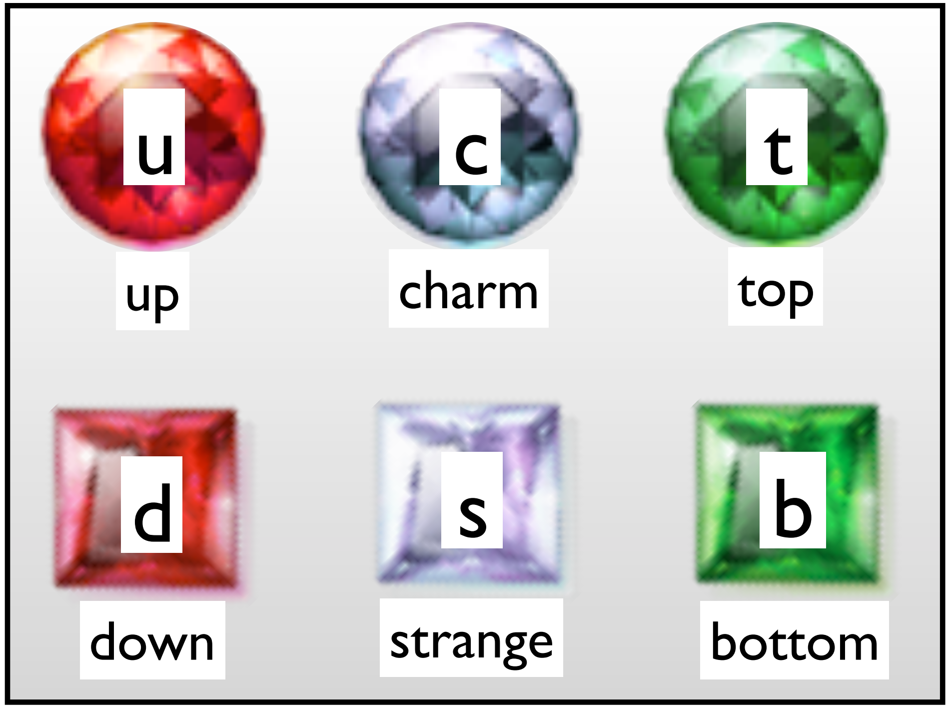
Heavy Flavours I

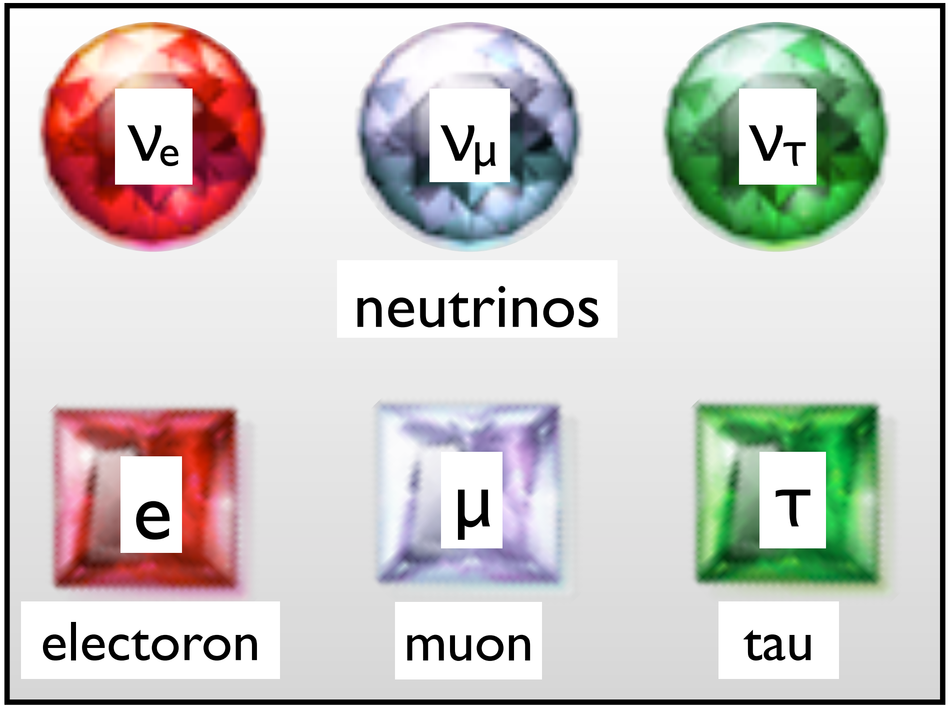
FAPPS 2011 at Les Houches

Emi KOU (LAL/IN2P3)

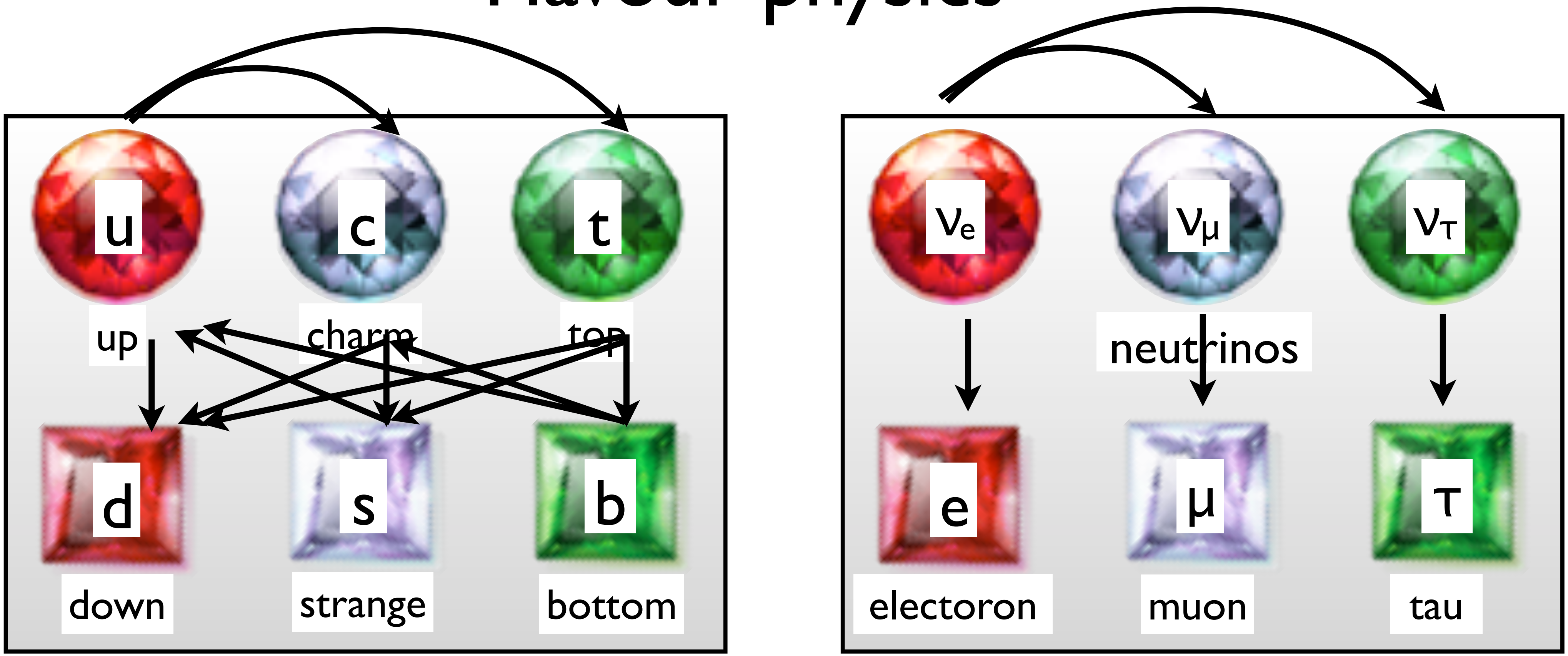
17/10/2011

Flavour physics

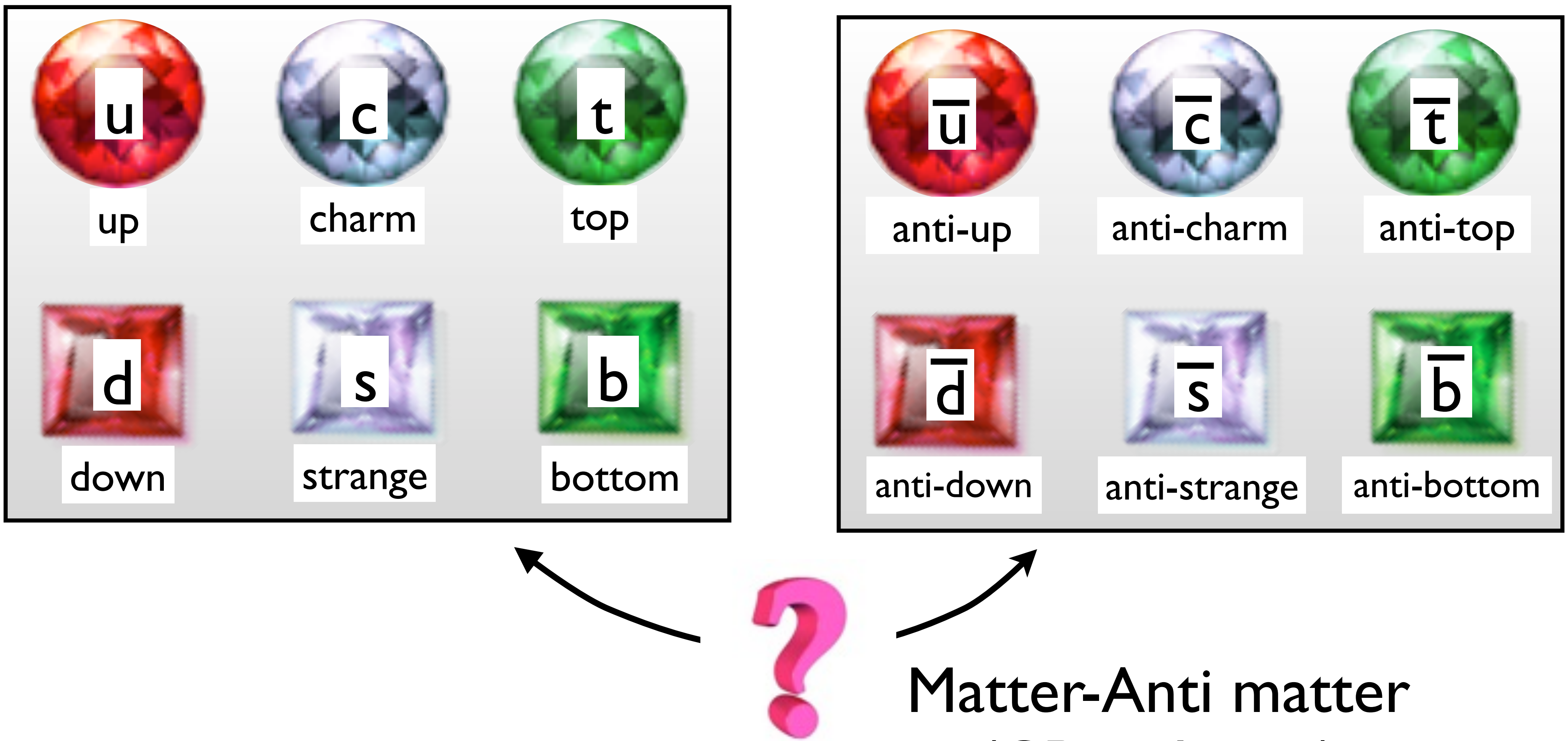




Flavour physics

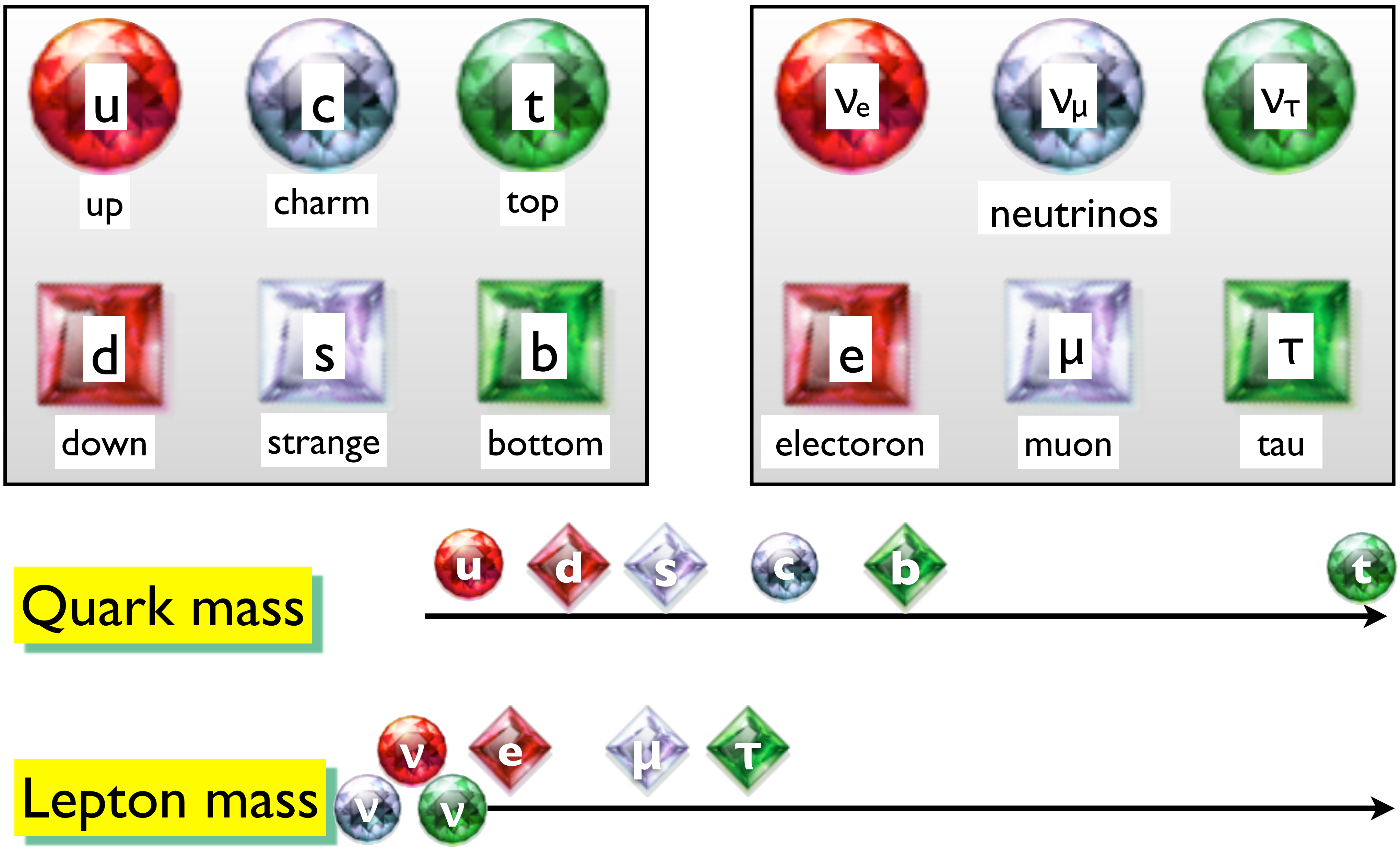


Flavour physics

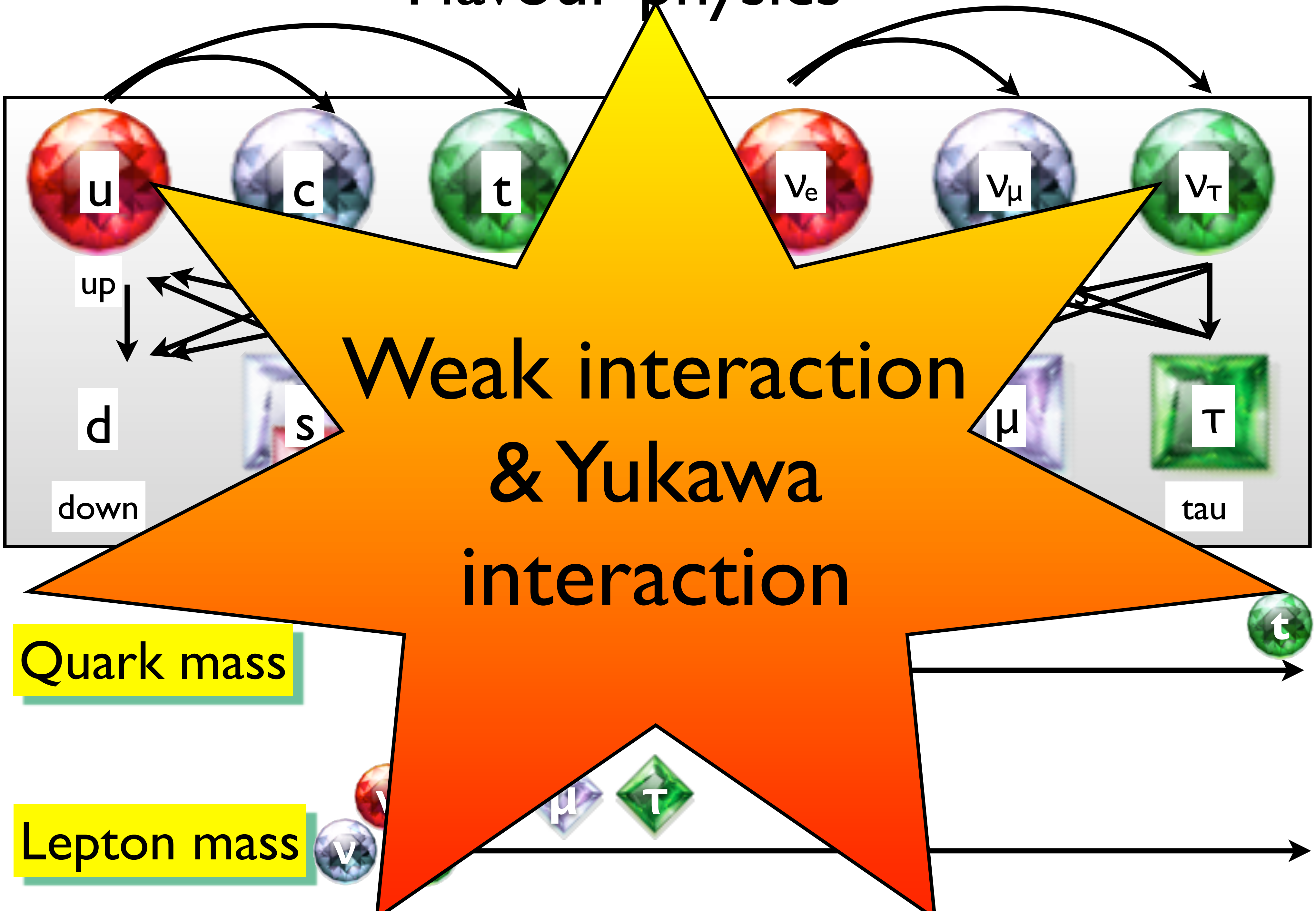


Matter-Anti matter
(CP violation)

Flavour physics



Flavour physics



Plan

- 1st lecture: Introduction to flavour physics
  - ★ Weak interaction processes (charges, neutral processes, GIM mechanism)
  - ★ Discovery of CP violation in the K system
  - ★ Measuring oscillation in the B system
- 2nd lecture: Describing oscillations within SM
  - ★ Kobayashi-Maskawa mechanism for CP violation
  - ★ Testing the unitarity of the CKM matrix

Plan

- 3rd lecture: Searching new physics with flavour physics
  - ★ Some examples in the past
  - ★ Some examples in the future

Flavour physics in SM

To learn in this part...

1. Weak interaction processes (charges, neutral processes, GIM mechanism)
2. Matter-Anti matter asymmetry: CP violation

What kind of weak interaction processes do you know?

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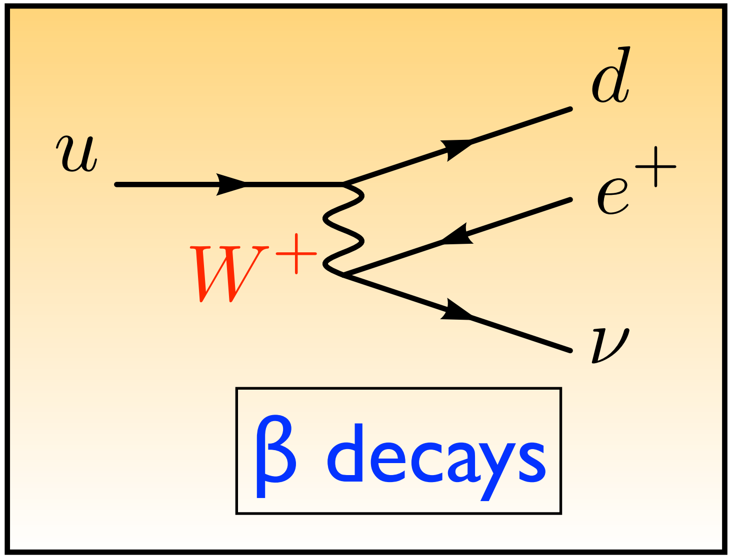
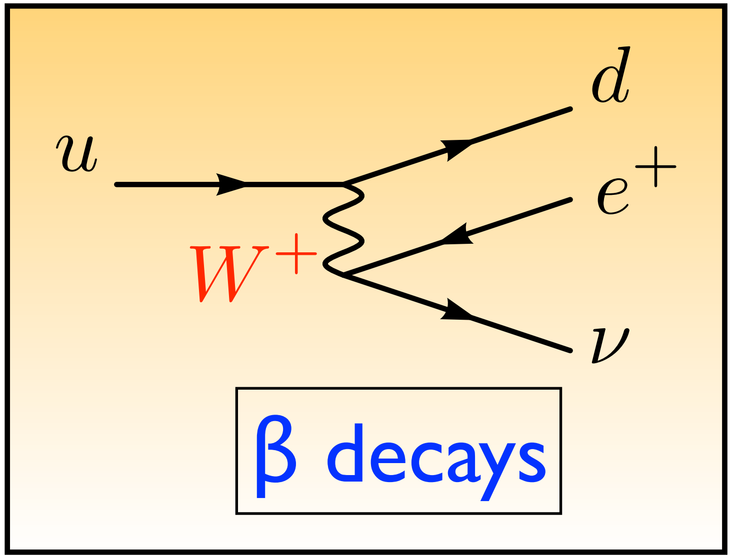
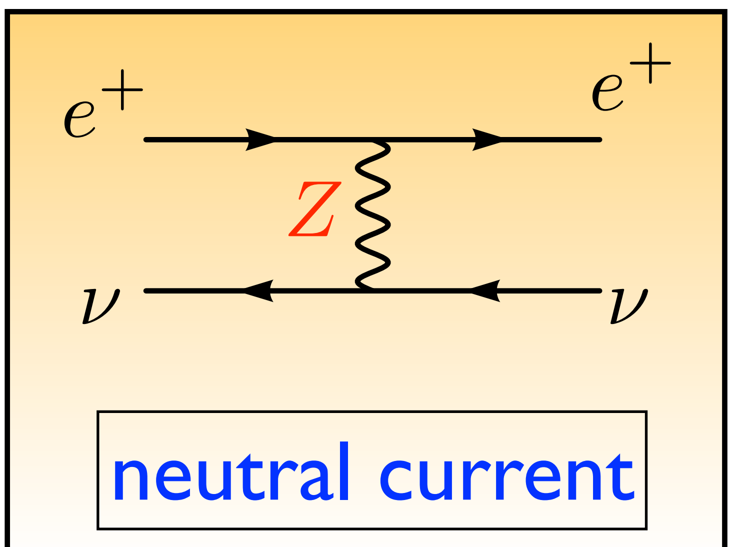


What kind of weak interaction processes do you know?





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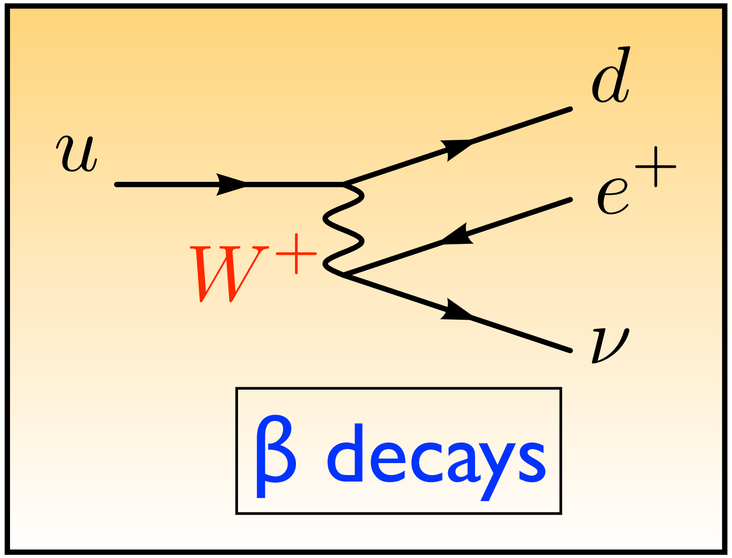

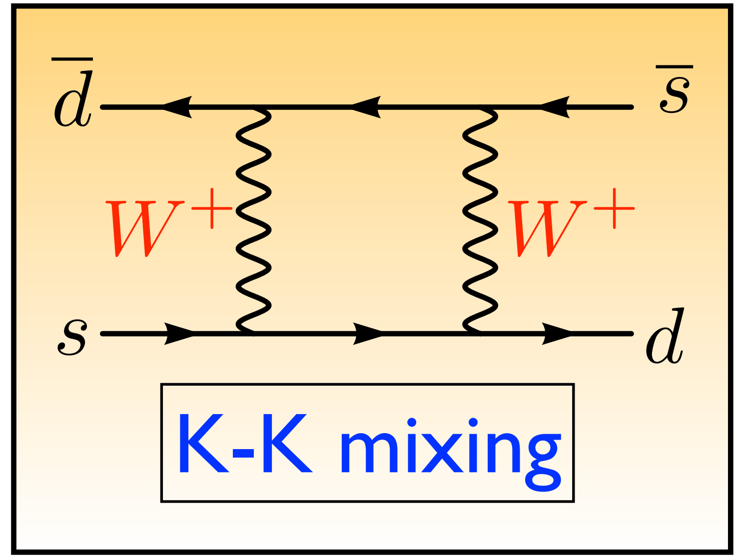

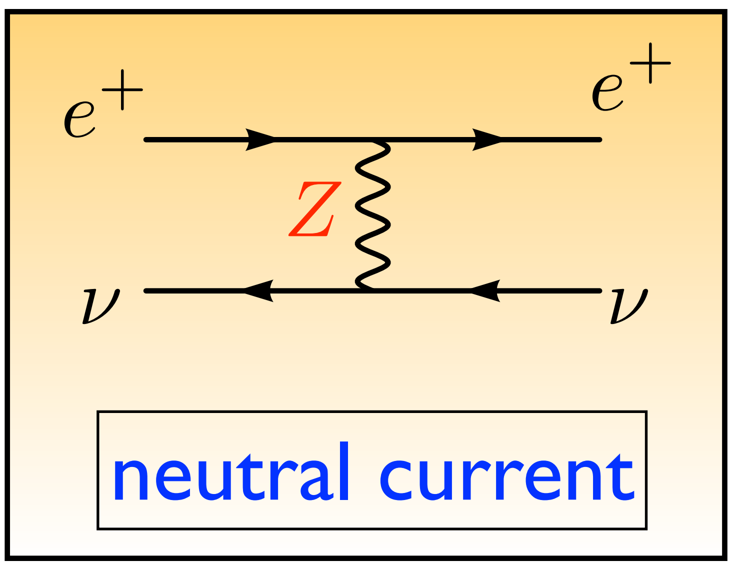

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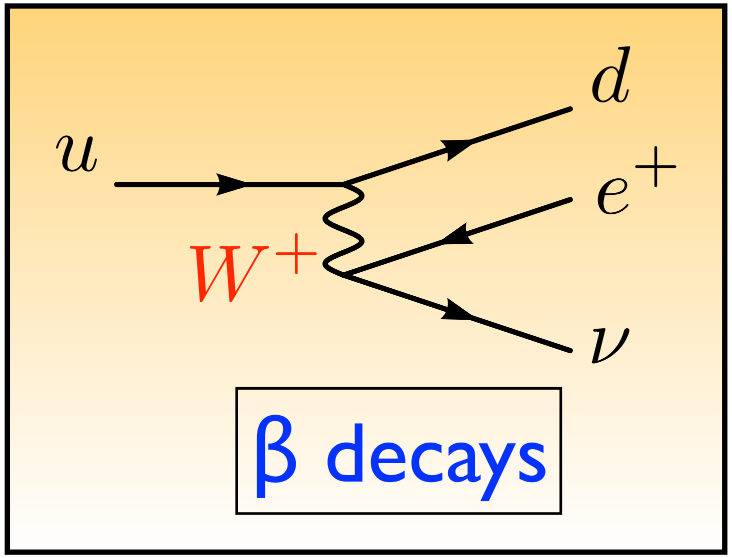

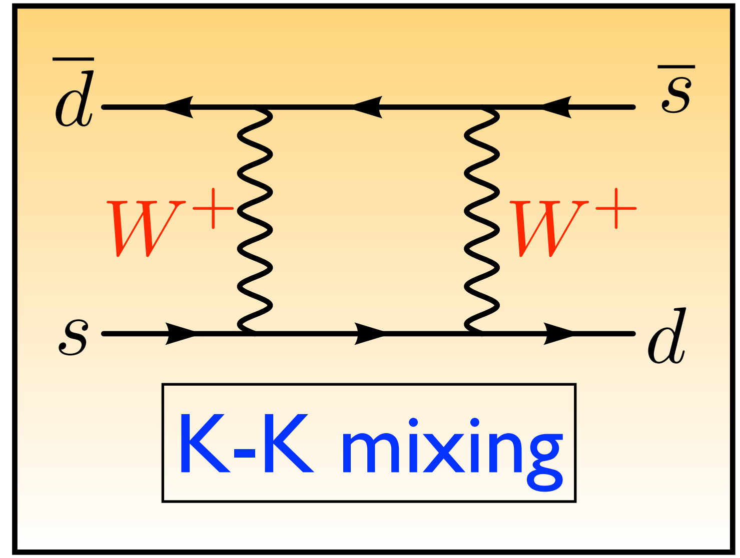

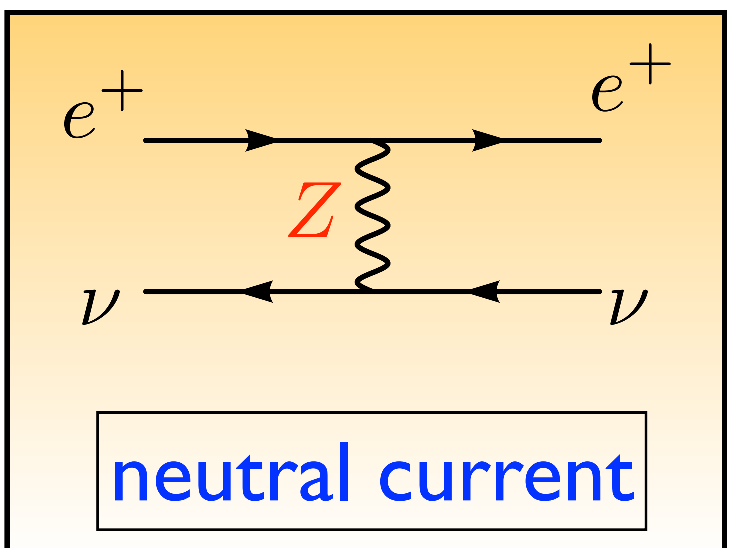

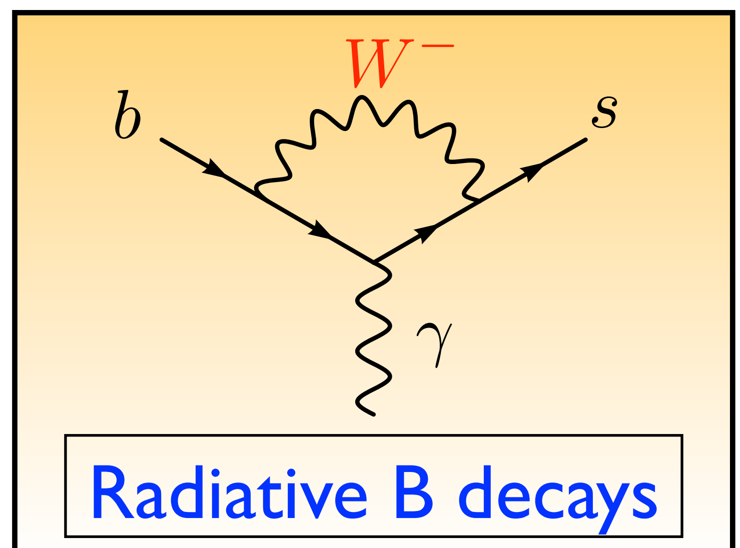

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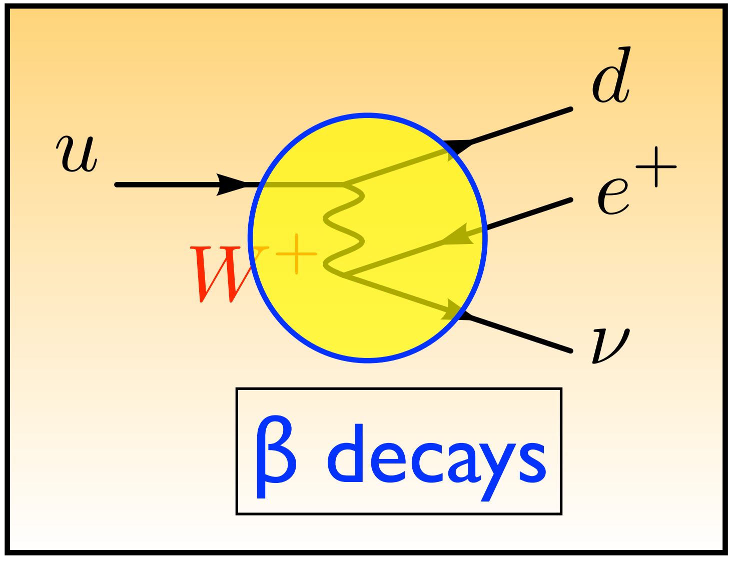

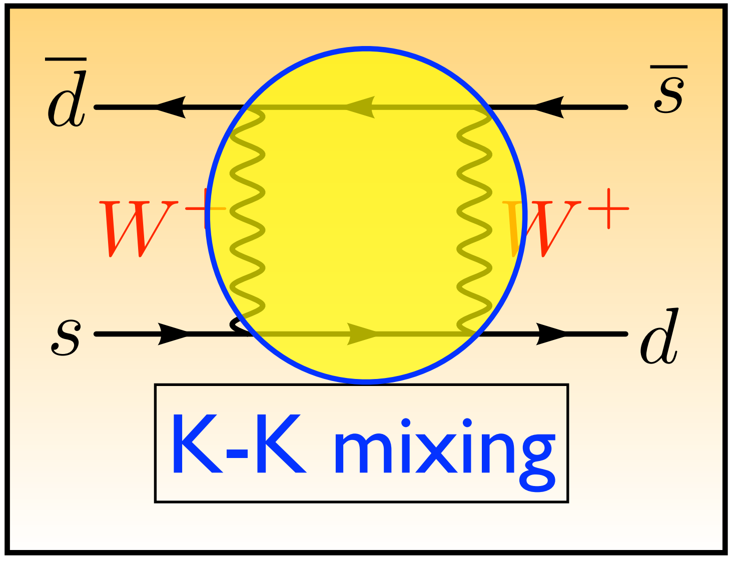

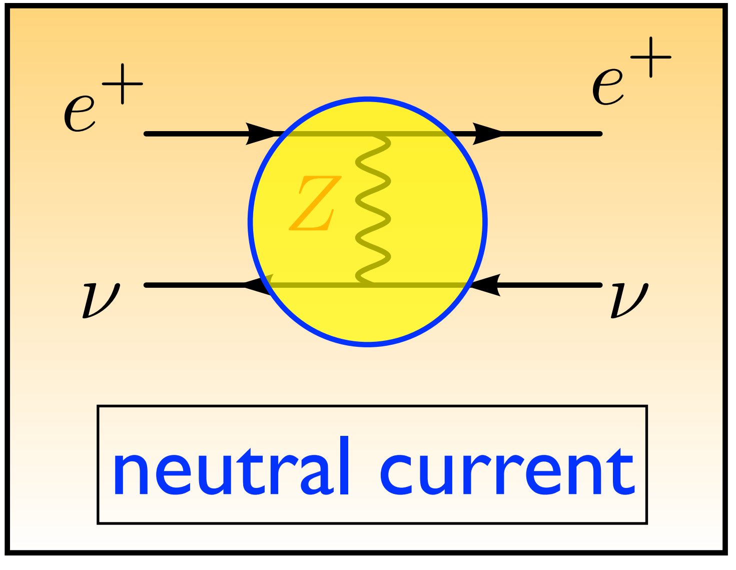

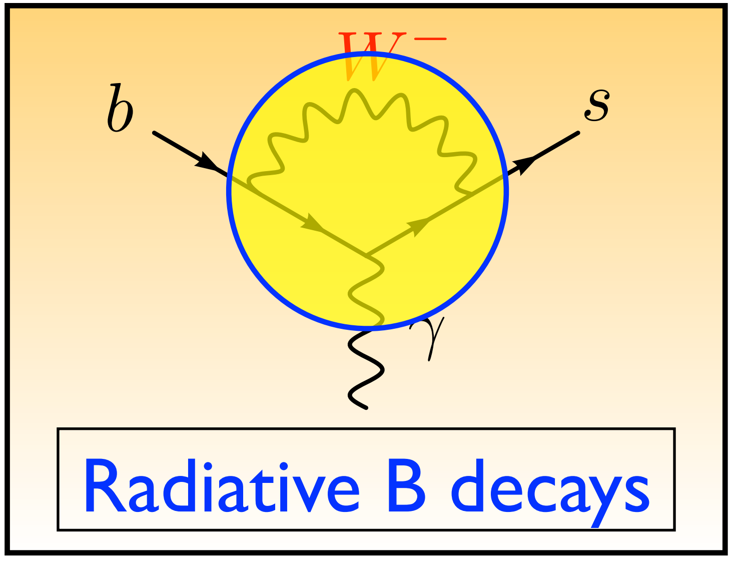

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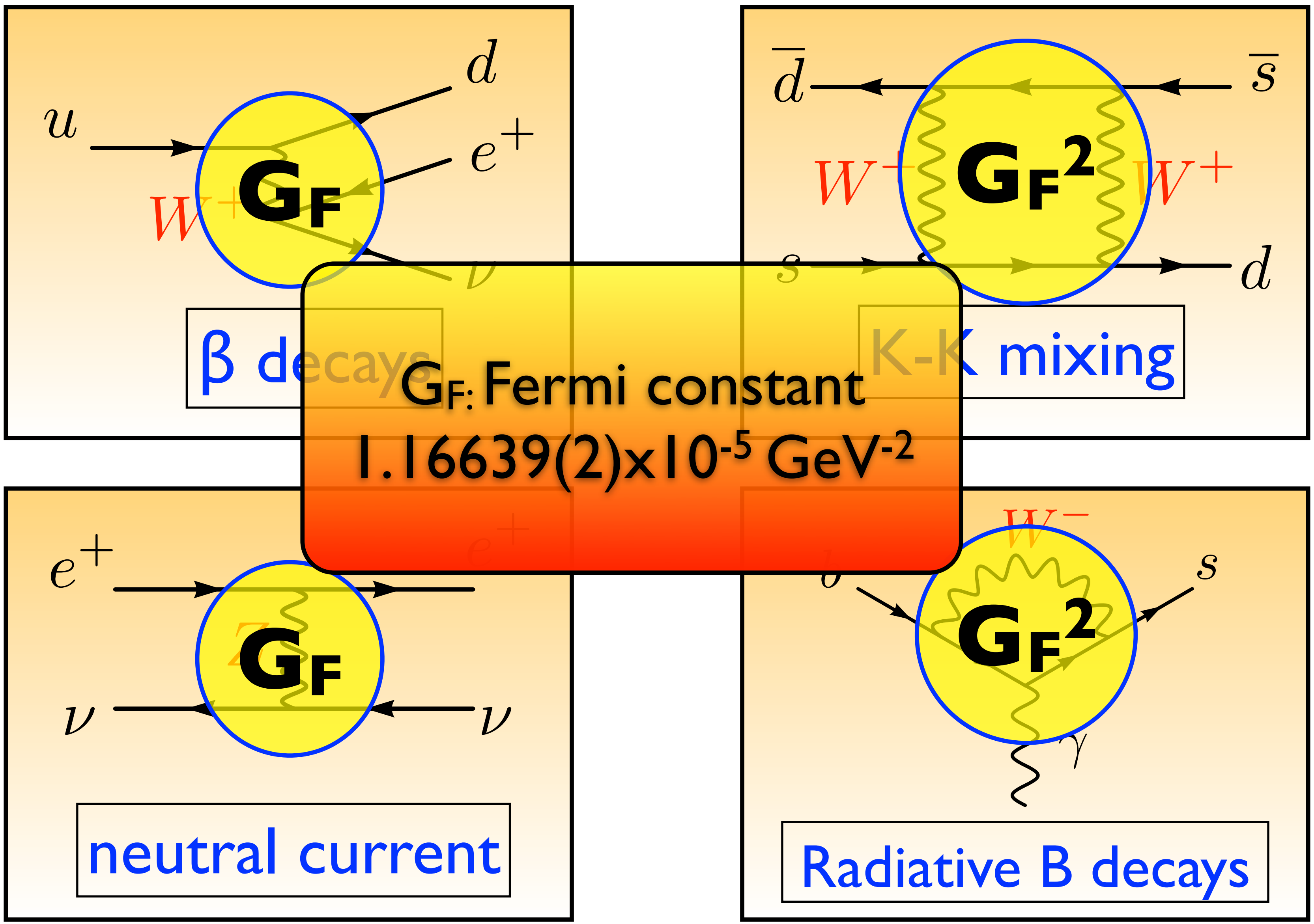
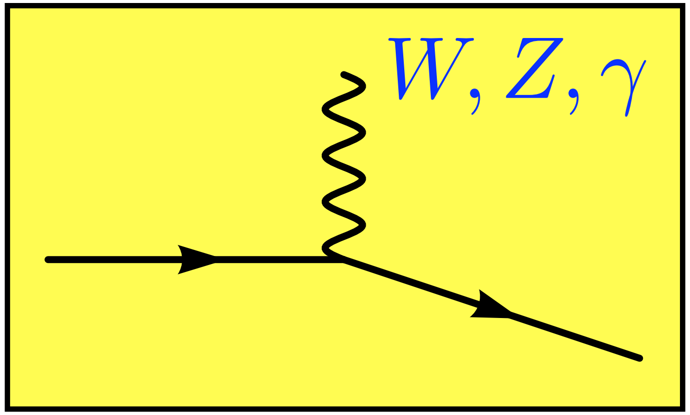
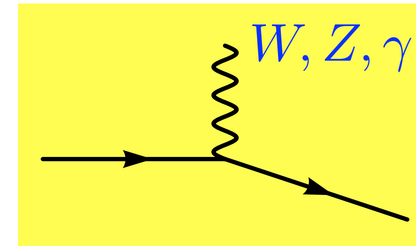


Theoretical description in SM: Charged and Neutral Currents



Theoretical description in SM: Charged and Neutral Currents



$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}}(J_\mu^+ W^{-\mu} + J_\mu^- W^{+\mu})$$

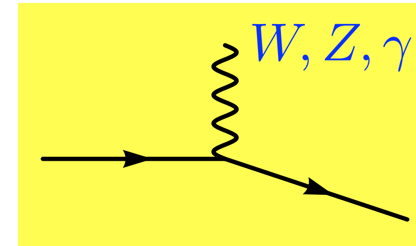
$$\mathcal{L}_{NC} = eJ_\mu^{\mathrm{em}} A^\mu + \frac{g}{\cos\theta_W}(J_\mu^3 - \sin^2\theta_W J_\mu^{\mathrm{em}}) Z^\mu$$

$$\boxed{G_F = \frac{g^2}{4\sqrt{2} m_W^2}}$$

SU(2) part only

$$\begin{aligned}
J_\mu^+ &= \overline{U}_L \gamma_\mu D_L + \bar{l}_L \gamma_\mu \nu_L \\
J_\mu^3 &= \frac{1}{2}(\overline{U}_L \gamma U_L - \overline{D}_L \gamma D_L - \bar{l}_L \gamma l_L + \overline{\nu}_L \gamma \nu_L) \\
J_\mu^{\mathrm{em}} &= \frac{2}{3}\overline{U}_L \gamma U_L - \frac{1}{3}\overline{D}_L \gamma D_L - \bar{l}_L \gamma_\mu l_L
\end{aligned}$$

Theoretical description in SM: Charged and Neutral Currents



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$$\boxed{G_F = \frac{g^2}{4\sqrt{2}m_W^2}}$$

Each has 3 Flavours = 3 generation

SU(2) part only

$$J_\mu^+ = \overline{U}_L \gamma_\mu D_L + \bar{l}_L \gamma_\mu \nu_L$$

$$J_\mu^3 = \frac{1}{2}(\overline{U}_L \gamma U_L - \overline{D}_L \gamma D_L - \bar{l}_L \gamma l_L + \overline{\nu}_L \gamma \nu_L)$$

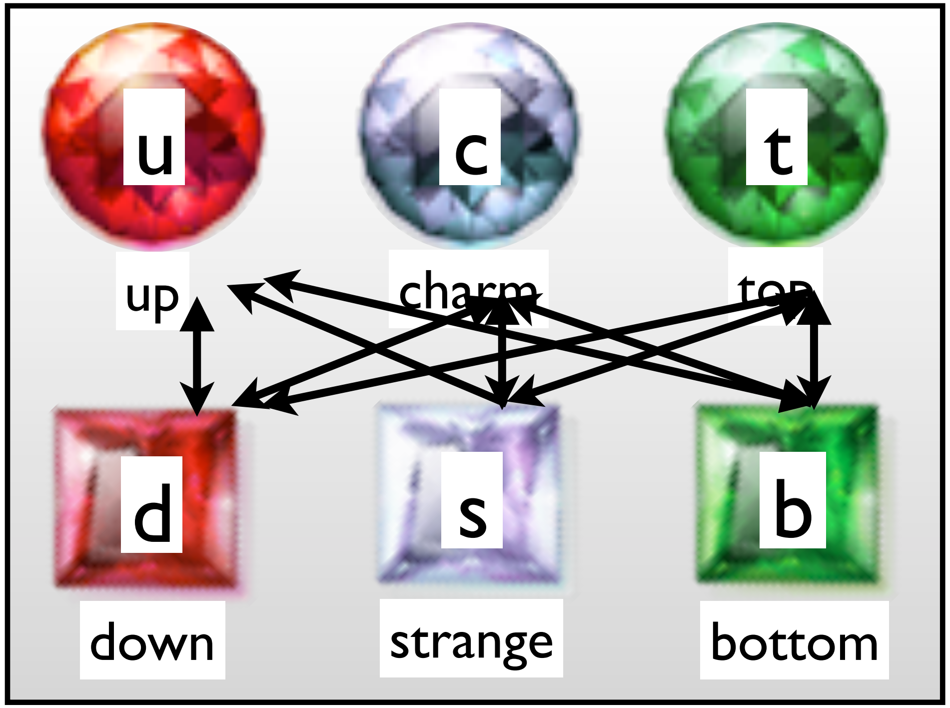
$$J_\mu^{\rm em} = \frac{2}{3}\overline{U}_L \gamma U_L - \frac{1}{3}\overline{D}_L \gamma D_L - \bar{l}_L \gamma_\mu l_L$$

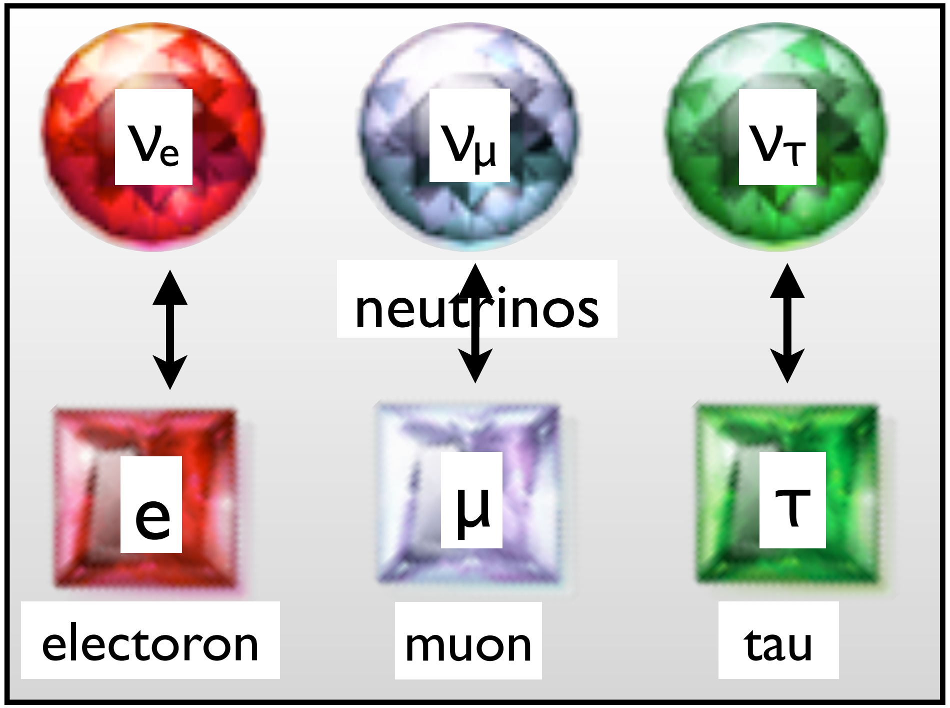
$$U_L = \begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix}$$

$$D_L = \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

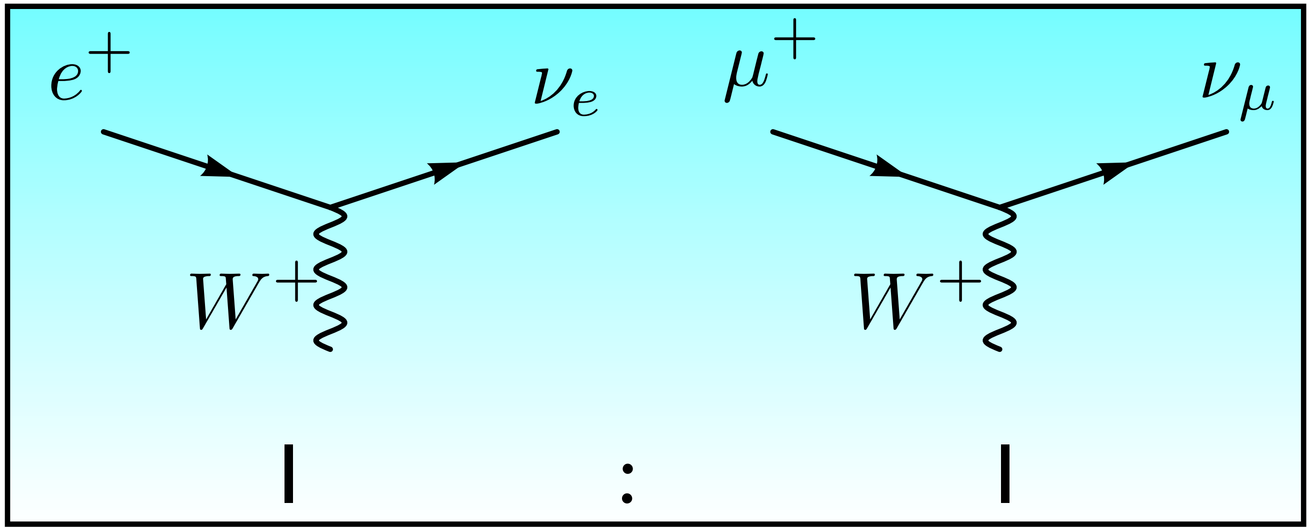
$$l_L = \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix}$$

Charged Current



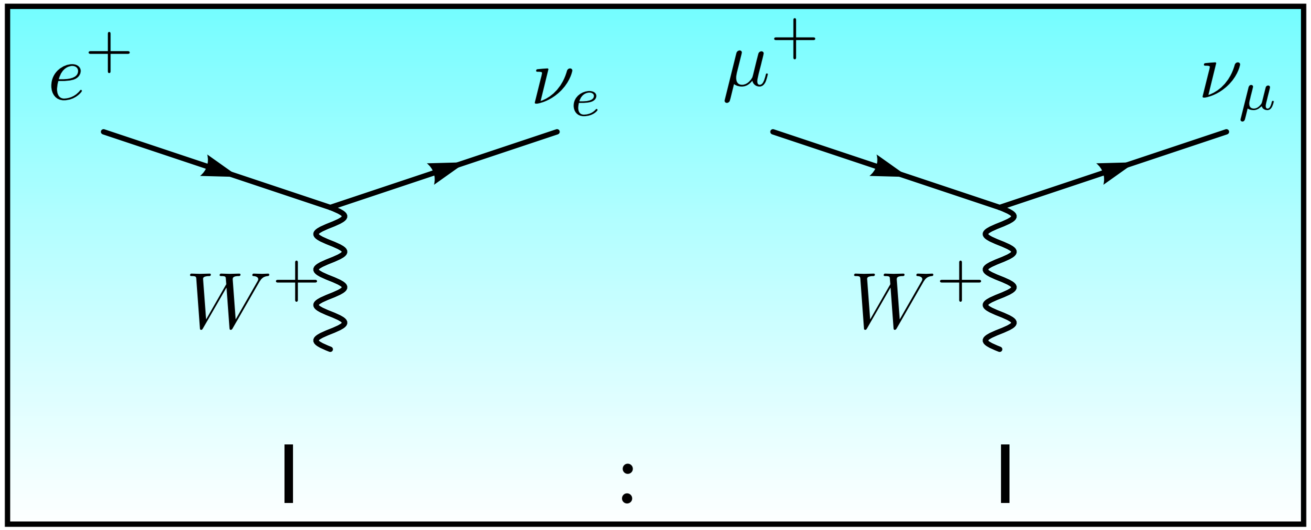


Different strength for different flavours?!



Lepton couplings are all the same strength

Different strength for different flavours?!



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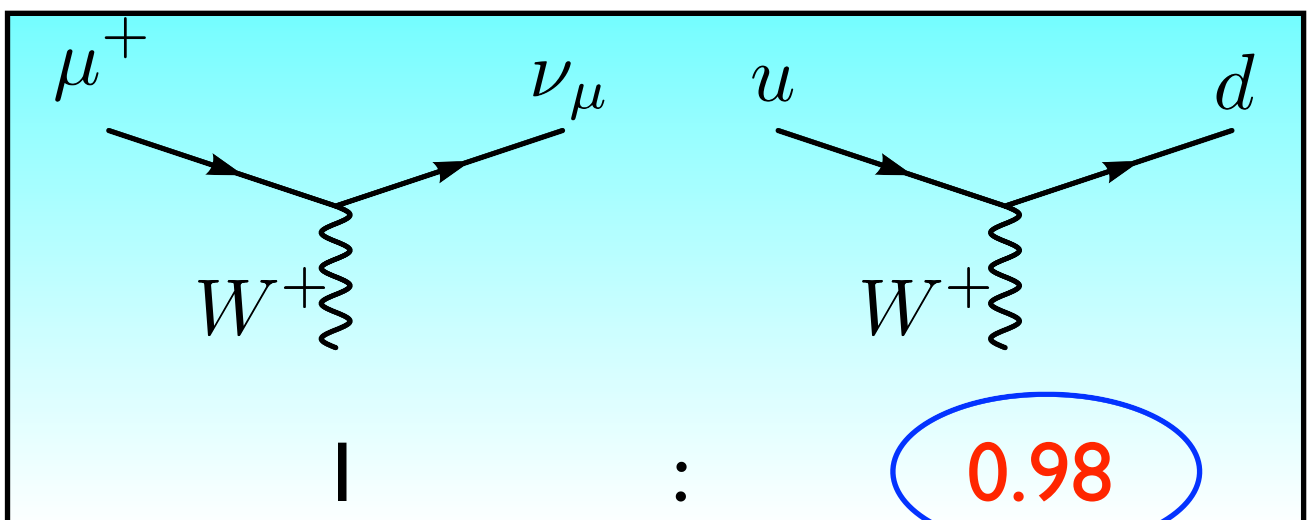
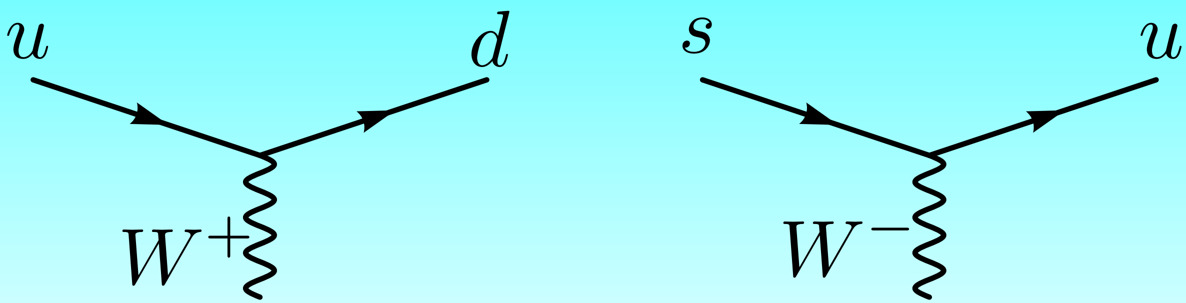


Up-Down coupling is slightly smaller than lepton's

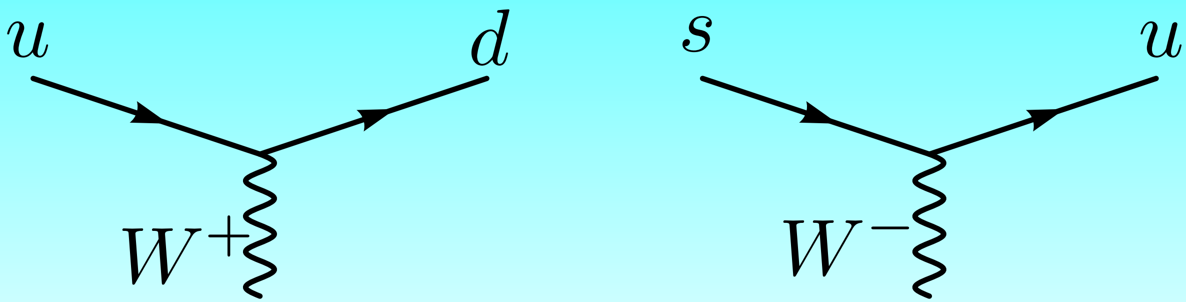
Different strength for different flavours?!



0.98 : 0.22

Strange-Up coupling is even smaller than Up-Down!!!

Different strength for different flavours?!



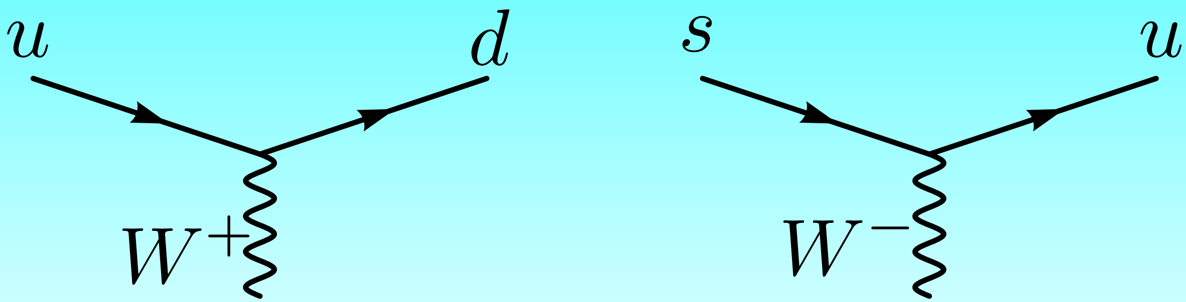
0.98 : 0.22

Strange-Up coupling is even smaller than Up-Down!!!

ANSWER

$$
\begin{aligned}
J_{weak} &= (\overline{u}_L, \overline{c}_L) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} d_L \\ s_L \end{pmatrix} \\
&= \overline{u}_L d_L + \overline{c}_L s_L \\
J_{mass} &= (\overline{u}_L, \overline{c}_L) \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d_L \\ s_L \end{pmatrix} \\
&= \overline{u}_L \cos\theta_c d_L + \overline{u}_L \sin\theta_c s_L + \overline{c}_L \cos\theta_c s_L - \overline{c}_L \sin\theta_c d_L
\end{aligned}
$$

Different strength for different flavours?!



0.98 : 0.22

Strange-Up coupling is even smaller than Up-Down!!!

ANSWER

$$J_{weak} = (\overline{u}_L, \overline{c}_L)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} d_L \\ s_L \end{pmatrix}$$

$$= \overline{u}_L d_L + \overline{c}_L s_L$$

$$J_{mass} = (\overline{u}_L, \overline{c}_L)\begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}\begin{pmatrix} d_L \\ s_L \end{pmatrix}$$

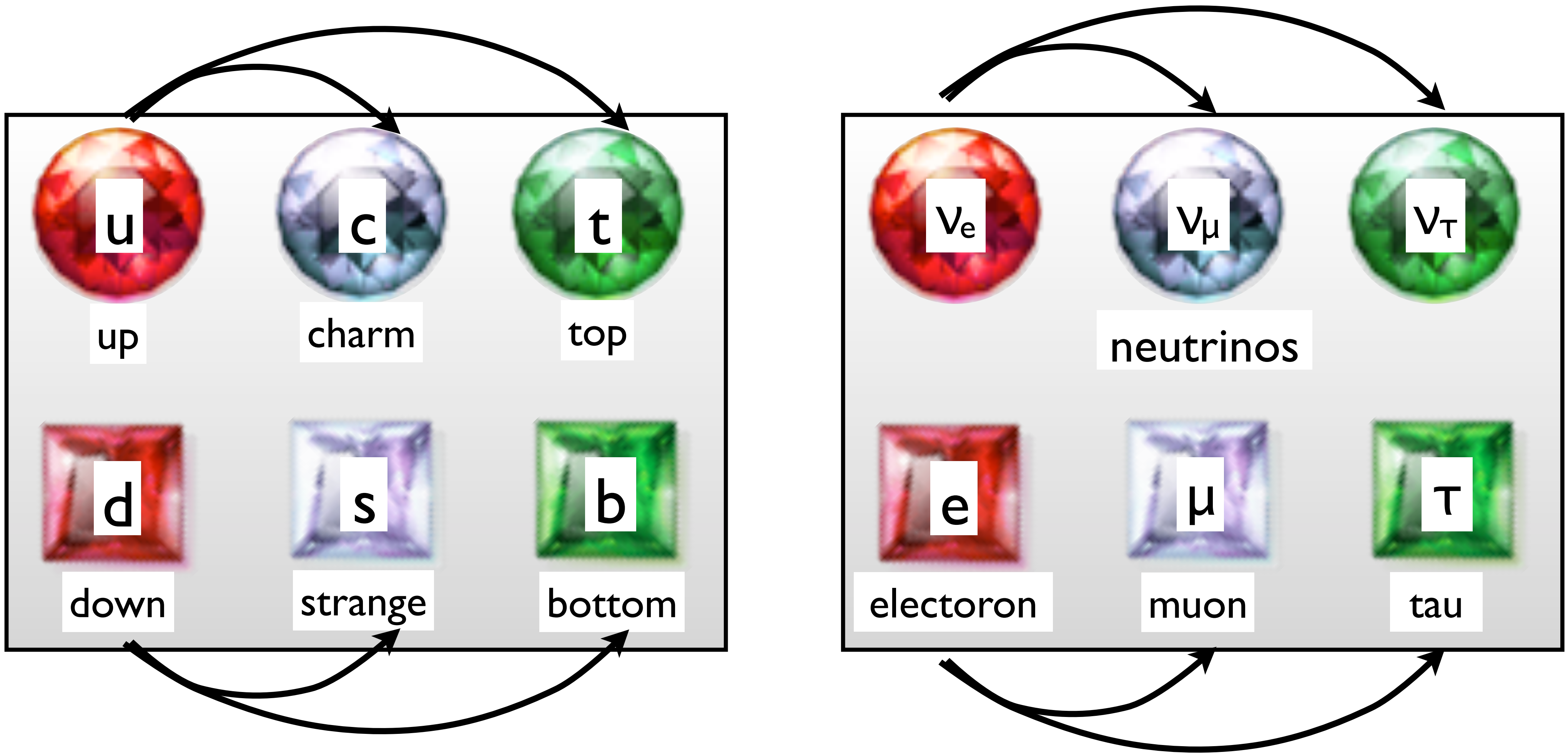
$$= \overline{u}_L \cos\theta_c d_L + \overline{u}_L \sin\theta_c s_L + \overline{c}_L \cos\theta_c s_L - \overline{c}_L \sin\theta_c d_L$$

$$\sin\theta_c = 0.22, \cos\theta_c = 0.98$$

Cabibbo angle

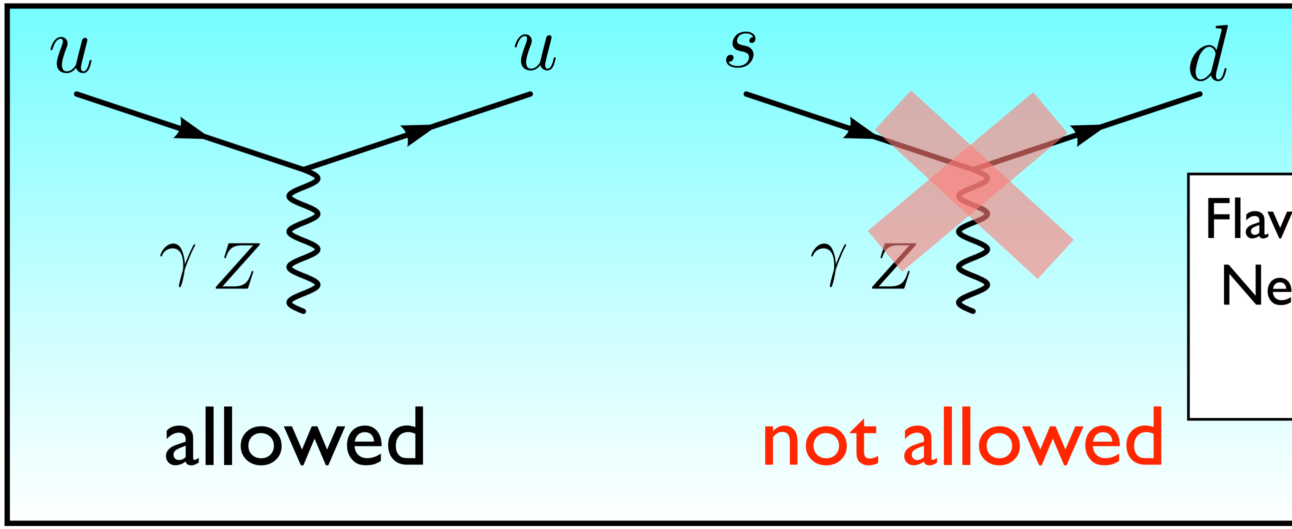
1963

Neutral Current



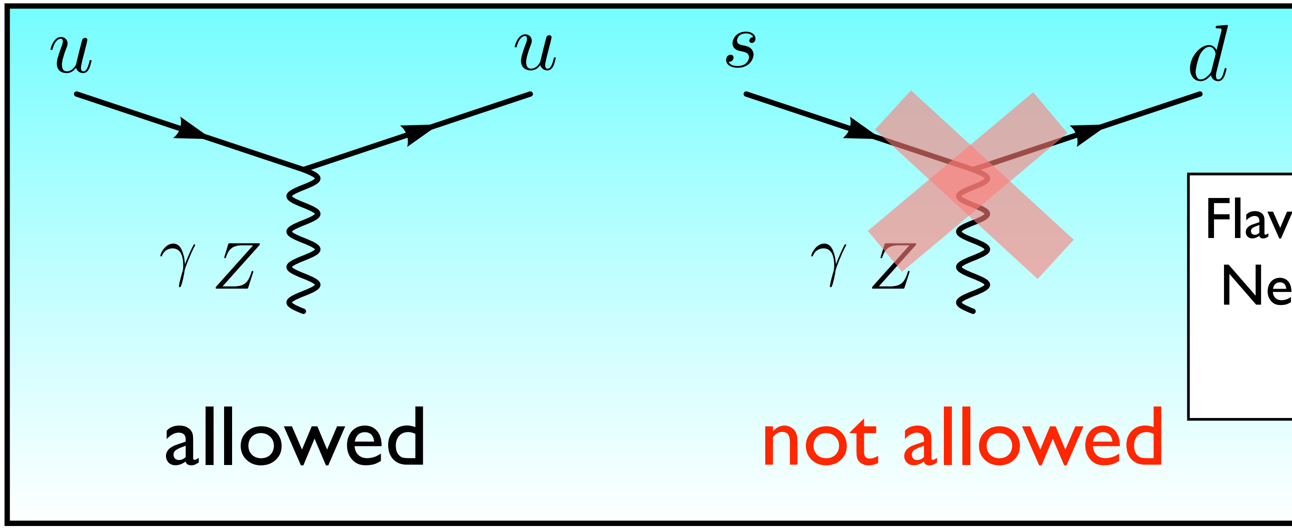
* Actually forbidden...

Forbidding the FCNC
~ GIM mechanism ~



Flavour Changing Neutral Current (FCNC)

Forbidding the FCNC
~ GIM mechanism ~



Flavour Changing Neutral Current (FCNC)

Charged current

$$J_{mass} = \underbrace{(\overline{u}_L, \overline{c}_L) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}}_{up-type} \underbrace{\begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d_L \\ s_L \end{pmatrix}}_{down-type}$$

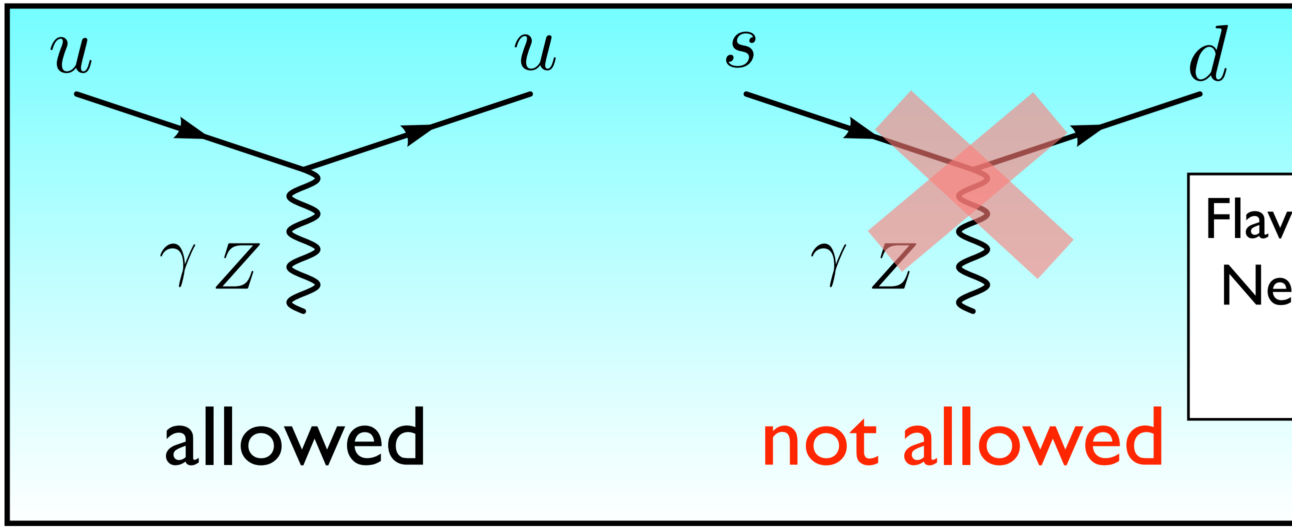
Neutral current

$$J_{weak} = (\overline{u}_L, \overline{c}_L) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} u_L \\ c_L \end{pmatrix} \quad \textit{up-type}$$

$$+ (\overline{d}_L, \overline{s}_L) \begin{pmatrix} \cos\theta_c & -\sin\theta_c \\ \sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d_L \\ s_L \end{pmatrix} \quad \textit{down-type}$$

$$= \overline{u}_L u_L + \overline{c}_L c_L + \overline{d}_L d_L + \overline{s}_L s_L$$

Forbidding the FCNC
~ GIM mechanism ~



Flavour Changing Neutral Current (FCNC)

Charged current

1970

$$J_{mass} = \underbrace{(\overline{u}_L, \overline{c}_L)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}}_{up-type} \underbrace{\begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}\begin{pmatrix} d_L \\ s_L \end{pmatrix}}_{down-type}$$

Glashow, Illiopolous, Maiani (GIM mechanism)

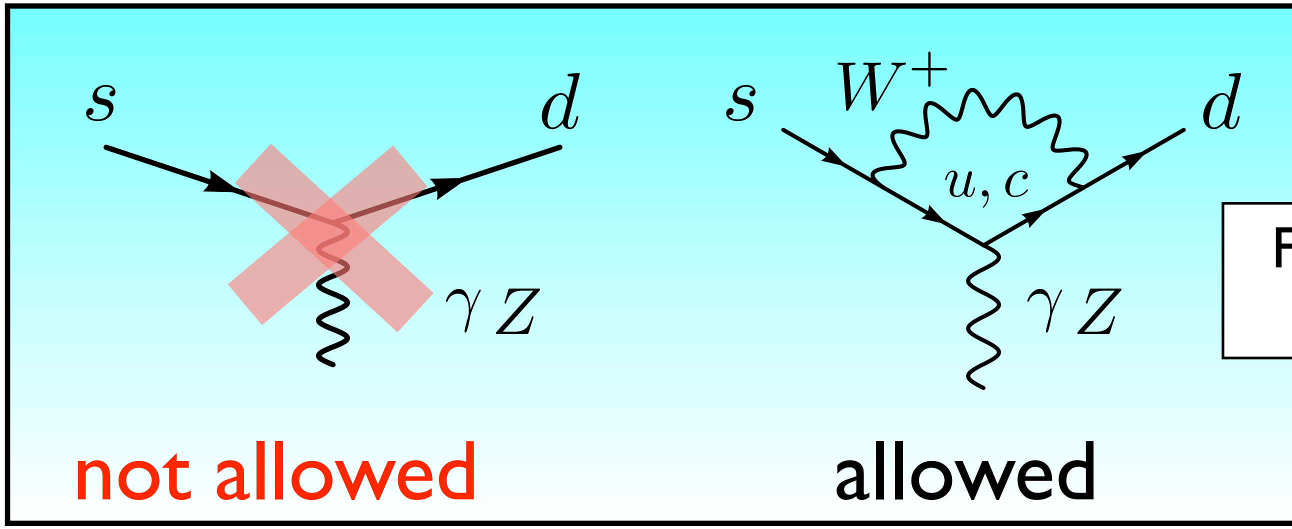
Neutral current

$$\begin{aligned} J_{weak} &= (\overline{u}_L, \overline{c}_L)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} u_L \\ c_L \end{pmatrix} \\ &= (\overline{d}_L, \overline{s}_L)\begin{pmatrix} \cos\theta_c & -\sin\theta_c \\ \sin\theta_c & \cos\theta_c \end{pmatrix}\begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}\begin{pmatrix} d_L \\ s_L \end{pmatrix} \\ &= \overline{u}_L u_L + \overline{c}_L c_L + \overline{d}_L d_L + \overline{s}_L s_L \end{aligned}$$

down-type

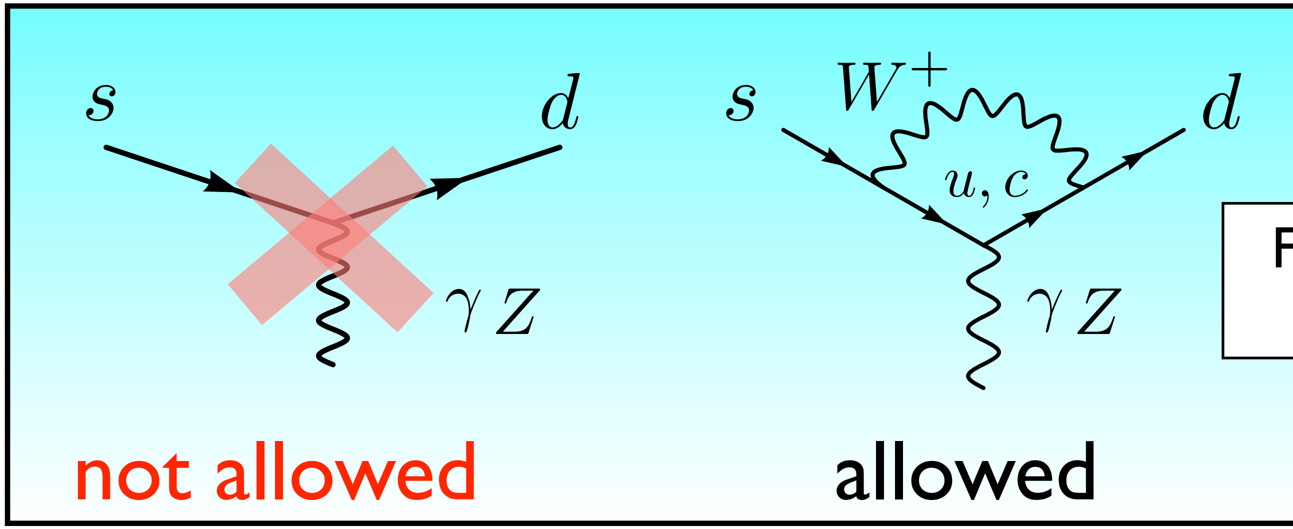
Only same flavour allowed

Forbidding the FCNC at loop level
~ GIM mechanism 2~



FCNC at loop level

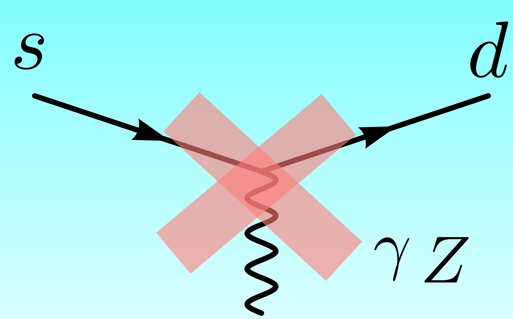
Forbidding the FCNC at loop level
~ GIM mechanism 2~



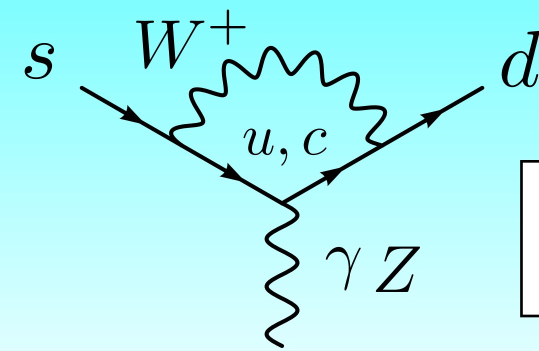
FCNC at loop level

HOWEVER

Forbidding the FCNC at loop level
~ GIM mechanism 2~

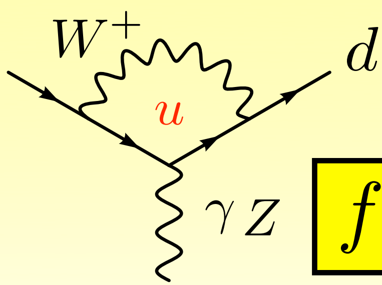


not allowed



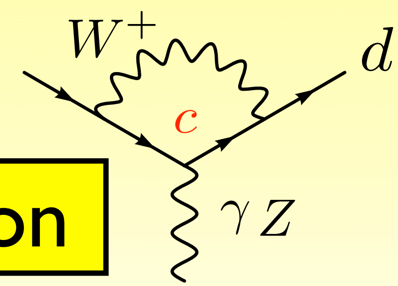
allowed

FCNC at loop level



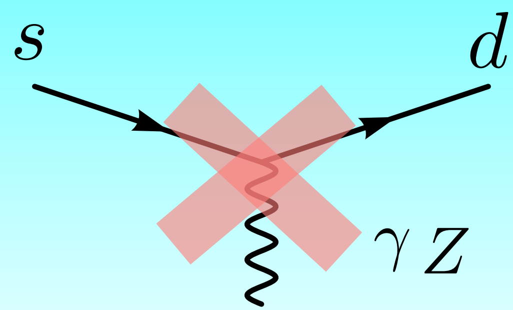
$(\overline{s}_L \sin\theta_c u_L)(\overline{u}_L \cos\theta_c d_L) f(m_u)$

$f(m)$ Loop Function



$-(\overline{s}_L \cos\theta_c c_L)(\overline{c}_L \sin\theta_c d_L) f(m_c)$

Forbidding the FCNC at loop level
~ GIM mechanism 2~



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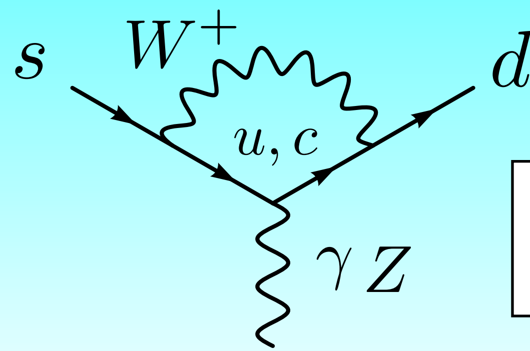
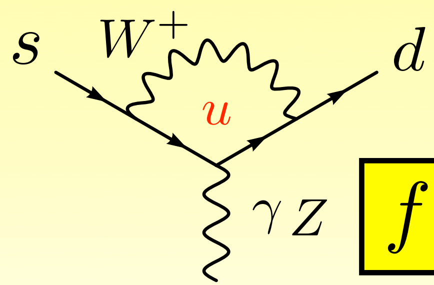


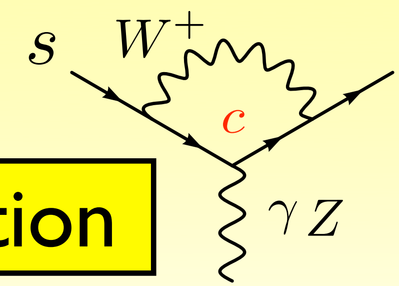
allowed

FCNC at loop level



$(\bar{s}_L \sin\theta_c u_L)(\bar{u}_L \cos\theta_c d_L) f(m_u)$

$f(m)$ Loop Function

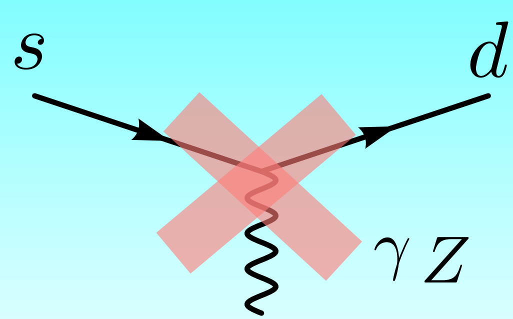


$-(\bar{s}_L \cos$

GIM mechanism at loop level

At the limit of mu=mc, two diagrams exactly cancel!!!

Forbidding the FCNC at loop level
~ GIM mechanism 2~



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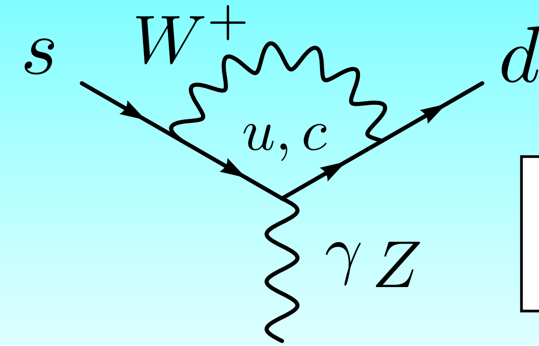
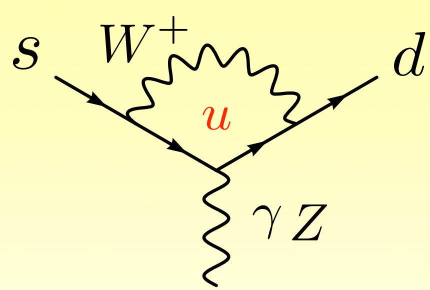
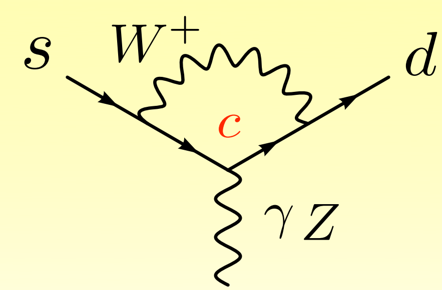


allowed

FCNC at loop level





Note: here, two-generation is assumed. Once the top quark is introduced, the FCNC at loop level becomes significantly large! (we'll see soon...)

By the way, what is the origin of that mixing ?

$$\begin{pmatrix} d_L \\ s_L \end{pmatrix} \longrightarrow \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d_L \\ s_L \end{pmatrix}$$

By the way, what is the origin of that mixing ?

Yukawa Interaction

$$\mathcal{L}_{yukawa} = \sum_{i,j} (Y_u)_{ij} (\overline{U}_i, \overline{D}_i,)_L \begin{pmatrix} \phi^0 \\ -\phi^- \end{pmatrix} U_{j,R} + \sum_{i,j} (Y_d)_{ij} (\overline{U}_i, \overline{D}_i,)_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} D_{j,R} + h.c.$$

$Y_{u,d}$ Yukawa coupling (non-diagonal 3x3 matrix)

Spontaneous Symmetry Breaking

$$\langle \phi^0 \rangle_{\mathrm{VAC}} = v$$

Origin of down-type quark mass

$$(\overline{d}, \overline{s}, \overline{b}) \begin{pmatrix} .. & .. & .. \\ .. & (Y_d)^2 & .. \\ .. & .. & .. \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Y_d is not-diagonal. Thus a rotaion to the mass eigen-basis required!

By the way, what is the origin of that mixing ?

Diagonalization

$$(\bar d, \bar s, \bar b)\begin{pmatrix} .. & .. & .. \\ .. & (Y_d)^2 & .. \\ .. & .. & .. \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad (\bar{\tilde d}, \bar{\tilde s}, \bar{\tilde b})_L \begin{pmatrix} m_d^2 & 0 & 0 \\ 0 & m_s^2 & 0 \\ 0 & 0 & m_b^2 \end{pmatrix}\begin{pmatrix} \tilde d \\ \tilde s \\ \tilde b \end{pmatrix}_R$$

Inserting the Unitary matrix which diagonalizes the Y_d^2

$$(\bar d, \bar s, \bar b)\, U_d^\dagger \underbrace{U_d \begin{pmatrix} .. & .. & .. \\ .. & (Y_d)^2 & .. \\ .. & .. & .. \end{pmatrix} U_d^\dagger}_{=\begin{pmatrix} m_d^2 & 0 & 0 \\ 0 & m_s^2 & 0 \\ 0 & 0 & m_b^2 \end{pmatrix}} \underbrace{U_d \begin{pmatrix} d \\ s \\ b \end{pmatrix}}_{=\begin{pmatrix} \tilde d \\ \tilde s \\ \tilde b \end{pmatrix}}$$

By the way, what is the origin of that mixing ?

Diagonalization

$$(\bar{d}, \bar{s}, \bar{b}) \begin{pmatrix} .. & .. & .. \\ .. & (Y_d)^2 & .. \\ .. & .. & .. \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \Rightarrow (\bar{\tilde{d}}, \bar{\tilde{s}}, \bar{\tilde{b}}) \begin{pmatrix} m_d^2 & 0 & 0 \\ 0 & m_s^2 & 0 \\ 0 & 0 & m_b^2 \end{pmatrix} \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix}$$

Unitary transformation to diagonalize the Yukawa matrix

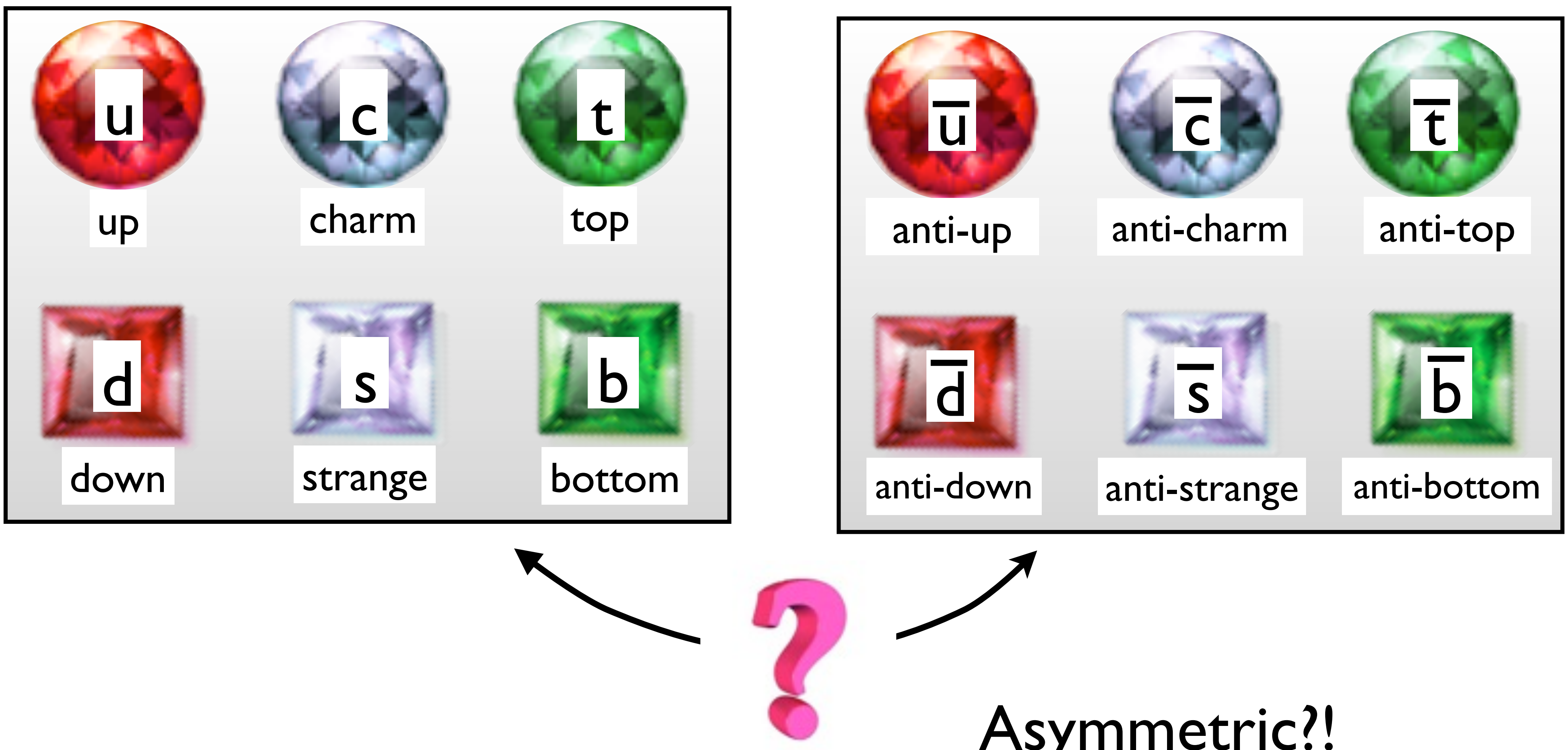
$$U_d (Y_d)^2 U_d^\dagger = (M_d^2)_{diag}$$

Transformation from interaction eigen-basis to mass eigen-basis

$$U_d \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix}$$

Origin of the Cabbibo angle

Matter Anti-Matter Asymmetry (CP violation)



CP transformation in a few words

C: Charge transformation
P: Parity transformation

A few key equations...

$$\mathcal{CP}|K^0\rangle = |\overline{K}^0\rangle \qquad K^0 = \bar{s}d$$

$$\mathcal{CP}|\overline{K}^0\rangle = |K^0\rangle \qquad \overline{K}^0 = \bar{d}s$$

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

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

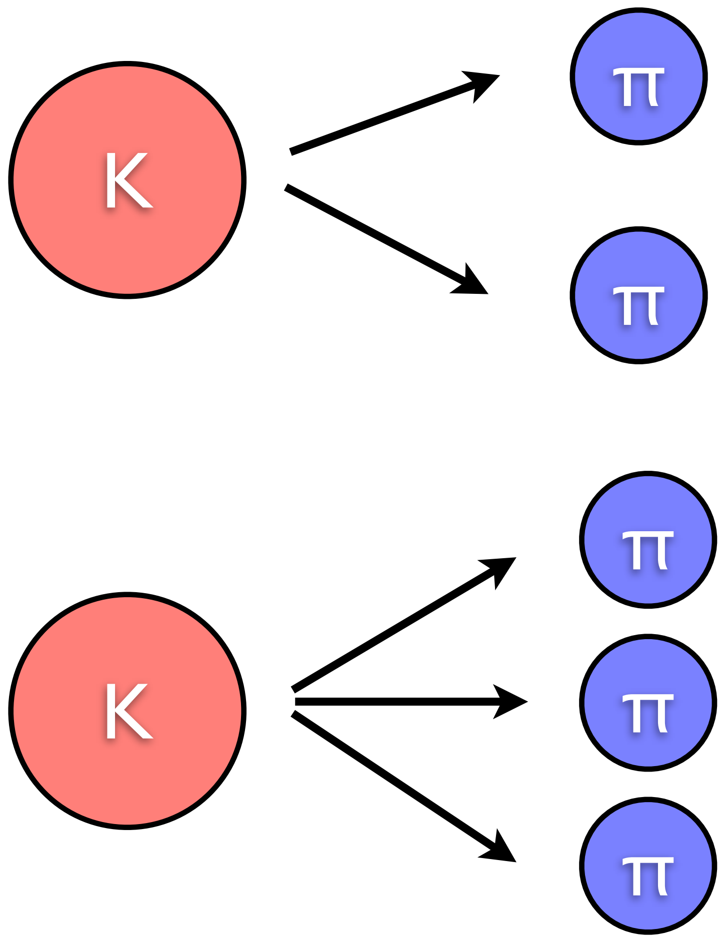
$$\mathcal{CP}|(\pi^+\pi^-)_l\pi^0\rangle = (-)^{l+1}|(\pi^+\pi^-)_l\pi^0\rangle$$

$$\pi^0 = u\bar{u} - d\bar{d}$$

$$\pi^+ = u\bar{d},\ \pi^- = d\bar{u}$$

CP "*invariance*" of K system

Two decay channels of K are observed... (θ-τ *puzzle*)



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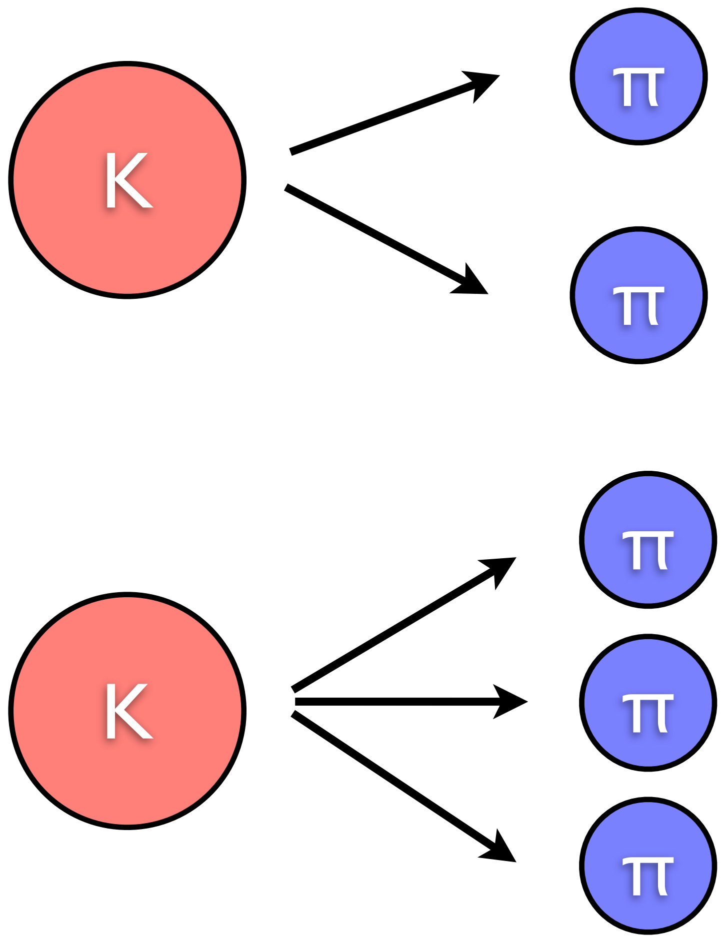


$$\mathcal{CP}|\pi^+\pi^-\rangle = +|\pi^+\pi^-\rangle$$

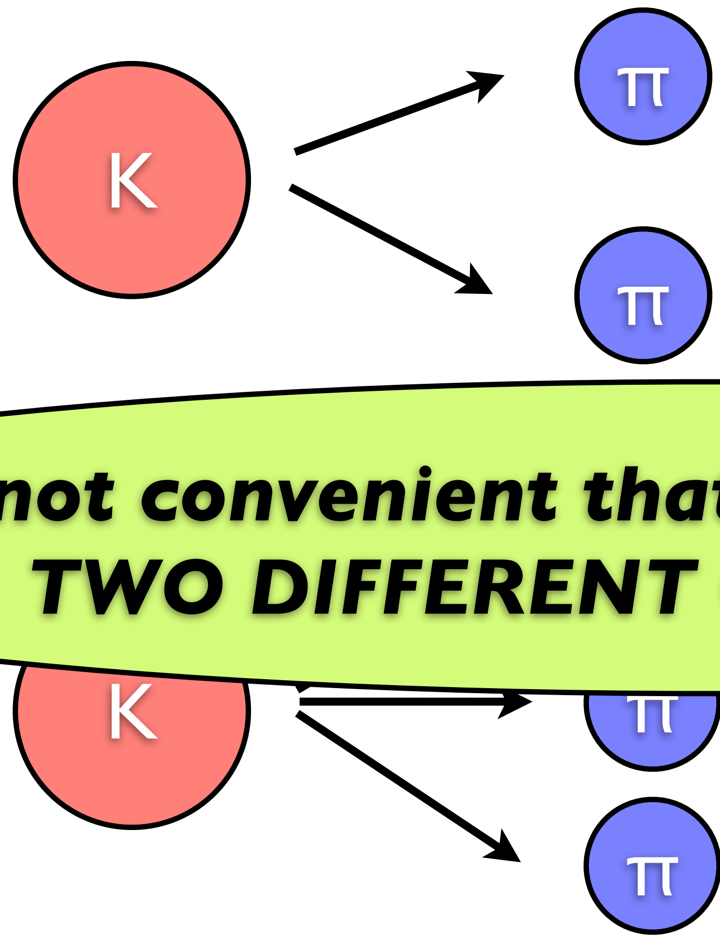
CP EVEN

$$\mathcal{CP}|(\pi^+\pi^-)_0\pi^0\rangle = -|(\pi^+\pi^-)_0\pi^0\rangle$$

CP ODD

CP "*invariance*" of K system

Two decay channels of K are observed... (θ-τ *puzzle*)



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

CP EVEN

It's not convenient that the same K decays to TWO DIFFERENT CP eigen-states!!!

CP ODD

CP "*invariance*" of K system

How can we make two CP (+ and -) states from K^0 and $\overline{K}^0$?

$$\begin{aligned} \mathcal{CP}|K^0\rangle &= |\overline{K}^0\rangle \\ \mathcal{CP}|\overline{K}^0\rangle &= |K^0\rangle \end{aligned}$$

$$K^0 = \bar{s}d$$
$$\overline{K}^0 = \bar{d}s$$

CP "*invariance*" of K system

How can we make two CP (+ and -) states from K^0 and $\overline{K}^0$?

$$\mathcal{CP}|K^0\rangle = |\overline{K}^0\rangle \qquad K^0 = \bar{s}d$$

$$\mathcal{CP}|\overline{K}^0\rangle = |K^0\rangle \qquad \overline{K}^0 = \bar{d}s$$

Gell-Mann and Pais ***(1955)***

ANSWER

If the K is a mixed state of K^0 and $\overline{K}^0$ in nature...

$$|K_1\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\overline{K}^0\rangle)$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\overline{K}^0\rangle)$$

CP "*invariance*" of K system

How can we make two CP (+ and -) states from K^0 and $\overline{K}^0$?

$$
\begin{aligned}
\mathcal{CP}|K^0\rangle &= |\overline{K}^0\rangle \\
\mathcal{CP}|\overline{K}^0\rangle &= |K^0\rangle
\end{aligned}
\qquad
\begin{aligned}
K^0 &= \overline{s}d \\
\overline{K}^0 &= \overline{d}s
\end{aligned}
$$

Gell-Mann and Pais ***(1955)***

ANSWER

If the K is a mixed state of K^0 and $\overline{K}^0$ in nature...

$$
\begin{aligned}
|K_1\rangle &= \frac{1}{\sqrt{2}}(|K^0\rangle + |\overline{K}^0\rangle) \\
|K_2\rangle &= \frac{1}{\sqrt{2}}(|K^0\rangle - |\overline{K}^0\rangle)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{CP}|K_1\rangle &= +\frac{1}{\sqrt{2}}(|K^0\rangle + |\overline{K}^0\rangle) \\
&= |K_1\rangle
\end{aligned}
$$

CP EVEN

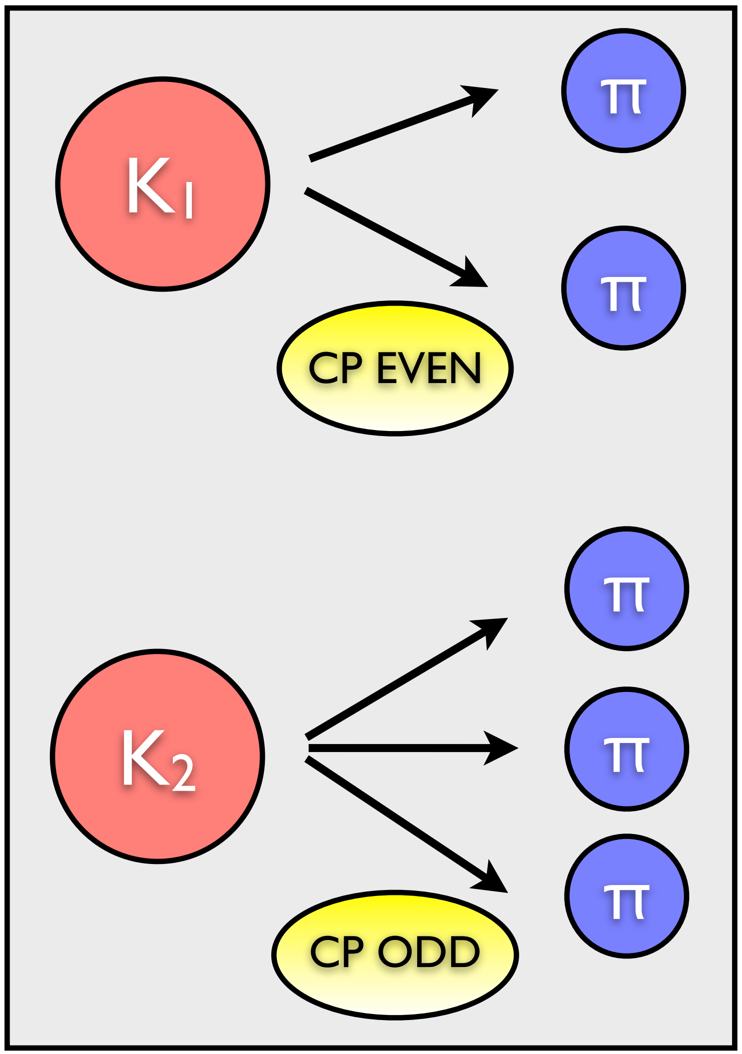
$$
\begin{aligned}
\mathcal{CP}|K_2\rangle &= -\frac{1}{\sqrt{2}}(|K^0\rangle - |\overline{K}^0\rangle) \\
&= -|K_2\rangle
\end{aligned}
$$

CP ODD

CP "*invariance*" of K system

Distinguishing K_1 and K_2

By the decay channel



By the life-time

M_K=498MeV

M_π=140 MeV

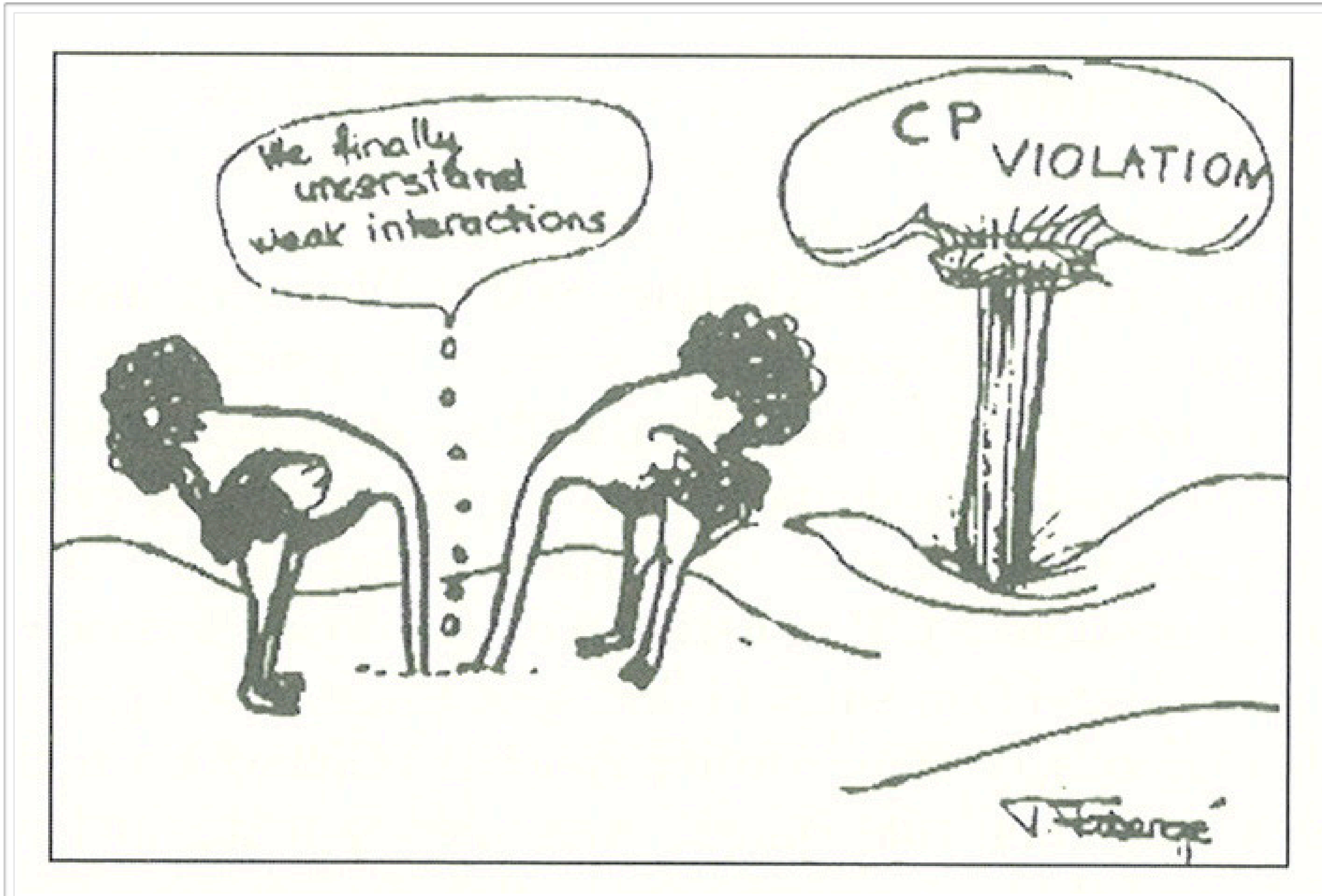
Phase space for 2π is about 600 larger than for 3π

$$\begin{aligned} \tau(K_1) &\simeq 0.90 \times 10^{-10} s \\ \tau(K_2) &\simeq 5.1 \times 10^{-8} s \end{aligned}$$

Accidental phase space suppression:

short-lived K is K_1 and long-lived one is K_2

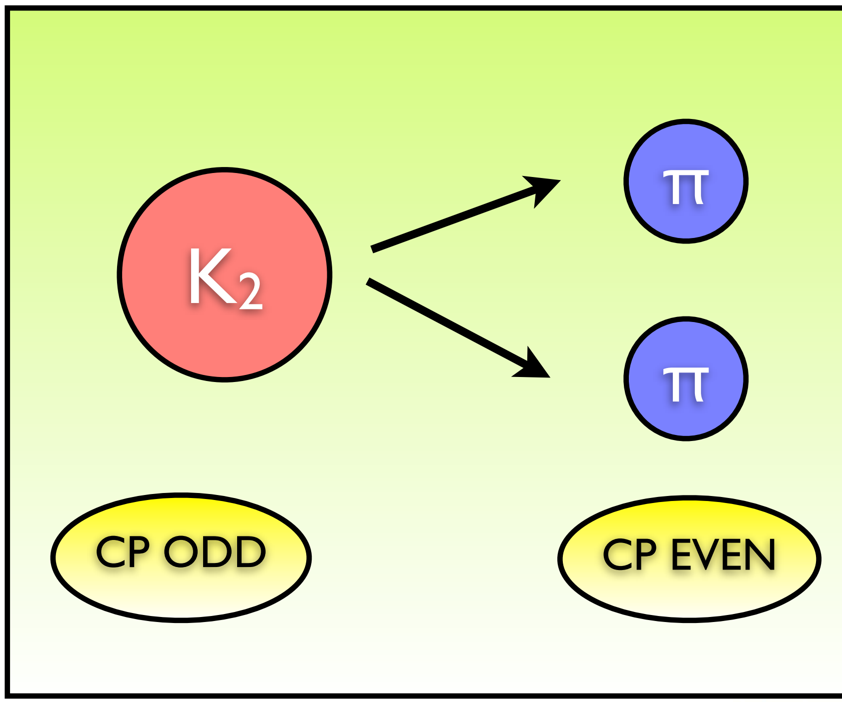
CP non-*invariance* of K system



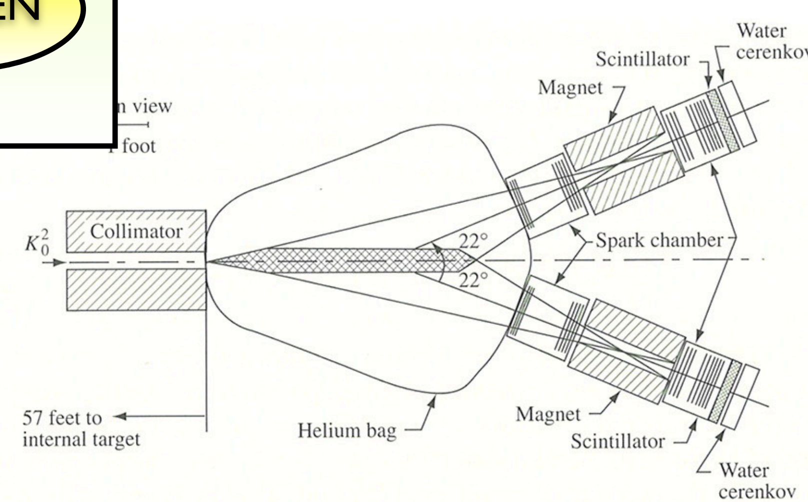
Cabibbo *(1966)*

CP *non-invariance* of K system

First observation of the CP violation



Cronin, Fitch
Christenson, Turlay
(1964)



Long-lived K_2
decaying to 2π!!!

CP *non-invariance* of K system

We thought...

$$
\begin{aligned}
|K_1\rangle &= \frac{1}{\sqrt{2}}(|K^0\rangle + |\overline{K}^0\rangle) \\
|K_2\rangle &= \frac{1}{\sqrt{2}}(|K^0\rangle - |\overline{K}^0\rangle)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{CP}|K_1\rangle &= +\frac{1}{\sqrt{2}}(|K^0\rangle + |\overline{K}^0\rangle) \\
&= |K_1\rangle \quad \boxed{\text{CP EVEN}} \\
\mathcal{CP}|K_2\rangle &= -\frac{1}{\sqrt{2}}(|K^0\rangle - |\overline{K}^0\rangle) \\
&= -|K_2\rangle \quad \boxed{\text{CP ODD}}
\end{aligned}
$$

CP *non-invariance* of K system

We thought...

$$|K_1\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\overline{K}^0\rangle)$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\overline{K}^0\rangle)$$

$$\mathcal{CP}|K_1\rangle = +\frac{1}{\sqrt{2}}(|K^0\rangle + |\overline{K}^0\rangle) = |K_1\rangle$$

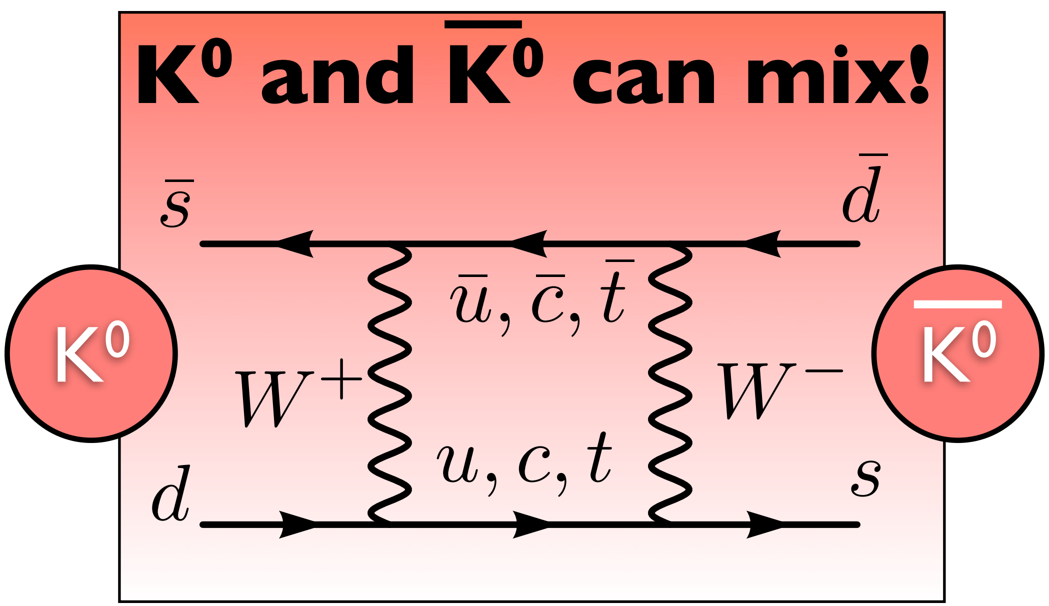
CP EVEN

$$\mathcal{CP}|K_2\rangle = -\frac{1}{\sqrt{2}}(|K^0\rangle - |\overline{K}^0\rangle) = -|K_2\rangle$$

CP ODD

But, actually...

K^0 and $\overline{K}^0$ can mix through box diagram. Thus, they are not mass eigenstate.



CP *non-invariance* of K system

So the mass eigenstate is a mixture of two CP eigenstate!

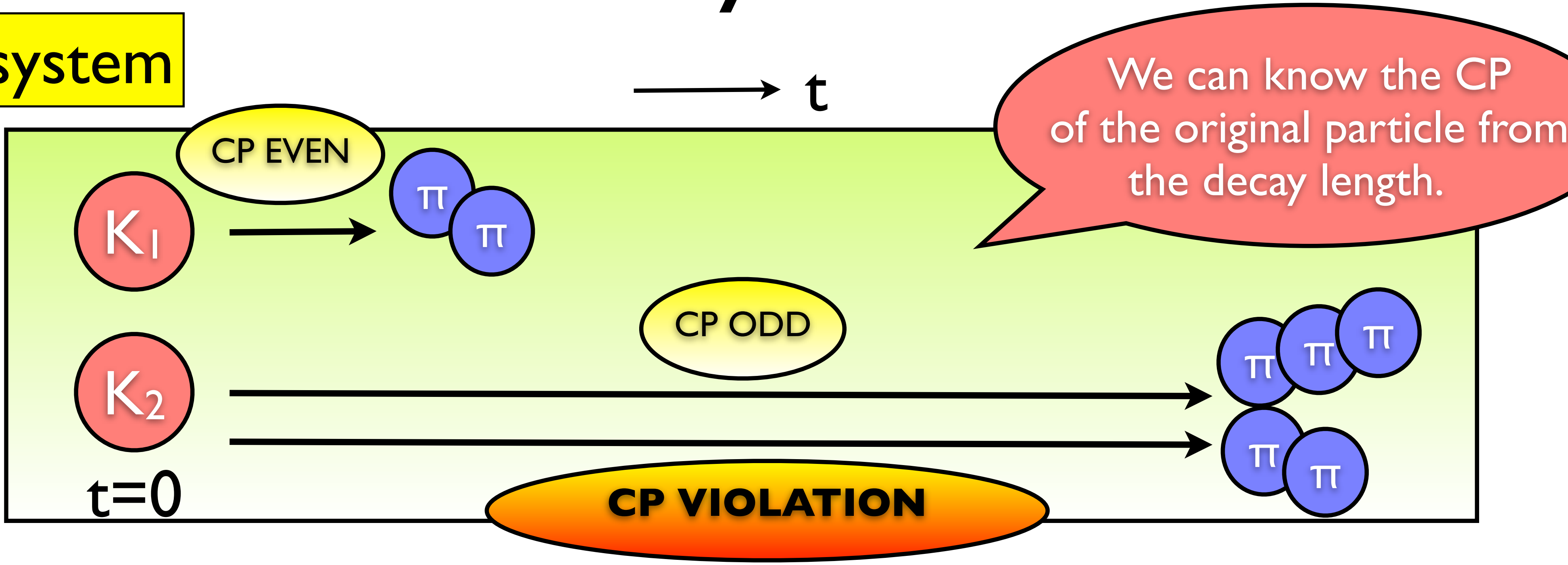
$$
\begin{aligned}
|K_S\rangle &= \frac{1}{\sqrt{2}}\left(p|K^0\rangle + q|\overline{K}^0\rangle\right) \\
&= \frac{p}{2}\left[(1+\frac{q}{p})|K_1\rangle + (1-\frac{q}{p})|K_2\rangle)\right] \\
|K_L\rangle &= \frac{1}{\sqrt{2}}\left(p|K^0\rangle - q|\overline{K}^0\rangle\right) \\
&= \frac{p}{2}\left[(1-\frac{q}{p})|K_1\rangle + (1+\frac{q}{p})|K_2\rangle)\right]
\end{aligned}
$$

✍ At $p=q=1$, we recover the previous result.

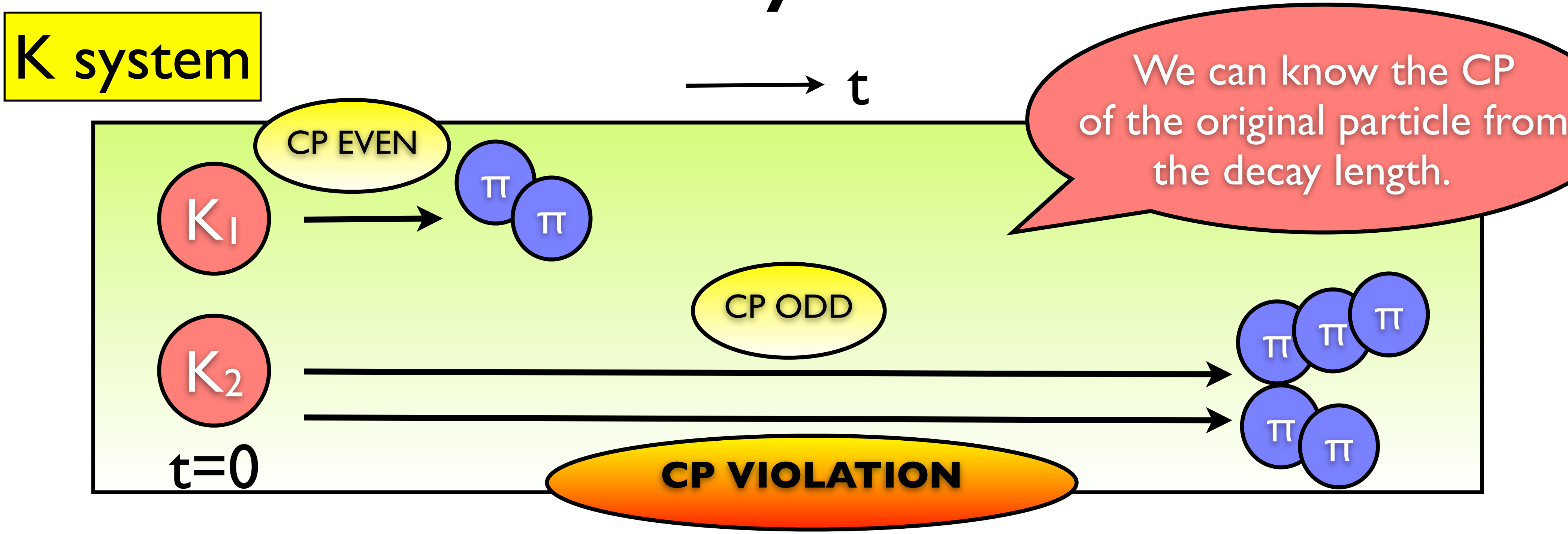
The CP violation comes from $q/p \neq 1$!!!

CP violation in K system vs B system

K system



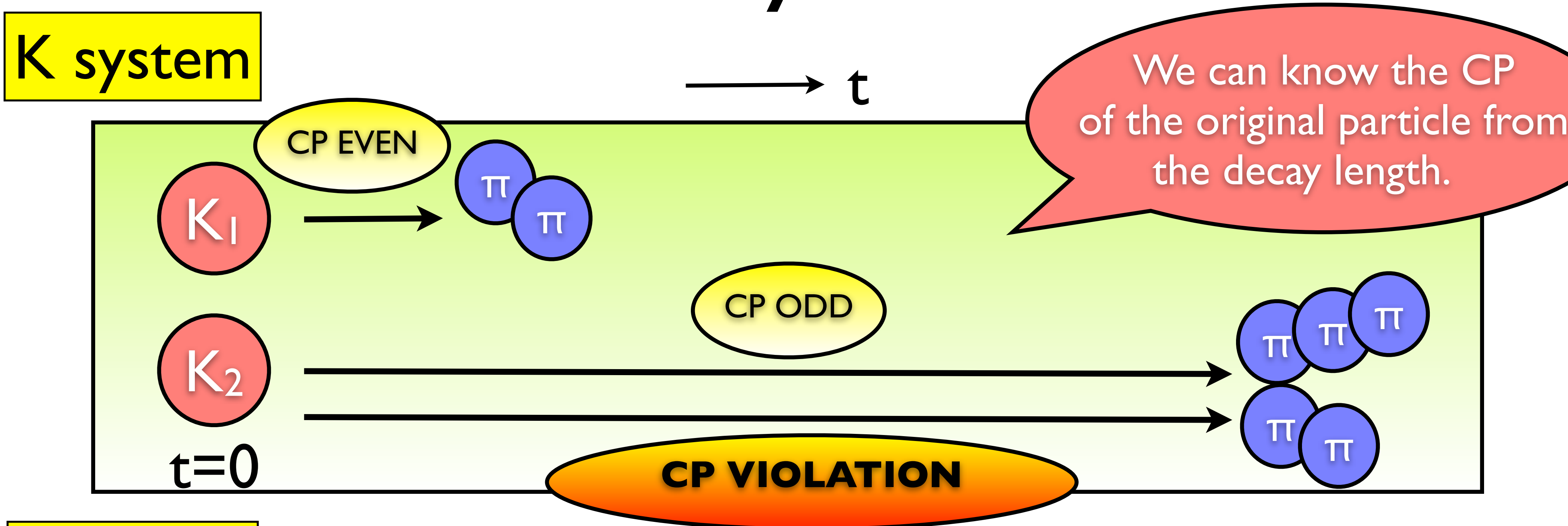
CP violation in K system vs B system

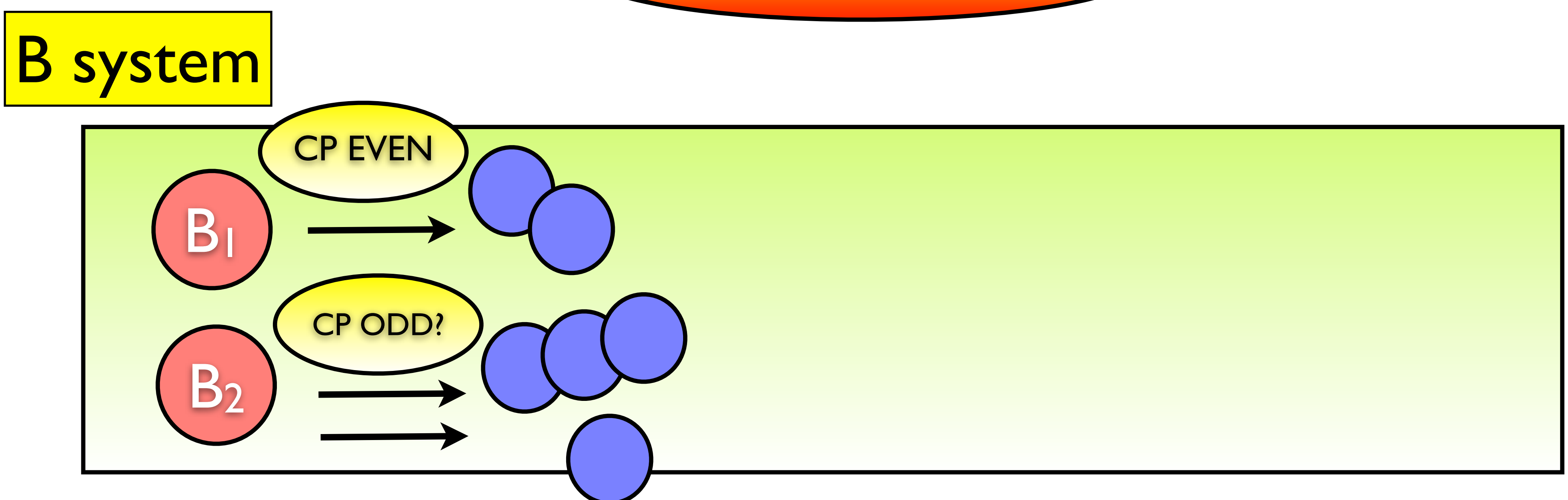


$$
\begin{aligned}
\mathcal{CP}|K_1\rangle &= +\frac{1}{\sqrt{2}}(|K^0\rangle + |\overline{K}^0\rangle) \\
&= |K_1\rangle \qquad \boxed{\textbf{CP EVEN}} \\
\mathcal{CP}|K_2\rangle &= -\frac{1}{\sqrt{2}}(|K^0\rangle - |\overline{K}^0\rangle) \\
&= -|K_2\rangle \qquad \boxed{\textbf{CP ODD}}
\end{aligned}
$$

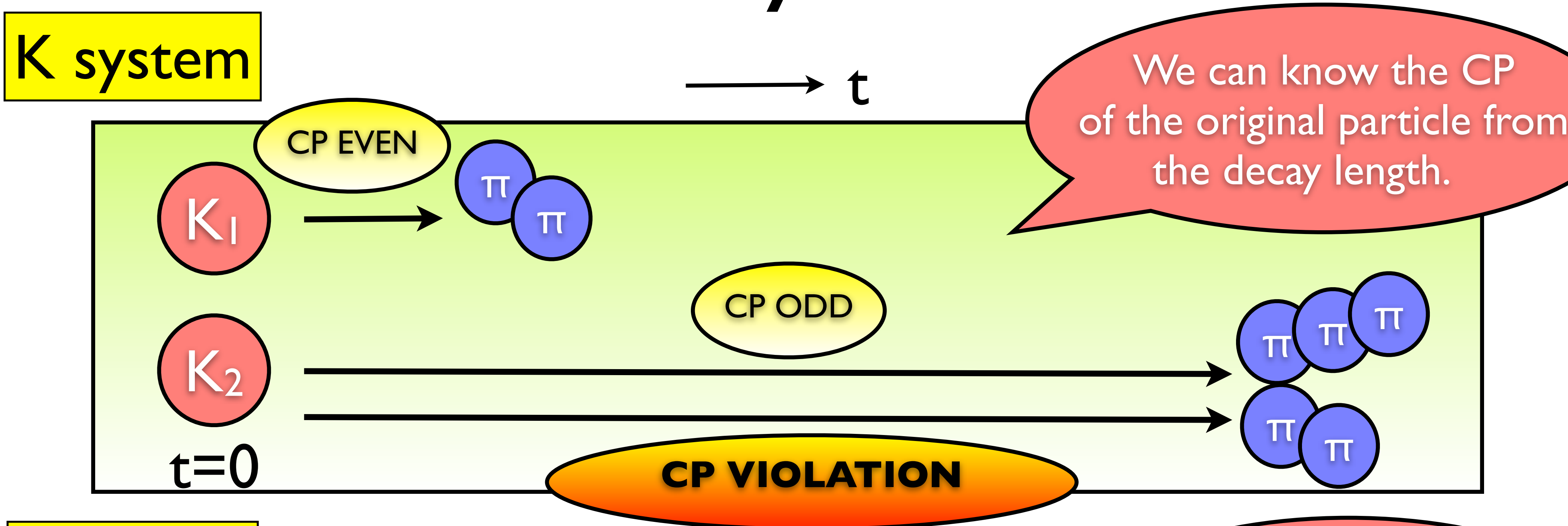
$$
\begin{aligned}
|K_S\rangle &= \frac{1}{\sqrt{2}}\left(p|K^0\rangle + q|\overline{K}^0\rangle\right) \\
&= \frac{p}{2}\left[(1+\frac{q}{p})|K_1\rangle + (1-\frac{q}{p})|K_2\rangle)\right] \\
|K_L\rangle &= \frac{1}{\sqrt{2}}\left(p|K^0\rangle - q|\overline{K}^0\rangle\right) \\
&= \frac{p}{2}\left[(1-\frac{q}{p})|K_1\rangle + (1+\frac{q}{p})|K_2\rangle)\right]
\end{aligned}
$$

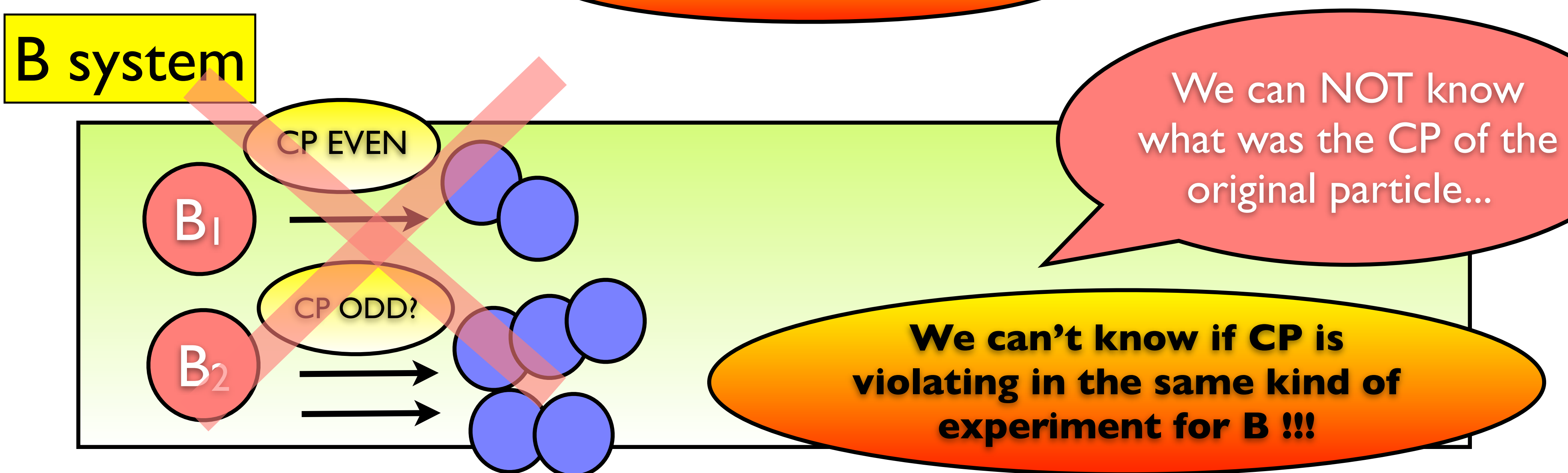
CP violation in K system vs B system





CP violation in K system vs B system





How do we observe the CP violation in B system

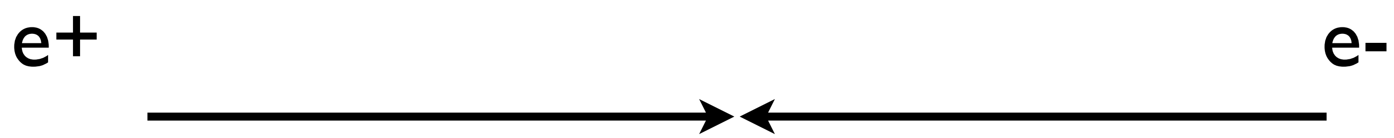
How do we observe the CP violation in B system

It’s actually even simpler...

If we can say the original particle was B^0 or B^0, then we can simply measure the difference of B^0 and B^0!

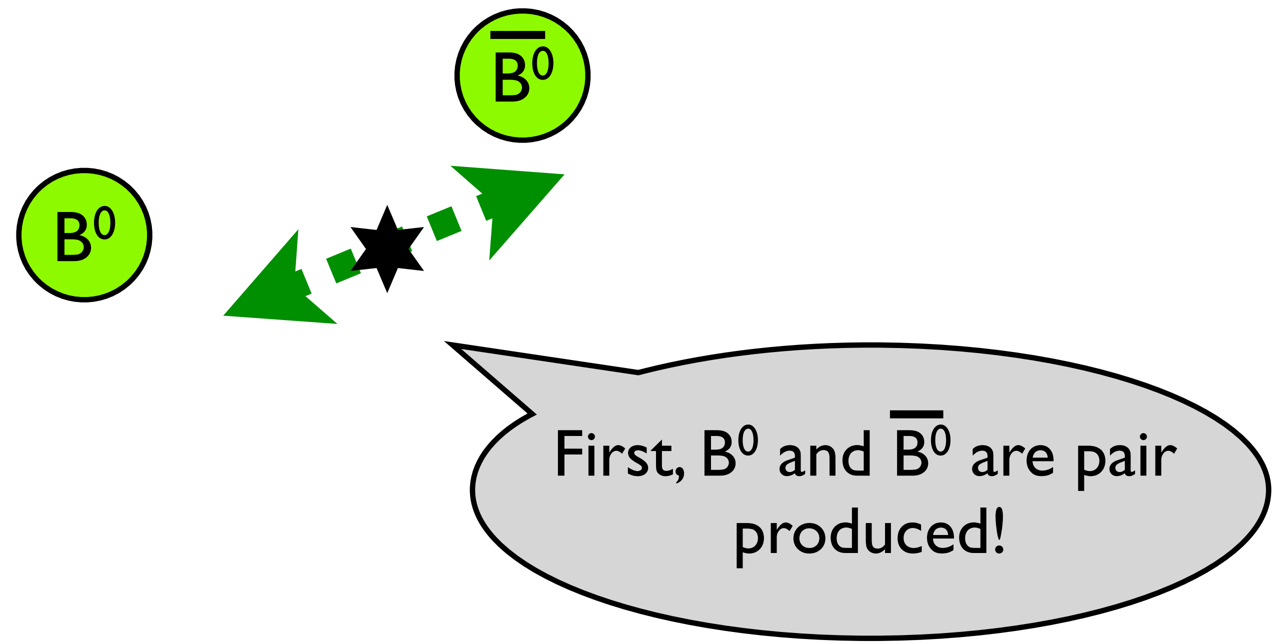
How do we observe the CP violation in B system

In the case of B factories...



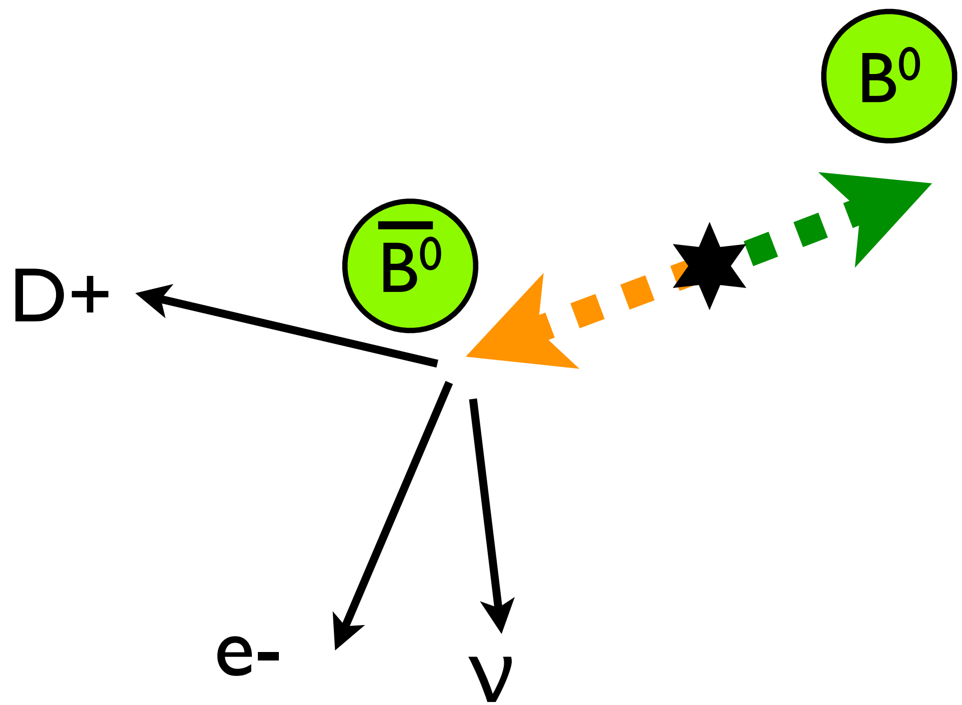
How do we observe the CP violation in B system

In the case of B factories...



How do we observe the CP violation in B system

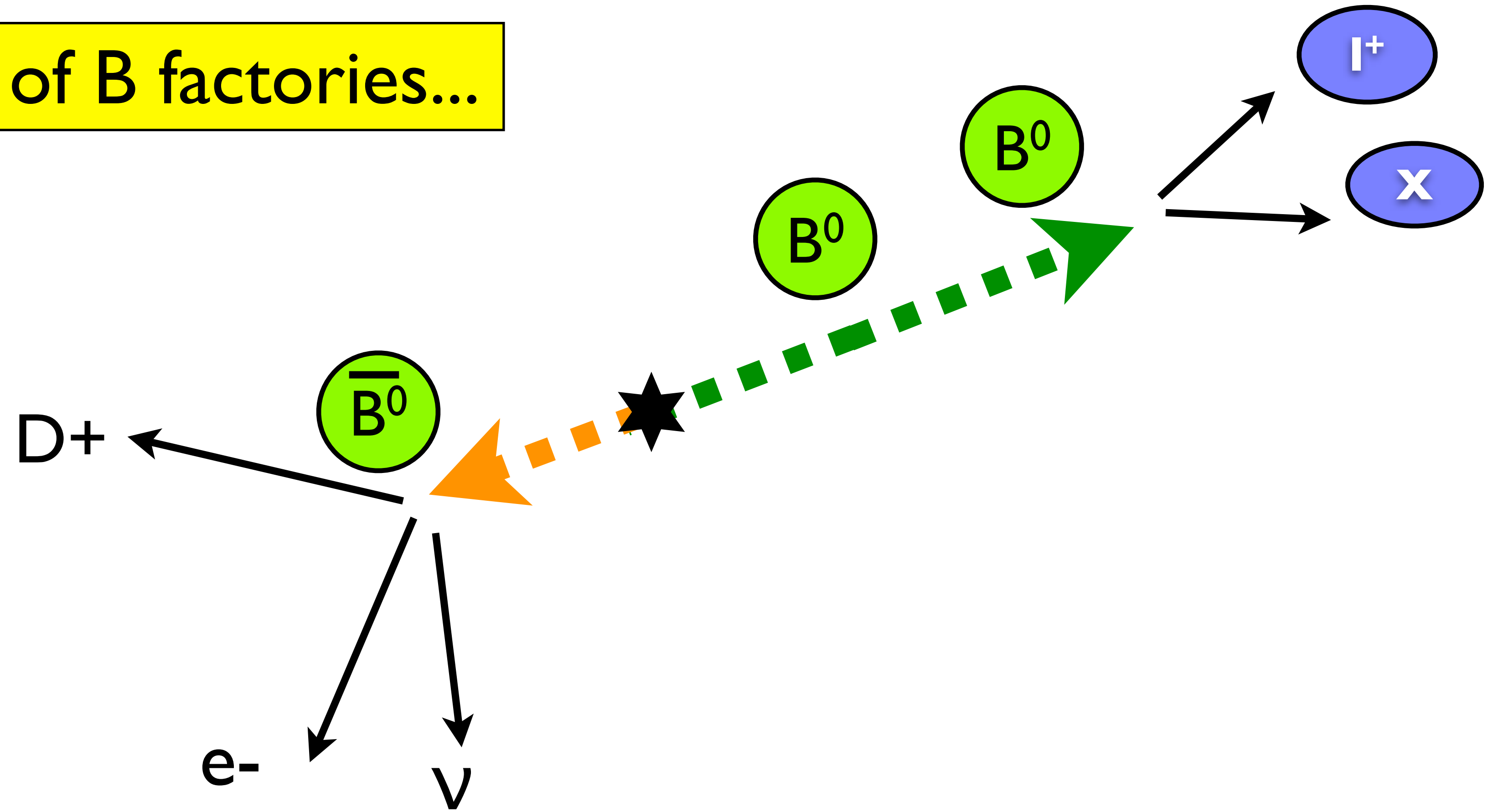
In the case of B factories...



If one of them decays semi-leptonically, we can tell if it was B^0 or $\overline{B}^0$ on one side at given time, which allows us to tell about the other side.

How do we observe the CP violation in B system

In the case of B factories...



How do we observe the CP violation in B system

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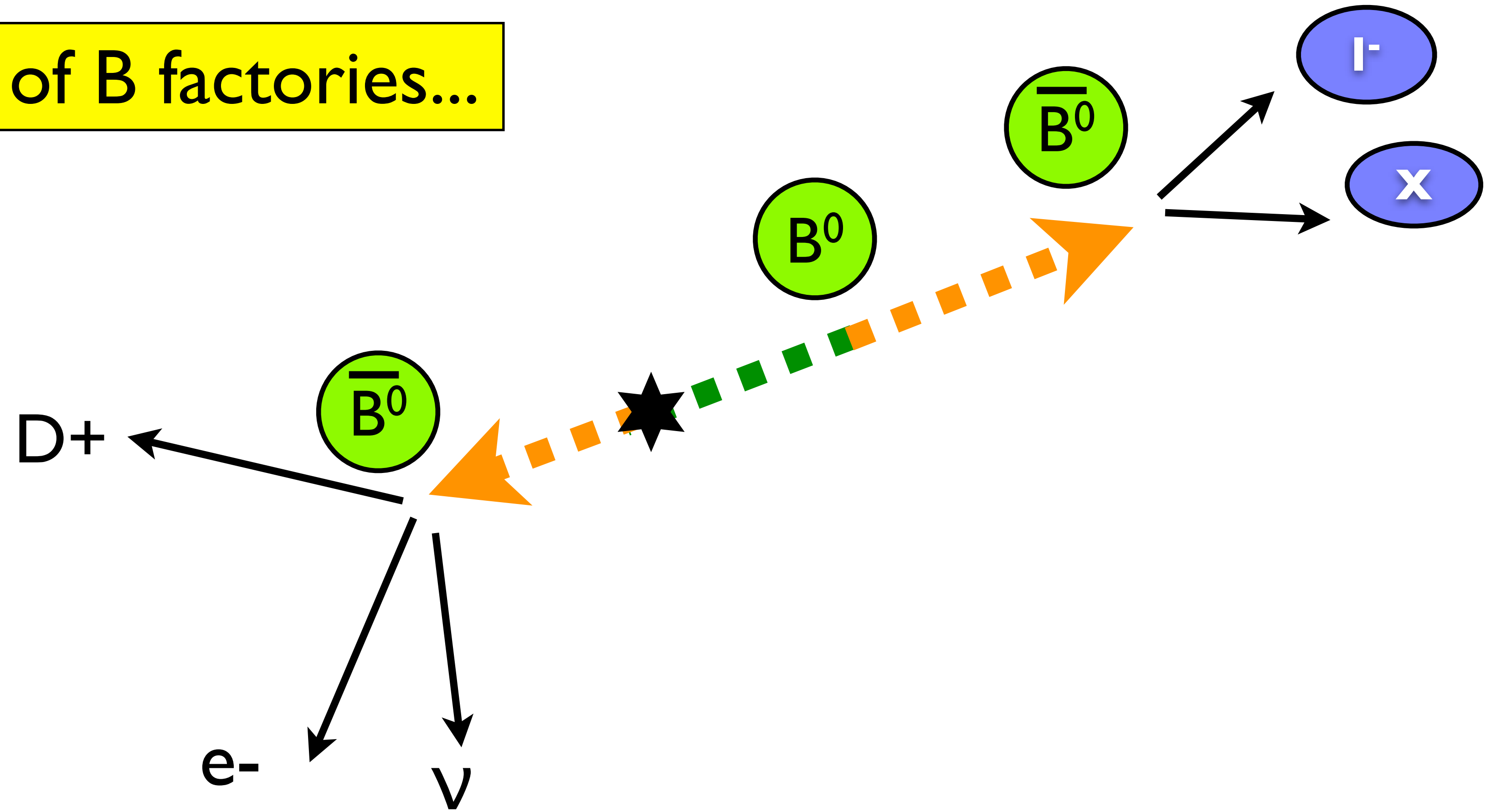
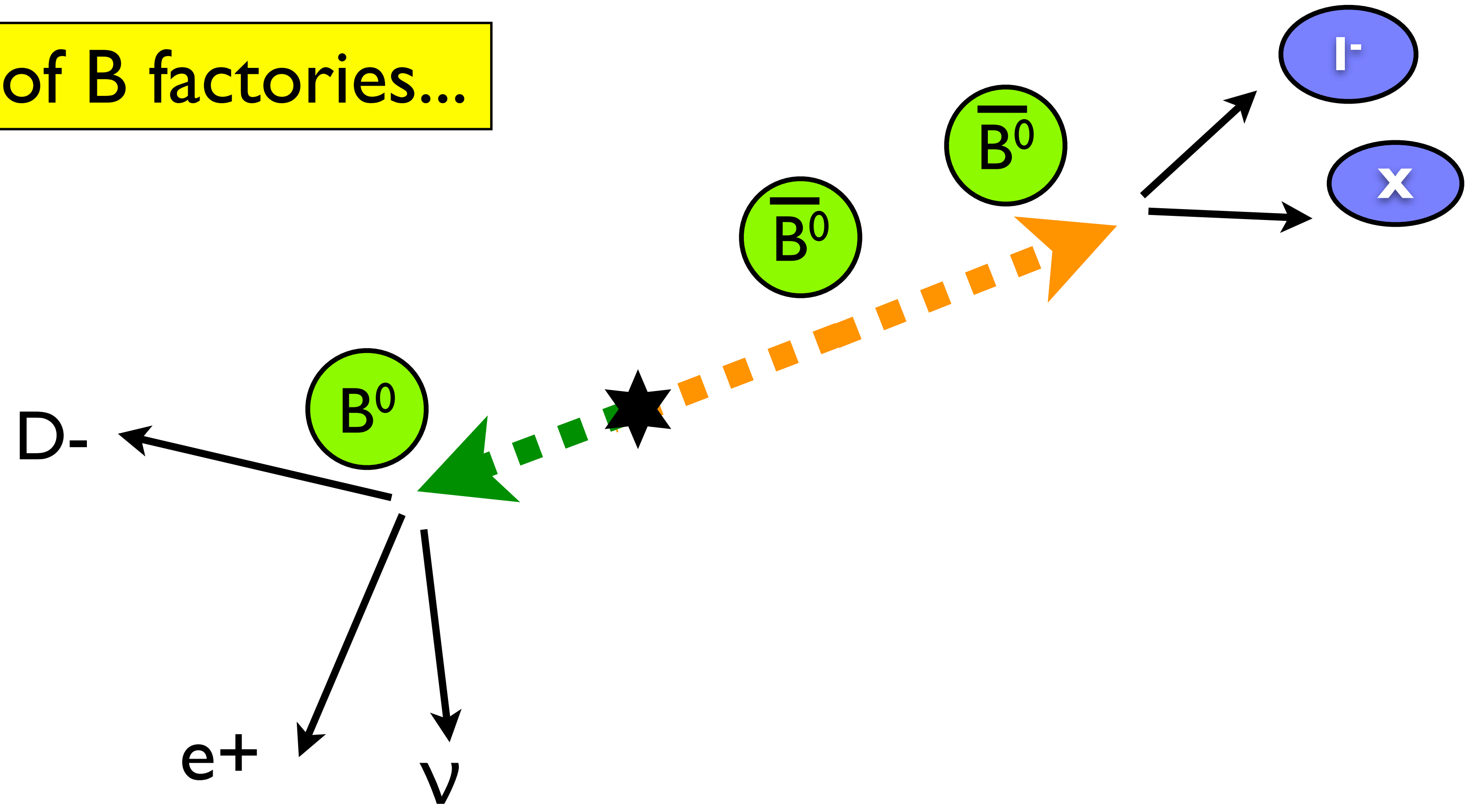


How do we observe the CP violation in B system

In the case of B factories...



How do we observe the CP violation in B system

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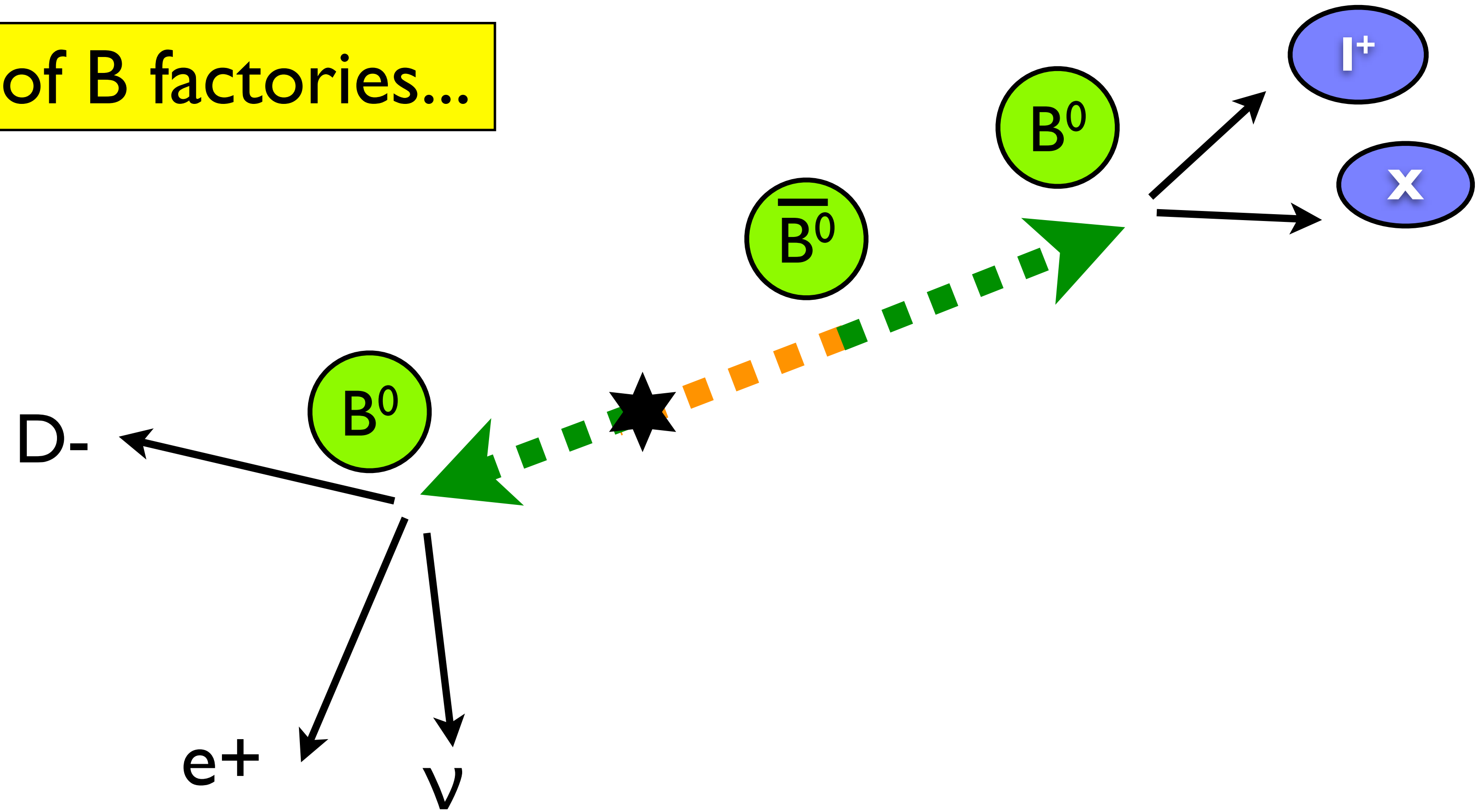
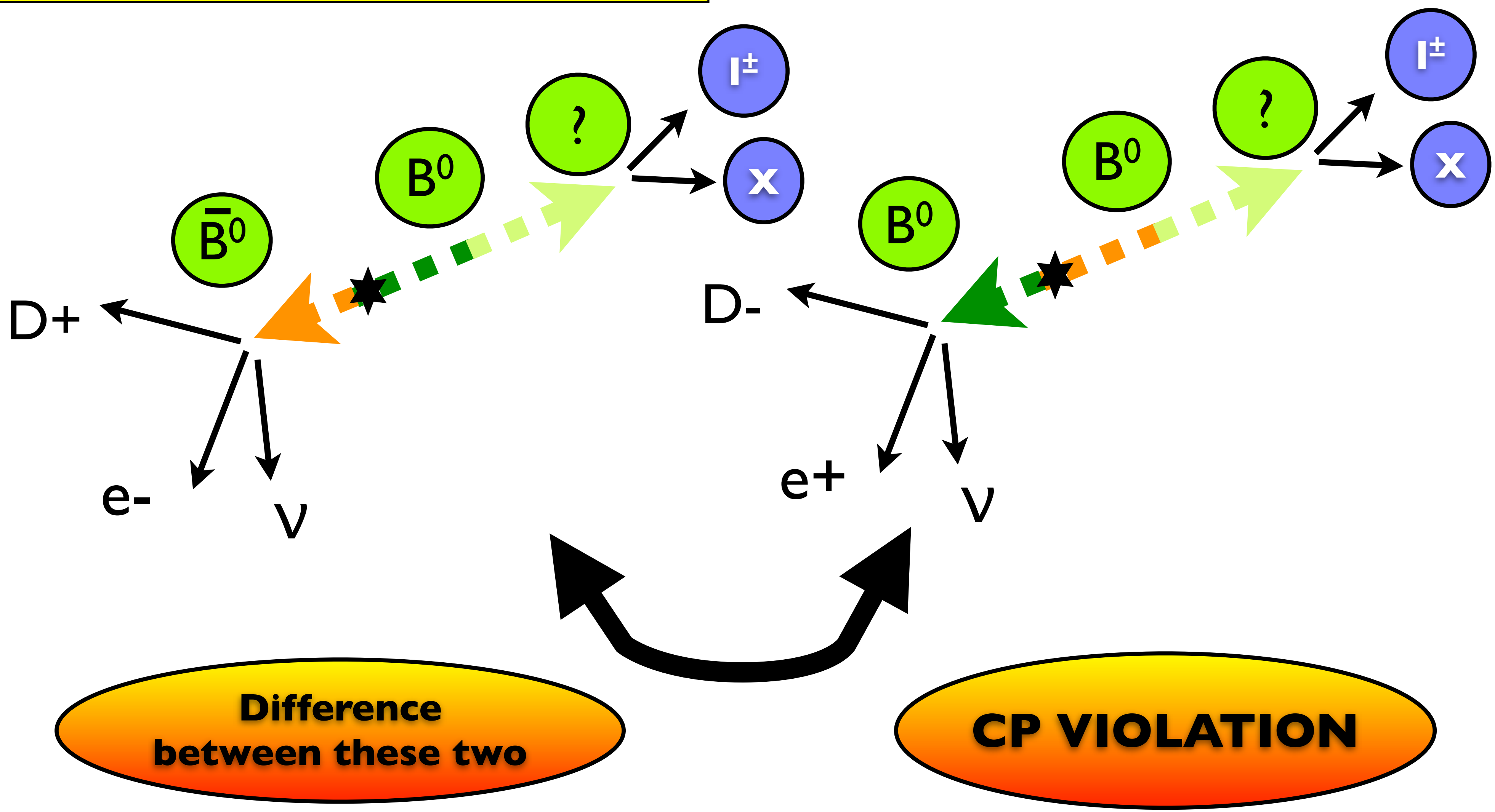


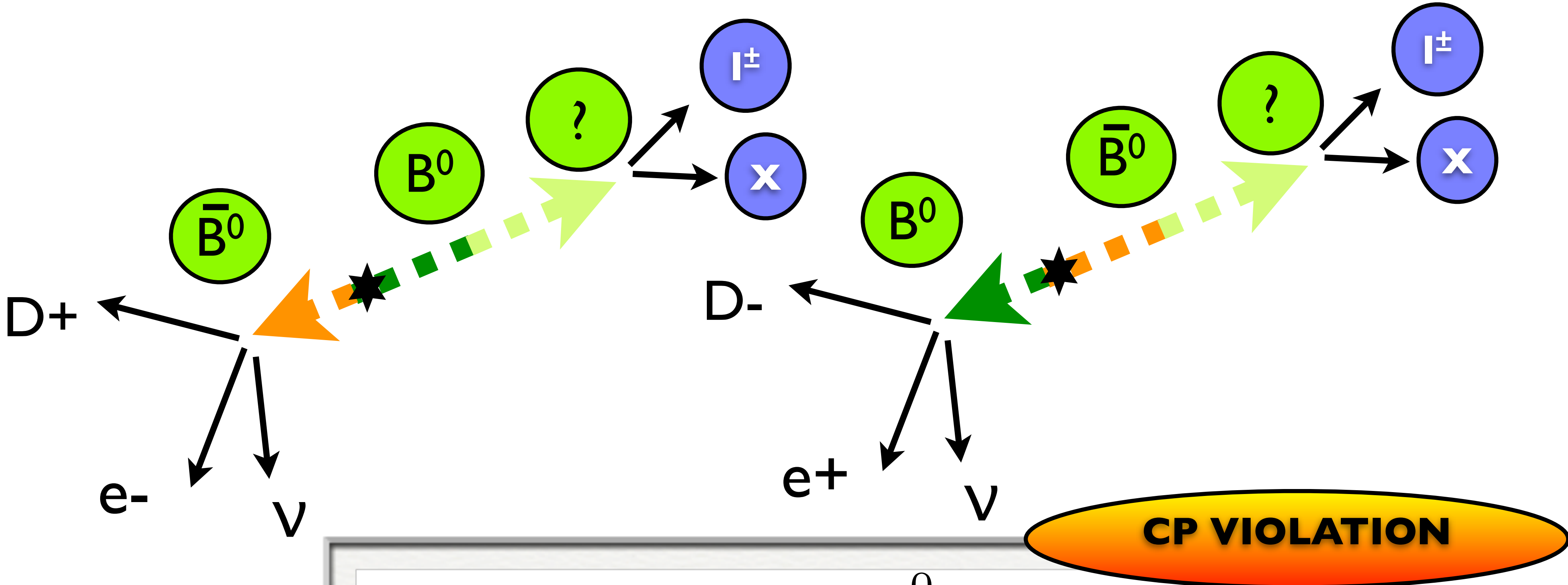
How do we observe the CP violation in B system

In the case of B factories...



How do we observe the CP violation in B system

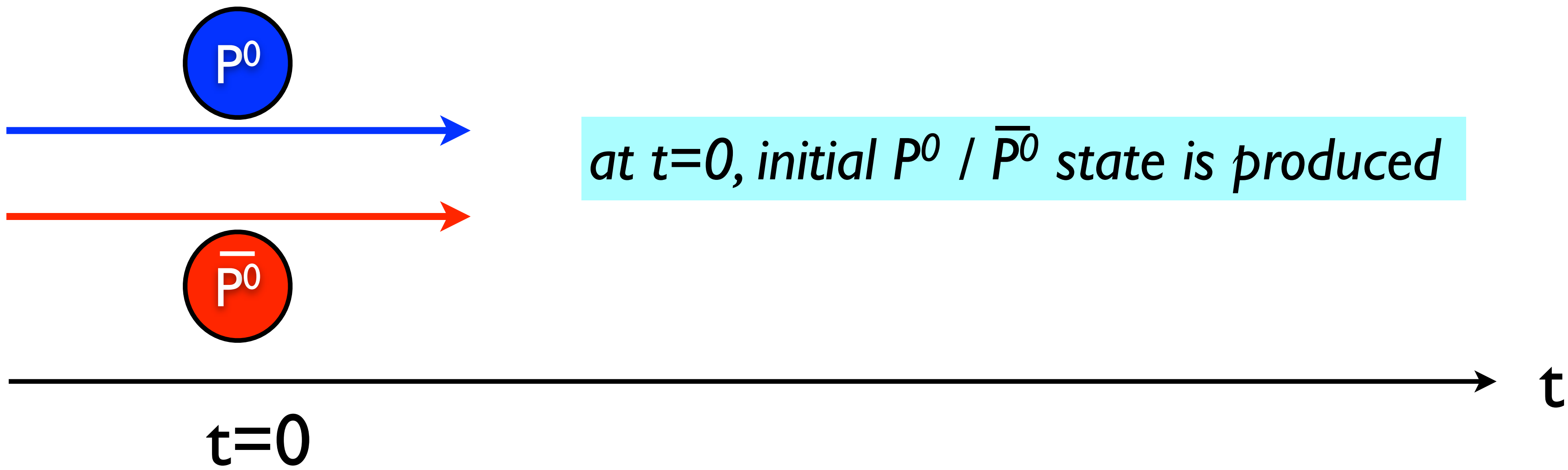
In the case of B factories...



$$\frac{\Gamma(B^0(t)\to f)-\Gamma(\overline{B}^0(t)\to f)}{\Gamma(B^0(t)\to f)+\Gamma(\overline{B}^0(t)\to f)}\neq 1$$

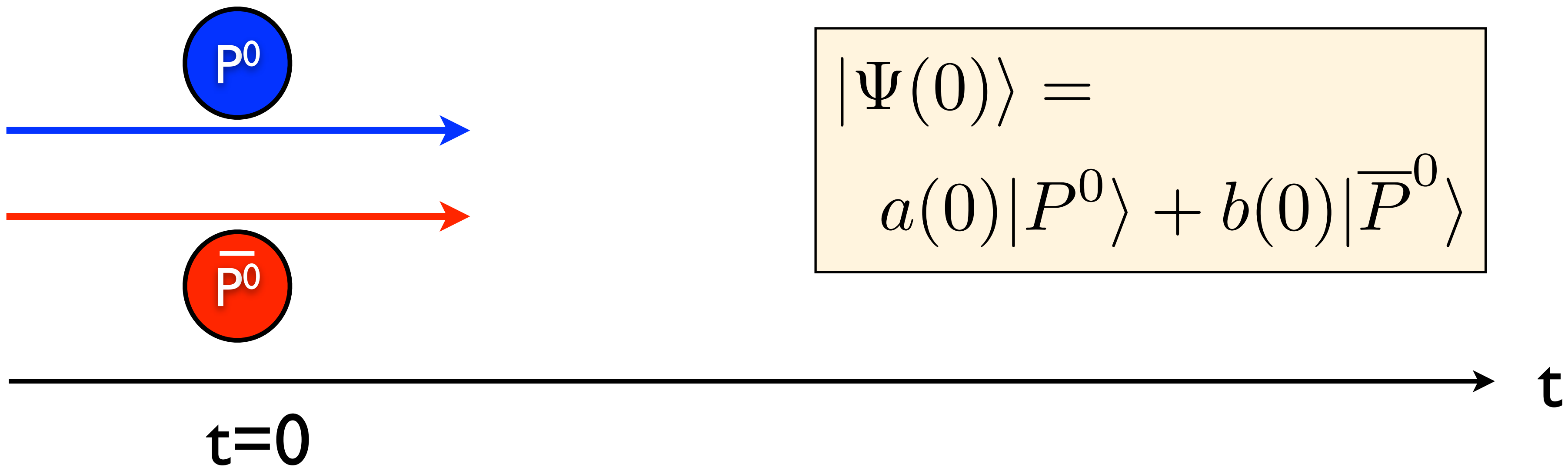
Oscillation with Weak interaction

Oscillation with Weak interaction

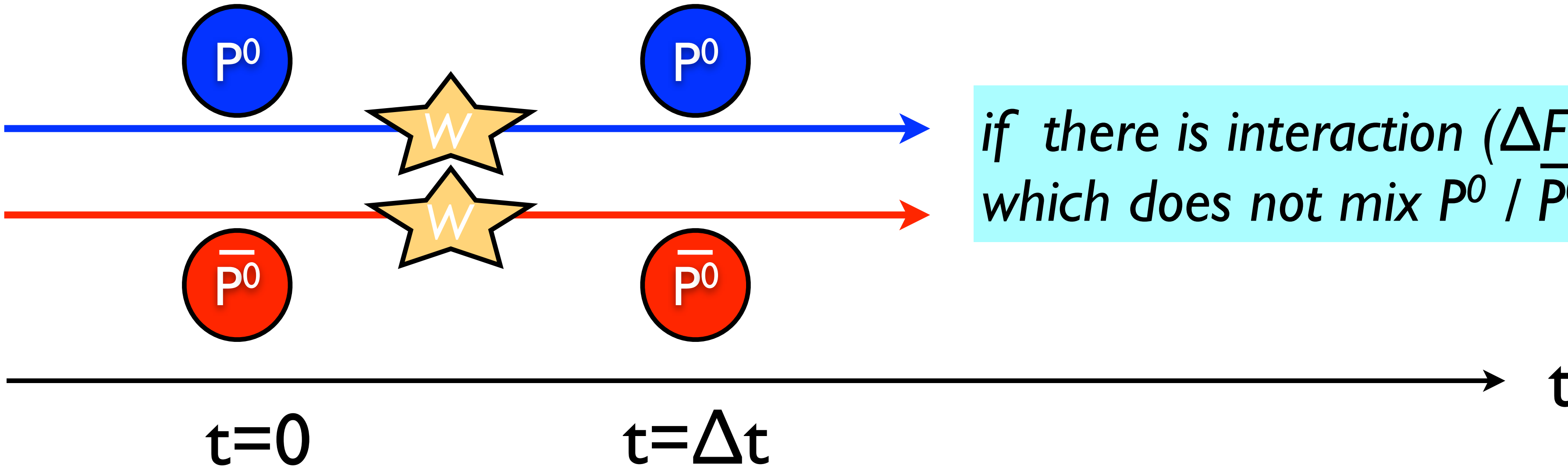


Oscillation with Weak interaction

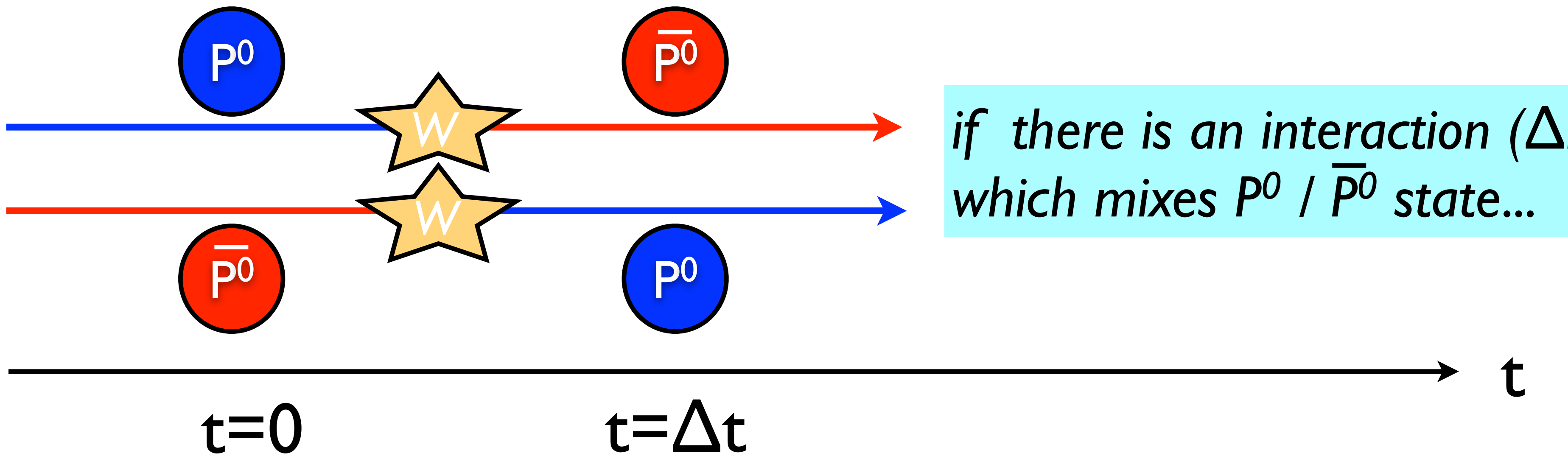
$$|\Psi(0)\rangle = a(0)|P^0\rangle + b(0)|\overline{P}^0\rangle$$



Oscillation with Weak interaction

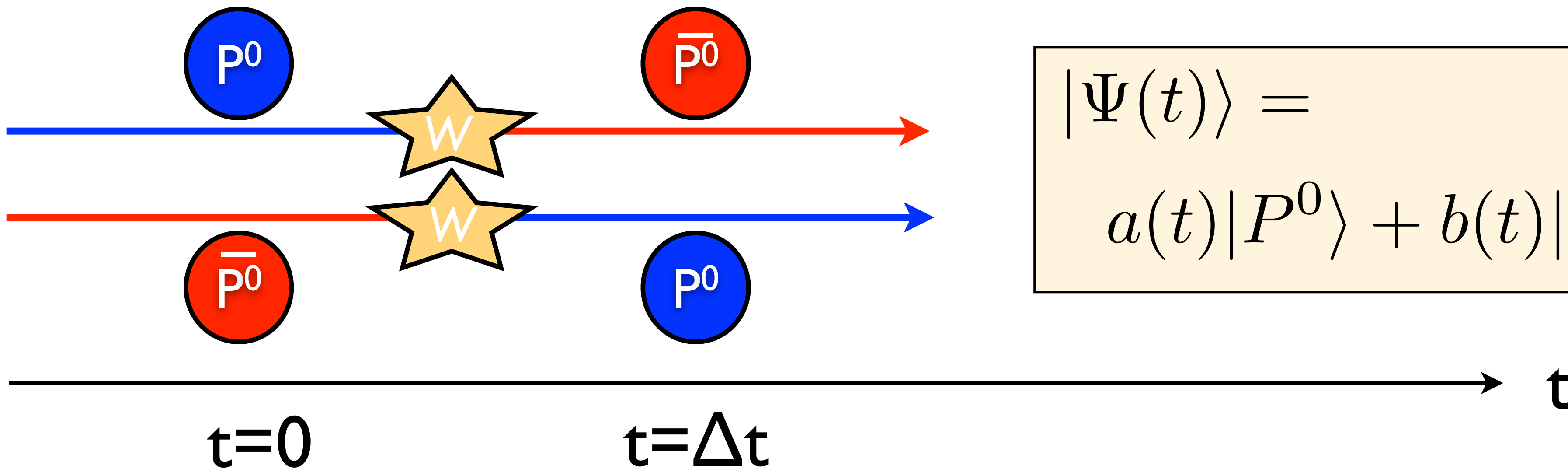


Oscillation with Weak interaction



if there is an interaction (ΔF=1,2) which mixes P^0 / $\overline{P}^0$ state...

Oscillation with Weak interaction



$$|\Psi(t)\rangle = a(t)|P^0\rangle + b(t)|\overline{P}^0\rangle$$

The time evolution can be obtained by solving

$$i\hbar\frac{\partial}{\partial t}\Psi(t) = \mathcal{H}\Psi(t)$$

Here H is the weak interaction Hamiltonian describing the ΔF=1,2 transition

H represents the transition between (P^0,$\bar{P}^0$) ⇔ (P^0,$\bar{P}^0$). M and Γ are the off-shell and the on-shell part, respectively.

$$\mathcal{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$$

$$= \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}$$

Oscillation with Weak interaction

Now we diagonalize this matrix

$$\begin{aligned}\mathcal{H} &= \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} \\ &= \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}\end{aligned}$$

Oscillation with Weak interaction

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Using CPT invariance ($M_{11}=M_{22}$, $\Gamma_{11}=\Gamma_{22}$) and ***M*** *and* **Γ** *being Hermitian, we find the mass eigenstate P_1 and P_2*

$$\begin{aligned}|P_1\rangle &= p|P^0\rangle + q|\overline{P}^0\rangle \\ |P_2\rangle &= p|P^0\rangle - q|\overline{P}^0\rangle\end{aligned} \quad ; \qquad \frac{q}{p} = \pm\sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

$$M_1 - \frac{i}{2}\Gamma_1 = M_{11} - \frac{i}{2}\Gamma_{11} + \frac{q}{p}(M_{12} - \frac{i}{2}\Gamma_{12})$$

$$M_2 - \frac{i}{2}\Gamma_2 = M_{11} - \frac{i}{2}\Gamma_{11} - \frac{q}{p}(M_{12} - \frac{i}{2}\Gamma_{12})$$

Oscillation with Weak interaction

Now we diagonalize this matrix

$$
\begin{aligned}
\mathcal{H} &= \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} \\
&= \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}
\end{aligned}
$$

*Using CPT invariance (M_{11}=M_{22}, Γ_{11}=Γ_{22}) and **M** and **Γ** being Hermitian, we find the mass eigenstate P_1 and P_2*

$$
\begin{aligned}
|P_1\rangle &= p|P^0\rangle + q|\overline{P}^0\rangle \\
|P_2\rangle &= p|P^0\rangle - q|\overline{P}^0\rangle
\end{aligned}
\quad ; \qquad \frac{q}{p} = \pm\sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}
$$

$$
M_1 - \frac{i}{2}\Gamma_1 = M_{11} - \frac{i}{2}\Gamma_{11} + \frac{q}{p}(M_{12} - \frac{i}{2}\Gamma_{12})
$$

$$
M_2 - \frac{i}{2}\Gamma_2 = M_{11} - \frac{i}{2}\Gamma_{11} - \frac{q}{p}(M_{12} - \frac{i}{2}\Gamma_{12})
$$

Oscillation with Weak interaction

Now we diagonalize this matrix

$$\mathcal{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$$
$$= \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}$$

*Using CPT invariance ($M_{11}=M_{22}$, $\Gamma_{11}=\Gamma_{22}$) and **M** and **Γ** being Hermitian, we find the mass eigenstate P_1 and P_2*

$$\begin{aligned} |P_1\rangle &= p|P^0\rangle + q|\overline{P}^0\rangle \\ |P_2\rangle &= p|P^0\rangle - q|\overline{P}^0\rangle \end{aligned} \quad ; \qquad \frac{q}{p} = \pm\sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

$$\begin{aligned} |P^0(t)\rangle &= f_+(t)|P^0\rangle + \frac{q}{p}f_-(t)|\overline{P}^0\rangle \\ |\overline{P}^0(t)\rangle &= f_+(t)|P^0\rangle + \frac{p}{q}f_-(t)|\overline{P}^0\rangle \end{aligned} \quad ; \; f_\pm(t) = \frac{1}{2}e^{-i(M_1 - i\Gamma_1/2)t}\left[1 \pm e^{-i(\Delta M + i\Delta\Gamma/2)t}\right]$$

Time evolution formula

Oscillation with Weak interaction

Now we diagonalize this matrix

$$
\begin{aligned}
\mathcal{H} &= \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} \\
&= \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}
\end{aligned}
$$

Remember...

CP violation

$q/p \neq 1$

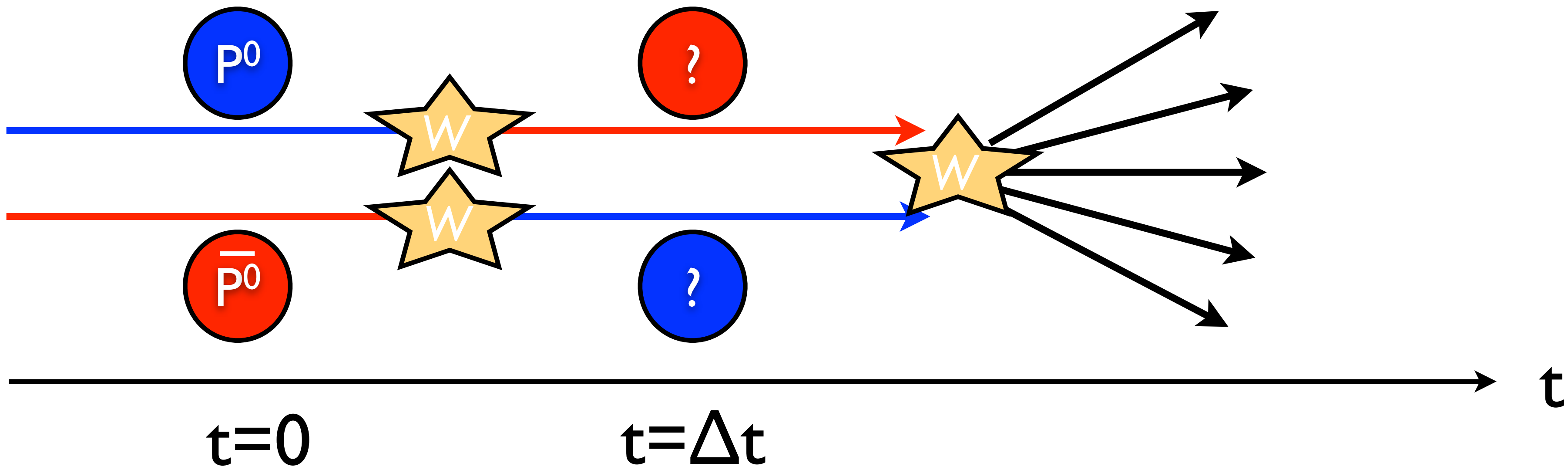
*Using CPT invariance ($M_{11}=M_{22}$, $\Gamma_{11}=\Gamma_{22}$) and **M** and Γ being Hermitian, we find the mass eigenstate P_1 and P_2*

$$
\begin{aligned}
|P_1\rangle &= p|P^0\rangle + q|\overline{P}^0\rangle \\
|P_2\rangle &= p|P^0\rangle - q|\overline{P}^0\rangle
\end{aligned}
\quad ; \qquad \frac{q}{p} = \pm\sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}
$$

$$
\begin{aligned}
|P^0(t)\rangle &= f_+(t)|P^0\rangle + \frac{q}{p} f_-(t)|\overline{P}^0\rangle \\
|\overline{P}^0(t)\rangle &= f_+(t)|P^0\rangle + \frac{p}{q} f_-(t)|\overline{P}^0\rangle
\end{aligned}
\; ; \; f_\pm(t) = \frac{1}{2} e^{-i(M_1 - i\Gamma_1/2)t}\left[1 \pm e^{-i(\Delta M + i\Delta\Gamma/2)t}\right]
$$

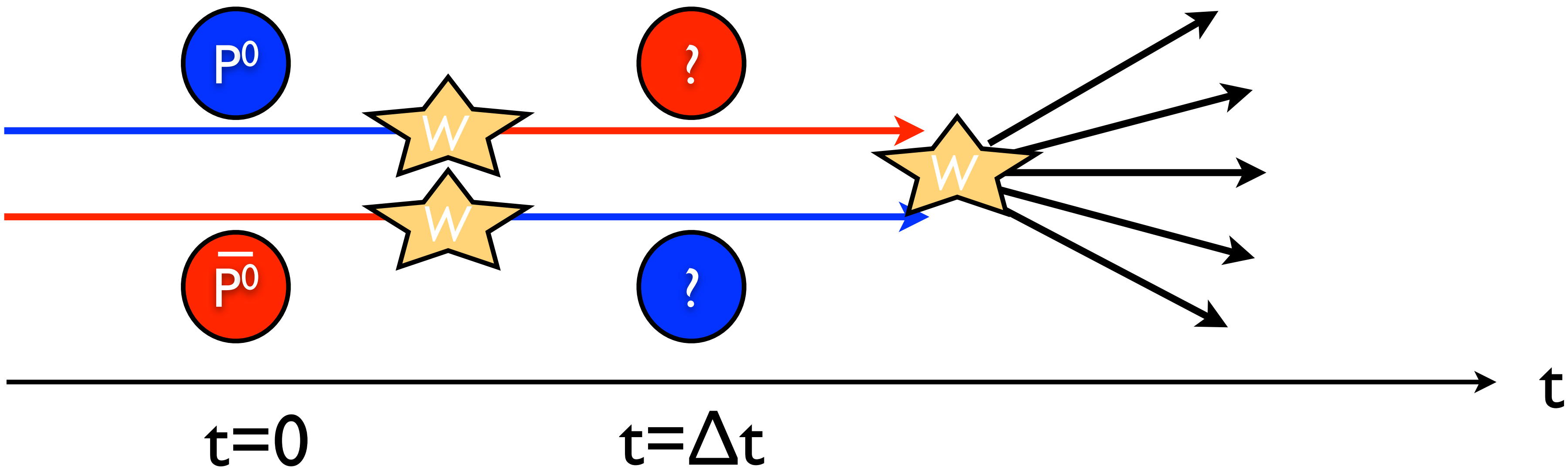
Time evolution formula

Decay width with Weak interaction



$$A(f) = \langle f | \mathcal{H}^{\Delta F=1} | P^0 \rangle \qquad \overline{A}(f) = \langle f | \mathcal{H}^{\Delta F=1} | \overline{P}^0 \rangle$$

Decay width with Weak interaction



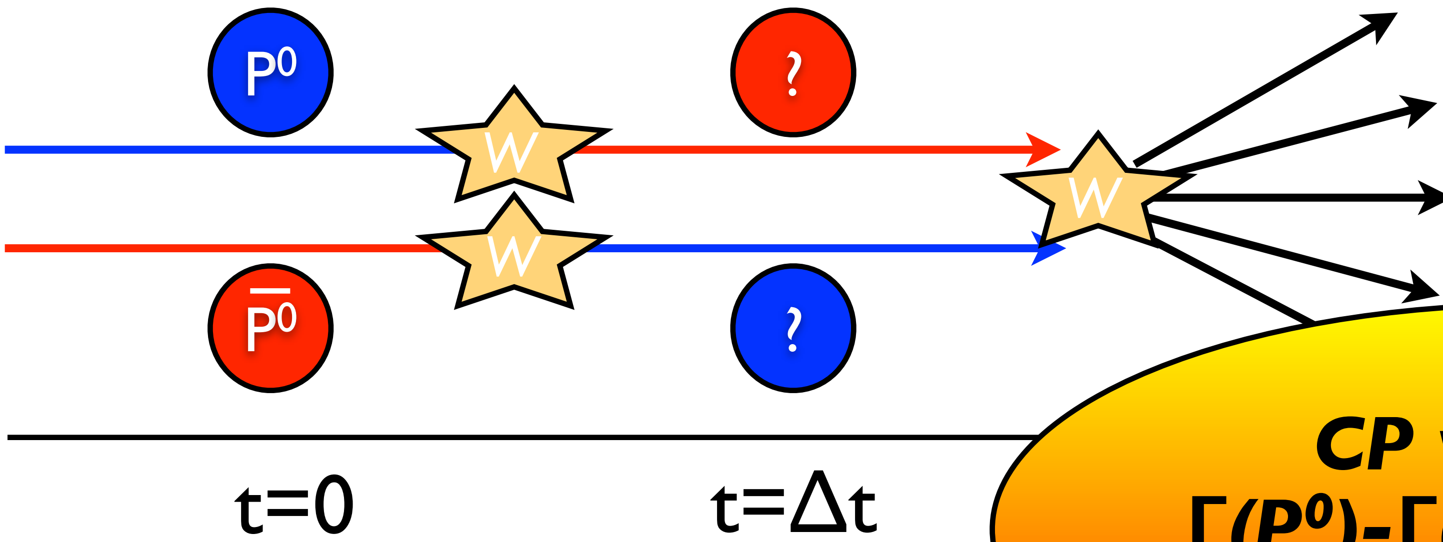
$$A(f) = \langle f|\mathcal{H}^{\Delta F=1}|P^0\rangle \qquad \overline{A}(f) = \langle f|\mathcal{H}^{\Delta F=1}|\overline{P}^0\rangle$$

$$\Gamma(P^0(t)\to f) \propto e^{-\Gamma_1 t}|A(f)|^2\left[K_+(t)+K_-(t)\left|\frac{q}{p}\right|^2\left|\frac{\overline{A}(f)}{A(f)}\right|^2 + 2Re\left[L^*(t)\left(\frac{q}{p}\right)\frac{\overline{A}(f)}{A(f)}\right]\right]$$

$$\Gamma(\overline{P}^0(t)\to f) \propto e^{-\Gamma_1 t}|\overline{A}(f)|^2\left[K_+(t)+K_-(t)\left|\frac{p}{q}\right|^2\left|\frac{A(f)}{\overline{A}(f)}\right|^2 + 2Re\left[L^*(t)\left(\frac{p}{q}\right)\frac{A(f)}{\overline{A}(f)}\right]\right]$$

$$K_\pm(t) = 1 + e^{\Delta\Gamma t} \pm 2e^{\frac{1}{2}\Delta\Gamma t}\cos\Delta M t, \quad L^*(t) = 1 - e^{\Delta\Gamma t} + 2ie^{\frac{1}{2}\Delta\Gamma t}\sin\Delta M t$$

Decay width with Weak interaction



CP violation
Γ(P^0)-Γ(P^0)≠0 when
q/p≠1 and/or A/$\overline{A}$≠1

$$A(f) = \langle f | \mathcal{H}^{\Delta F=1} | P^0(t) \rangle$$

$$\Gamma(P^0(t) \to f) \propto e^{-\Gamma_1 t} |A(f)|^2 \left[K_+(t) + K_-(t) \left| \frac{q}{p} \right|^2 \left| \frac{\overline{A}(f)}{A(f)} \right|^2 + 2Re \left[L^*(t) \left(\frac{q}{p} \right) \frac{\overline{A}(f)}{A(f)} \right] \right]$$

$$\Gamma(\overline{P}^0(t) \to f) \propto e^{-\Gamma_1 t} |\overline{A}(f)|^2 \left[K_+(t) + K_-(t) \left| \frac{p}{q} \right|^2 \left| \frac{A(f)}{\overline{A}(f)} \right|^2 + 2Re \left[L^*(t) \left(\frac{p}{q} \right) \frac{A(f)}{\overline{A}(f)} \right] \right]$$

$$K_\pm(t) = 1 + e^{\Delta\Gamma t} \pm 2 e^{\frac{1}{2}\Delta\Gamma t} \cos \Delta M t, \quad L^*(t) = 1 - e^{\Delta\Gamma t} + 2i e^{\frac{1}{2}\Delta\Gamma t} \sin \Delta M t$$

Gold-plated $B \to J/\psi K_S$ mode

Example of $B \to J/\psi K_S$ mode where CPV is the best measured in the B system

$$A_{J/\psi K_S} = \frac{\Gamma(\overline{B}^0 \to J/\psi K_S) - \Gamma(B^0 \to J/\psi K_S)}{\Gamma(\overline{B}^0 \to J/\psi K_S) + \Gamma(B^0 \to J/\psi K_S)}$$

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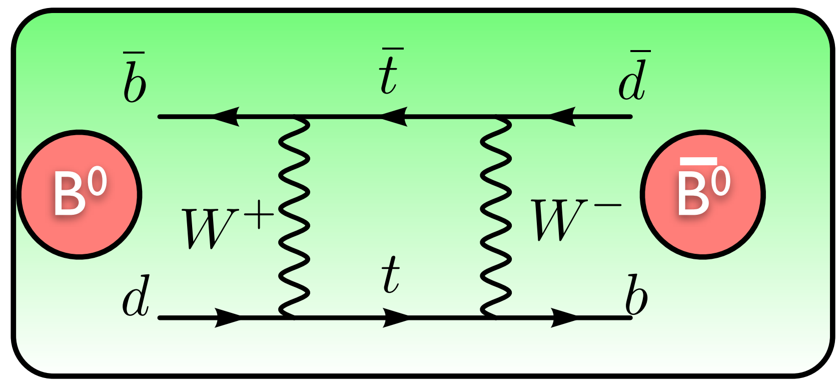
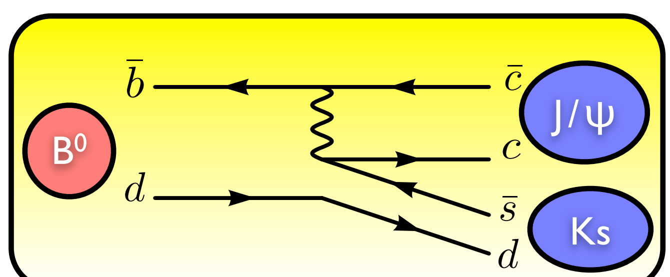
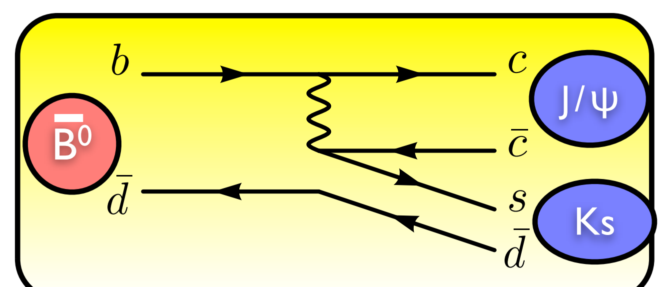
$q/p \neq 1$



$A/\bar{A} = 1$



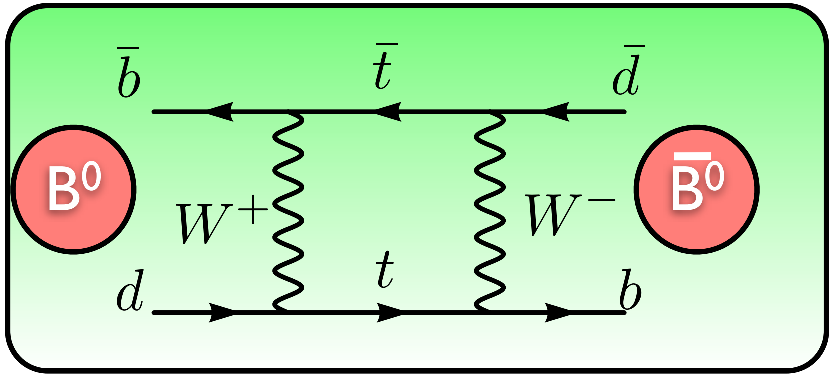


Gold-plated B→J/ψK$_S$ mode

Example of B→J/ψK$_S$ mode where CPV is the best measured in the B system

$$A_{J/\psi K_S} = \frac{\Gamma(\overline{B}^0 \to J/\psi K_S) - \Gamma(B^0 \to J/\psi K_S)}{\Gamma(\overline{B}^0 \to J/\psi K_S) + \Gamma(B^0 \to J/\psi K_S)}$$

q/p≠1

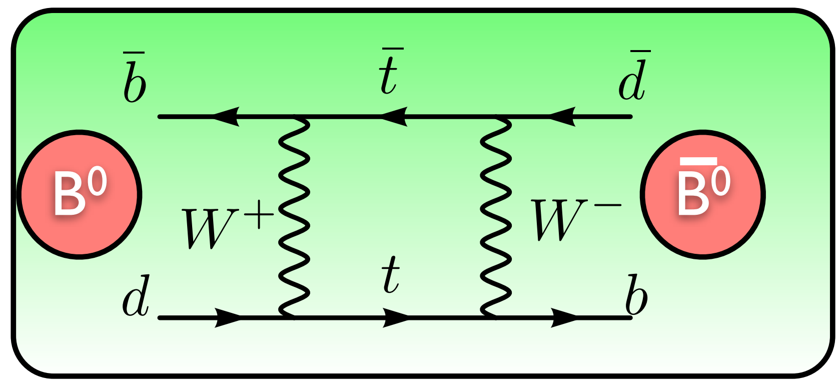


Gold-plated $B\to J/\psi K_S$ mode

Example of $B\to J/\psi K_S$ mode where CPV is the best measured in the B system

$$A_{J/\psi K_S} = \frac{\Gamma(\overline{B}^0\to J/\psi K_S)-\Gamma(B^0\to J/\psi K_S)}{\Gamma(\overline{B}^0\to J/\psi K_S)+\Gamma(B^0\to J/\psi K_S)}$$

$q/p\neq 1$



In the B system, we have $M_{12} >> \Gamma_{12}$, thus

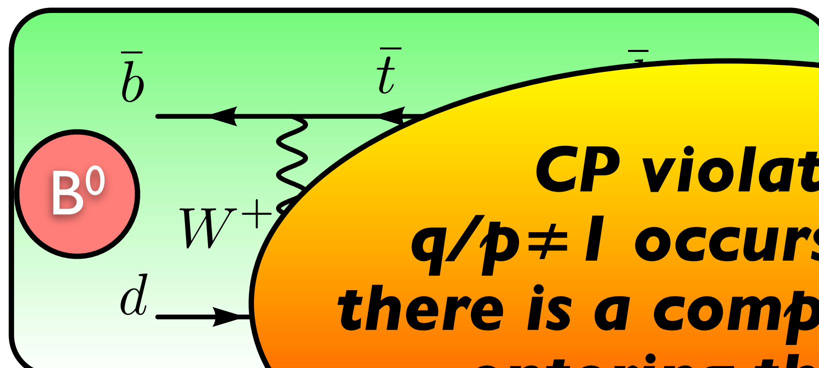
$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \simeq \sqrt{\frac{M_{12}^*}{M_{12}}} \equiv e^{i\phi}$$

Gold-plated B→J/ψK$_S$ mode

Example of B→J/ψK$_S$ mode where CPV is the best measured in the B system

$$A_{J/\psi K_S} = \frac{\Gamma(\overline{B}^0 \to J/\psi K_S) - \Gamma(B^0 \to J/\psi K_S)}{\Gamma(\overline{B}^0 \to J/\psi K_S) + \Gamma(B^0 \to J/\psi K_S)}$$

q/p≠1



CP violation
***q/p≠1* occurs only if there is a complex phase entering the box diagram**

In the B system, we have $M_{12} >> \Gamma_{12}$, thus

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \simeq \sqrt{\frac{M_{12}^*}{M_{12}}} \equiv e^{i\phi}$$

Gold-plated B→J/ψK$_S$ mode

$$\frac{\Gamma(\overline{B}^0(t) \to J/\psi K_S) - \Gamma(B^0(t) \to J/\psi K_S)}{\Gamma(\overline{B}^0(t) \to J/\psi K_S) + \Gamma(B^0(t) \to J/\psi K_S)} = \sin 2\phi \sin \Delta M_B \Delta t$$