mixing between the first and second generation of quarks (only u, d, s were known at the time)

    - 1972: Kobayashi and Maskawa extended this idea, predicting the existence of a third generation of quarks (t, b), and introducing the CKM matrix, to explain CP violation observed in some particle decays (*Kaon system*)

CP Violation in the Standard Model

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

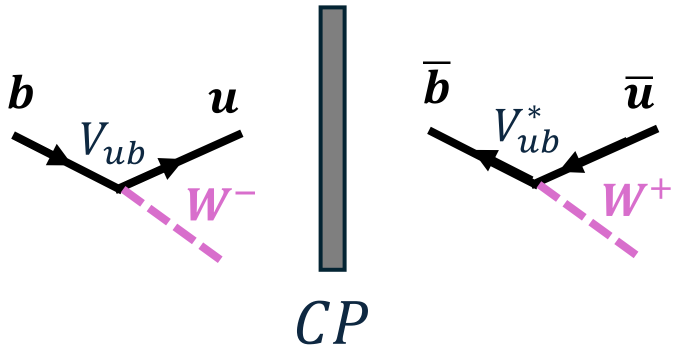


Relative magnitude

Wolfenstein parametrization, $\lambda \sim 0.22$

$$= \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Complex number, origin of CP violation



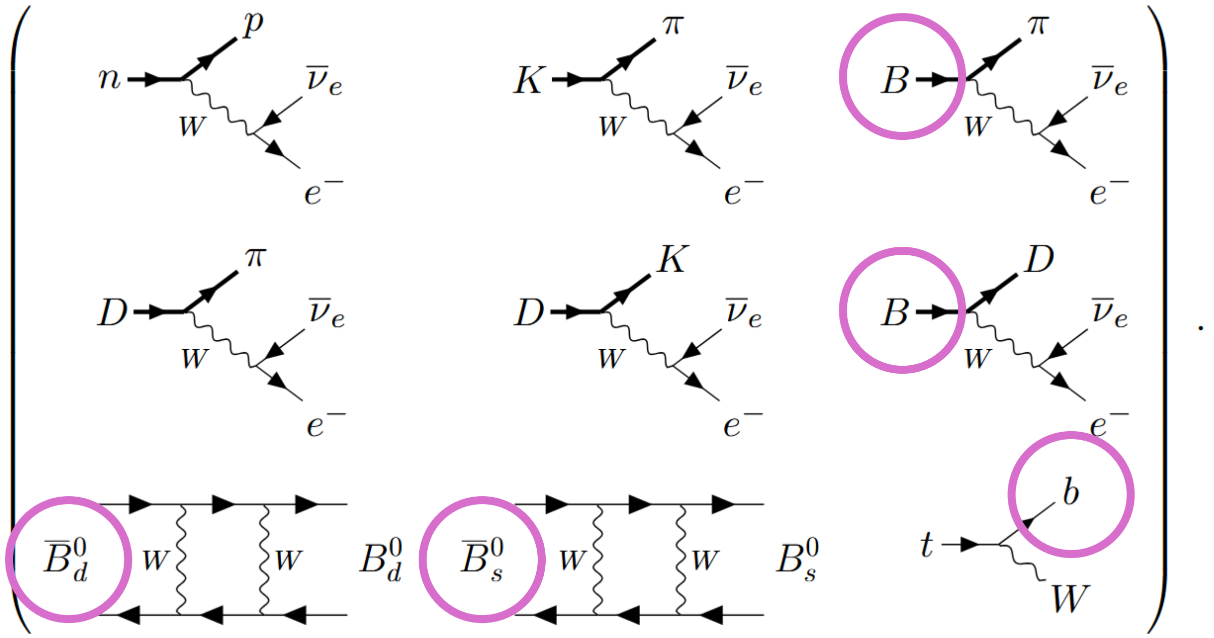
V_{ub} and V_{ub}^* can be different

Measurement of CKM matrix elements

- CP Violation predicted by the SM is orders of magnitude too small to account for matter-antimatter asymmetry of the Universe

- Precise measurements of V can be sensitive to new sources of CP violation from new particles and interactions

$V_{\mathrm{CKM}} =$

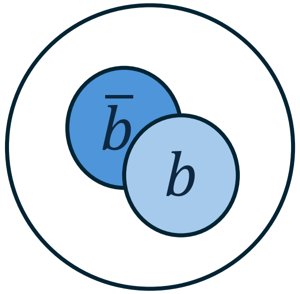


The *b* quark plays a special role in the determination of the CKM matrix element magnitudes

B-Factories

- B^0 meson = $d\bar{b}$
- B^+ meson = $u\bar{b}$

- Collision of e^+ and e^- at $E_{CMS} = 10.58$ GeV

$e^+e^- \rightarrow$ 

$\Upsilon(4s)$

$\rightarrow B^0\bar{B}^0$ or B^+B^-

Production of large and clean $B\bar{B}$ samples, that can be used for flavor physics studies

- Experiments at the B-Factories:

BABAR

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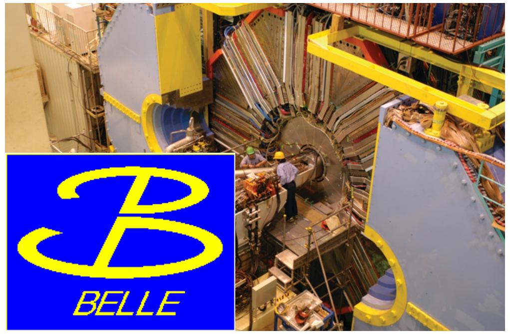
BaBar at SLAC, U.S.
1999-2008



Belle at KEK, Japan
1999-2010

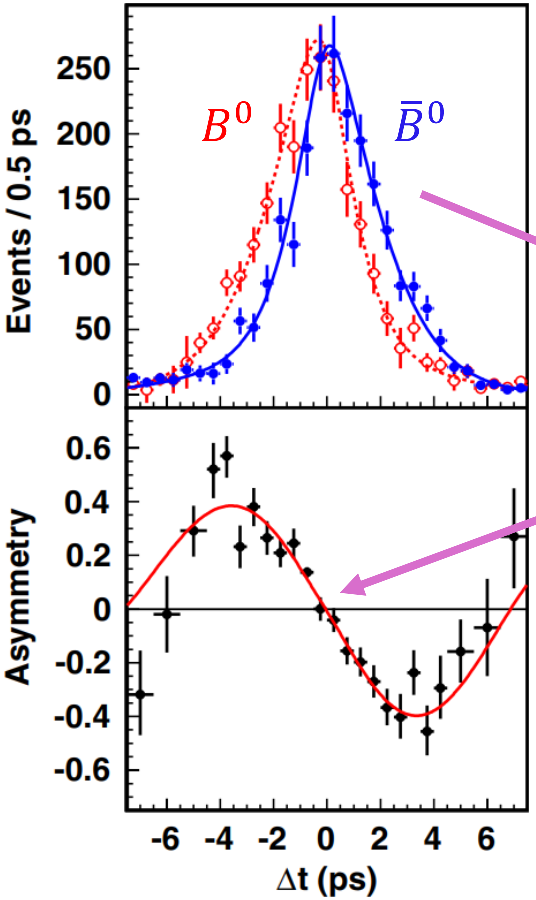
More on the Belle II Experiment after the break, in Dr Haruki Kindo's talk!

- Ongoing
- Belle detector upgrade
- Goal: ~50x the amount of data collected by Belle

CP violation in the B-meson system

Belle and BaBar experiments first **observed CP violation in B-meson** system in 2001, proving Kobayashi and Maskawa scheme for CP violation in the Standard Model.

Kobayashi and Maskawa were **awarded the Nobel Prize** 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"*



Phys. Rev. Lett. **108**, 171802

Difference in the decay time is not the same for the two B flavors: ***CP* violation**

Summary

- We introduced the concept of **flavor** for the Standard Model fermions

- Charged current **weak interactions** ($W^{\pm}$) **change the flavor** of fermions and **violate $\boldsymbol{CP}$**, the particle-antiparticle symmetry (CKM mechanism)

- While the Standard Model has been remarkably successful, it fails at explaining some experimental observations (e.g. **matter antimatter asymmetry**)

- To search for signs of **new particles and interactions beyond the Standard Model**, we rely on precise measurements, like the ones that can be performed at **flavor physics experiments** like **Belle II**.

Thank you! ☺

Backup

Why “flavor”?

- The term *flavor* was first used in particle physics in the context of the quark model of hadrons.
- It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena.
- **Just as ice cream has both color and flavor so do quarks.** (Fritzsch, 2008)

Rev. Mod. Phys. **81**, 1887

Flavor of hadrons

For systems of quarks (e.g. *mesons*, $q\bar{q}$, or *baryons*, qqq):

- **Strangeness** $S = n(\bar{s}) - n(s)$
- **Bottomness** (or beauty) $\mathrm{B} = n(\bar{b}) - n(b)$
- **Charm** $\mathrm{C} = n(c) - n(\bar{c})$
- **Topness** (or truth): $\mathrm{T} = n(t) - n(\bar{t})$
- For u and d quarks we use the **Isospin**
  - Each u quark contributes with $I_3 = \frac{1}{2}$
  - Each d quark contributes with $I_3 = -\frac{1}{2}$

Hadrons are particles made up of quarks. In particular:

- **Mesons:** $q\bar{q}$ bound states, e.g. B^0 meson = $d\bar{b}$
- **Baryons:** made up of three quarks, e.g. proton = uud

Neutrino Oscillations

- Neutrinos are hard to detect, since they do not interact much
  - 100 billion neutrinos pass through your thumbnail every second
  - And yet, you can expect one/two neutrino interactions in your body during your entire lifetime

- Atmospheric neutrinos problem:
  - From cosmic rays: $\pi^+ \to \mu^+ \nu_\mu$ and $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
  - But, early experiments measured a reduced rate of ν_μ wrt the prediction
  - **Solution → muon neutrinos can convert to neutrinos of different flavor, e.g. $\nu_\mu \to \nu_\tau$**

TABLE 1. Comparison of the number of observed events in Kamiokande with the expectation from simulations. The detector exposure was 2.87 kiloton years.

	Data	Prediction
e-like (mostly CC ν_e interactions)	93	88.5
μ-like (mostly CC ν_μ interactions)	85	144.0

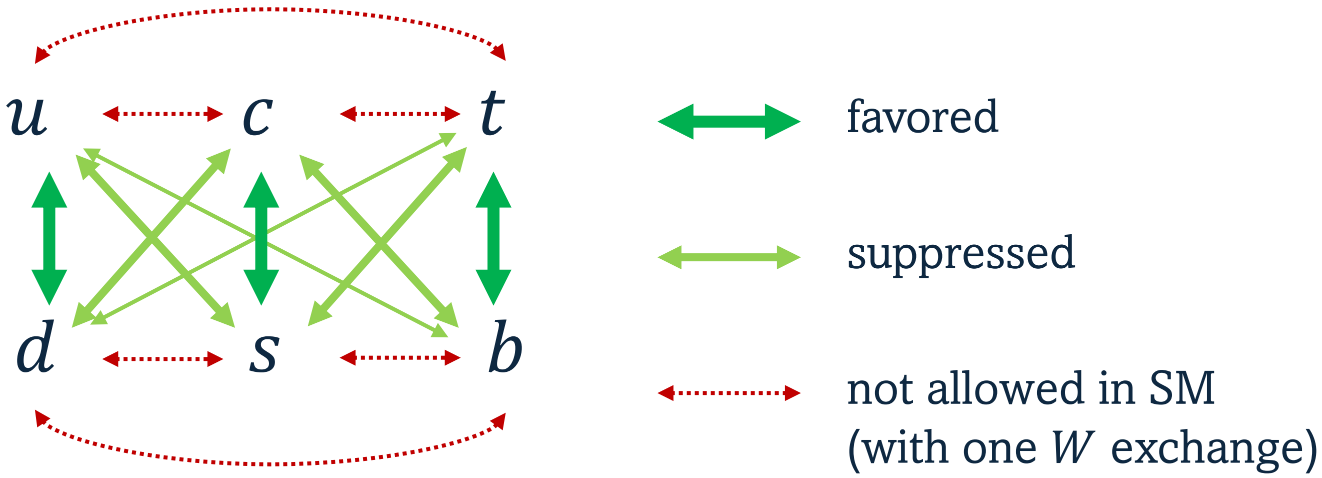
$$P_{\nu_e \to \nu_\mu} = \left(\sin(2\theta) \sin \frac{(m_1^2 - m_2^2) c^3}{4\hbar E} z \right)^2$$

non-zero mixing between the flavors

non-zero mass difference

Flavor Changing Interactions

- Quark vertices
  - Flavor changing processes **across generations**



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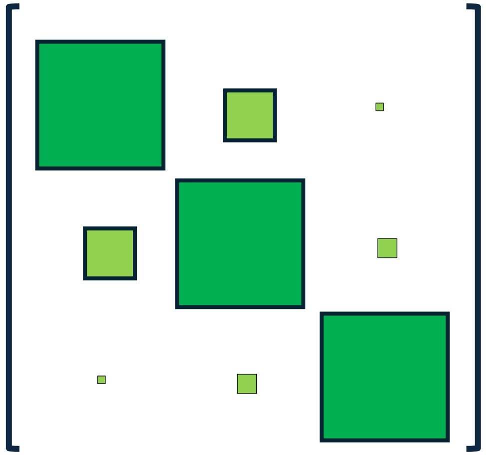
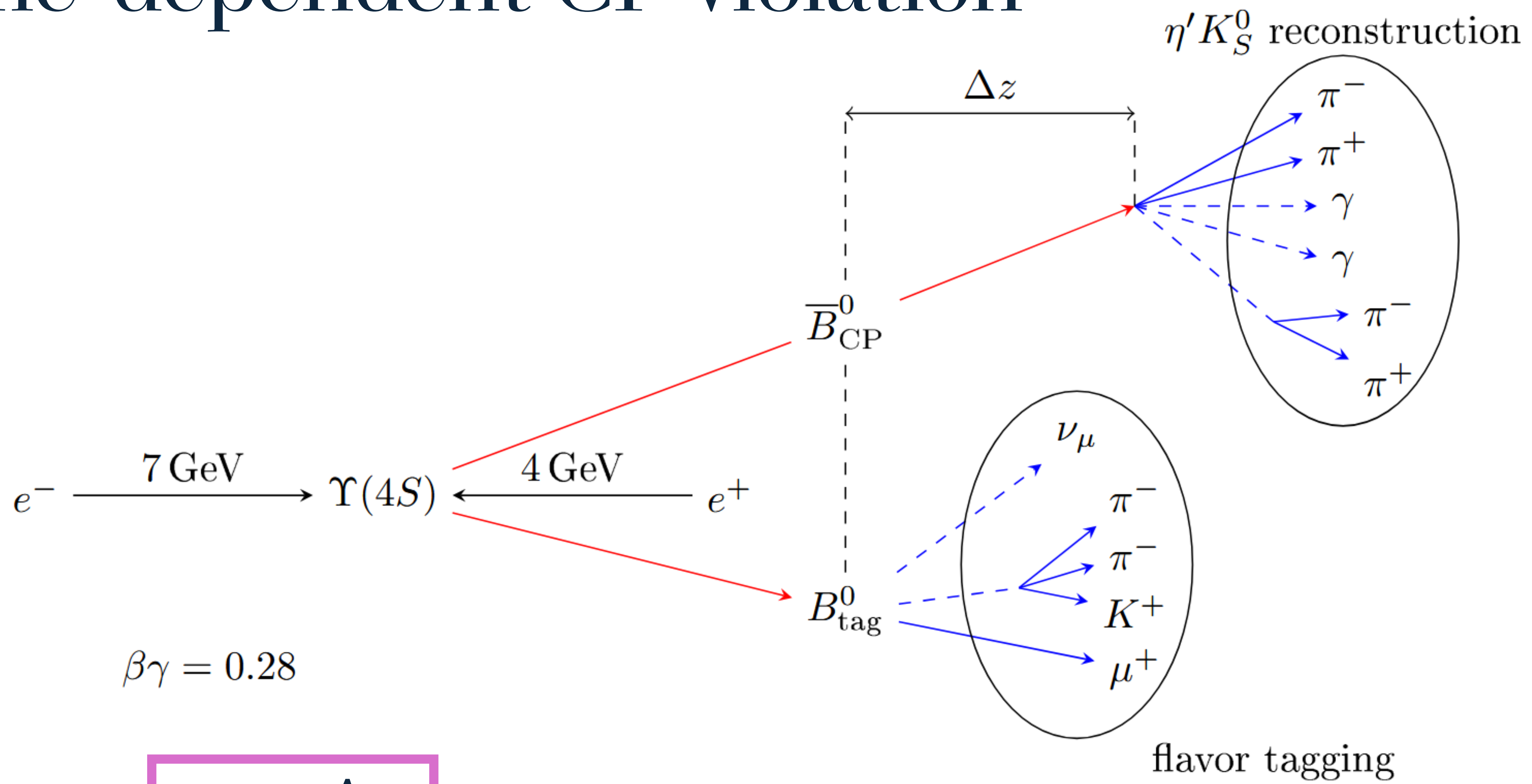


Time-dependent CP violation



$$\boxed{\Delta t \sim \frac{\Delta z}{\beta\gamma c}}$$

this is the quantity in the histogram of slide 15

CKM Matrix

- The origin of the CKM matrix V is the **difference between mass eigenstates and weak interaction eigenstates**, i.e. flavor eigenstates

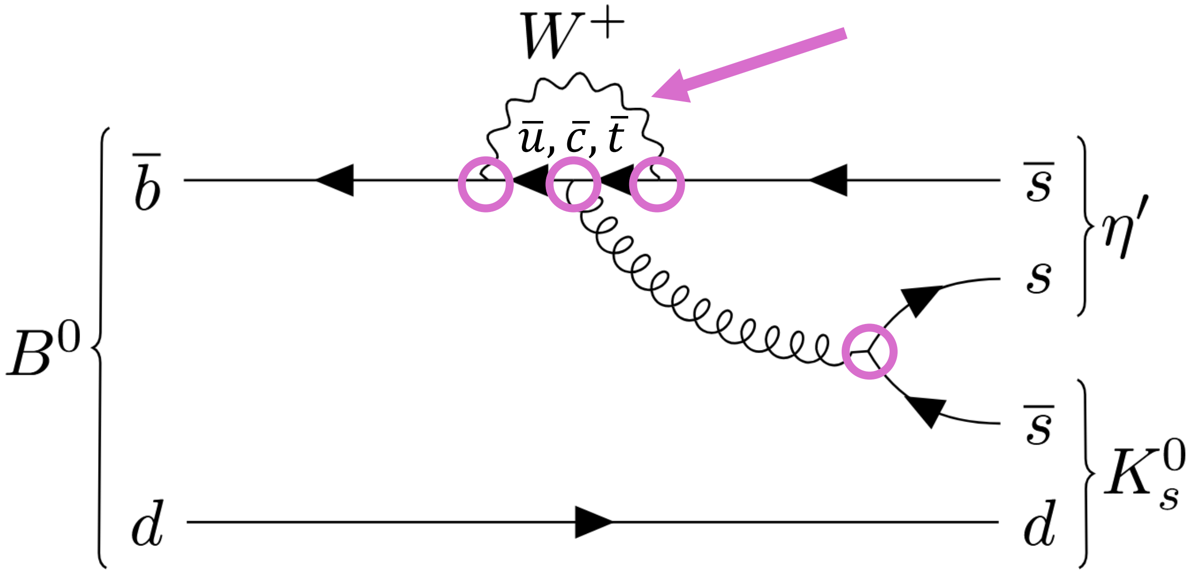
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Flavor eigenstates

Mass eigenstates

- $W^{\pm}$ interacts with $\binom{u}{d'}, \binom{c}{s'}, \binom{t}{b'}$ with universal strength g, but universality is broken when we move to mass eigenbasis

CP violation in loop processes



- Comparing CP violation in these transitions to the one in transitions with no loops we are potentially sensitive to new physics occurring in the loop

Types of CP Violation

- In the Standard Model there are **three types** of CP violation:

  1. **CP violation in the wave function**, also called violation in mixing
     - It happens when the wave functions of the free Hamiltonian are not CP eigenstates. It is a small effect that has been observed in the neutral kaon system.

  2. **CP violation in decays**, also called <u>direct</u> CP violation
     - Let M be a meson decaying into the final state f . If CP is conserved the amplitude $M \to f$ should be equal to $\bar{M} \to \bar{f}$.

     This type of CP violation can be observed in both neutral and charged mesons, e.g. $B^0 \to K^+\pi^-$

Types of CP Violation

- In the Standard Model there are **three types** of CP violation:

  3. **Violation in the interference between decays with and without oscillation**
     - This type of CP violation is due to the interference of the decay without mixing $M \rightarrow f$ and the decay with mixing $M \rightarrow \bar{M} \rightarrow f$. This effect can be observed in the decay to final states common to both M and $\bar{M}$. It was observed for the first time in 2001 by Belle and BaBar experiments **(result of slide 15)**

$$B^0 \rightarrow J/\psi K_S^0$$

Decay without oscillation

$$B^0 \rightarrow \bar{B}^0 \rightarrow J/\psi K_S^0$$

Decay with oscillation