Particle Physics

Dr Victoria Martin, Spring Semester 2013

Lecture 16: More CP Violation and Introduction to Electroweak Theory

W BOSON *W-, W+*

The **W BOSON** is a messenger particle which communicates the weak force. Unlike the photon and gluon bosons, it has a mass. Like the Z boson, it is one of the most short-lived particles known, with a mere 10^{-25} second lifetime. It can be negatively charged (W-) or positively charged (W+). Luckily you can have both, as the toy is double-sided.

Wool felt with gravel fill for maximum mass.

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Z BOSON *Z*

The **Z BOSON** is a very massive carrier particle for the weak force. Unlike its siblings the W-/W+ particles, the Z is neutrally charged. Living only 10^{-25} second, the Z quickly decays into other particles. Discovered in 1983, the Z has allowed physicists to further study electroweak theory.

Wool felt with gravel fill for maximum mass.

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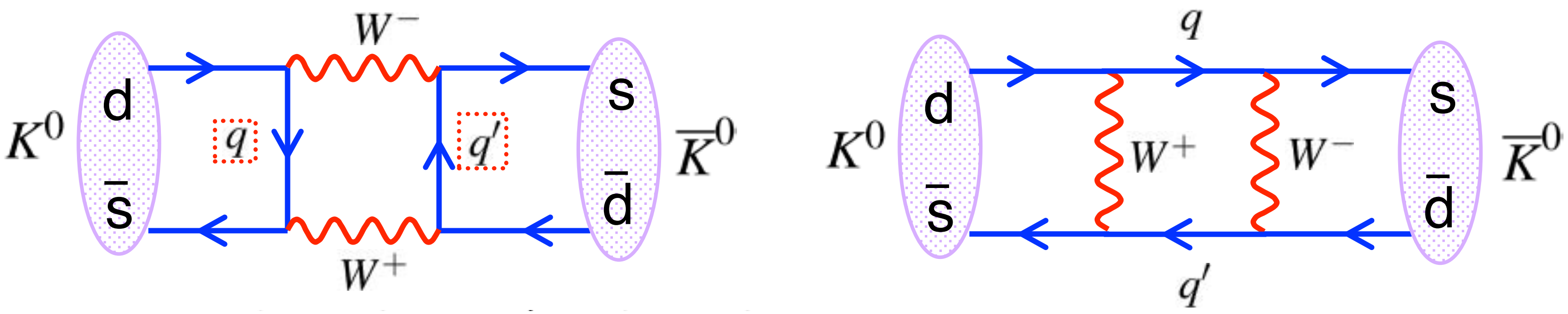
- ★Kaon mixing revisited
- ★CKM matrix
- ★Weak Isospin and Weak Hypercharge

Kaon Mixing Revisited



- Indirect *CP* violation in mixing occurs because the rate between $\mathbf{K^0 \rightarrow \overline{K}^0}$ transitions is smaller than the rate between $\mathbf{\overline{K}^0 \rightarrow K^0}$ transition.

$$\Gamma(\mathbf{K^0 \rightarrow \overline{K}^0}) \neq \Gamma(\mathbf{\overline{K}^0 \rightarrow K^0})$$

- Slightly more matter ($\mathbf{K^0}$) is created than anti-matter ($\mathbf{\overline{K}^0}$)
- Therefore both decay eigenstates contain slightly more (ϵ more) matter than anti-matter:

$$|\mathrm{K_S}\rangle = \frac{1}{N}\Big((1+\epsilon)|\mathrm{K}^0\rangle - (1-\epsilon)|\overline{\mathrm{K}}^0\rangle\Big)$$

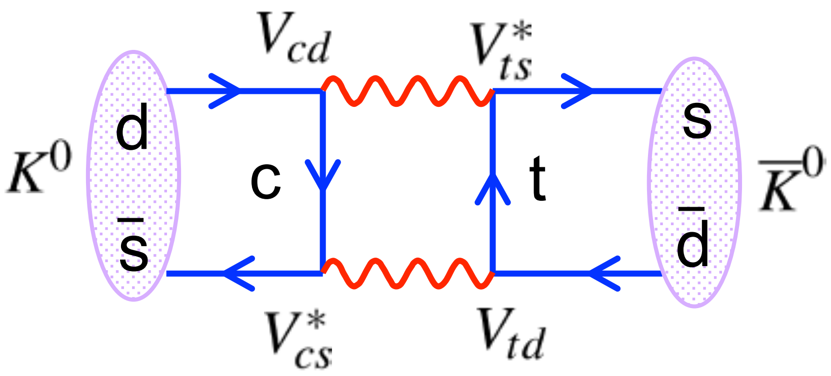
$$|\mathrm{K_L}\rangle = \frac{1}{N}\Big((1+\epsilon)|\mathrm{K}^0\rangle + (1-\epsilon)|\overline{\mathrm{K}}^0\rangle\Big)$$

CKM elements for kaon mixing

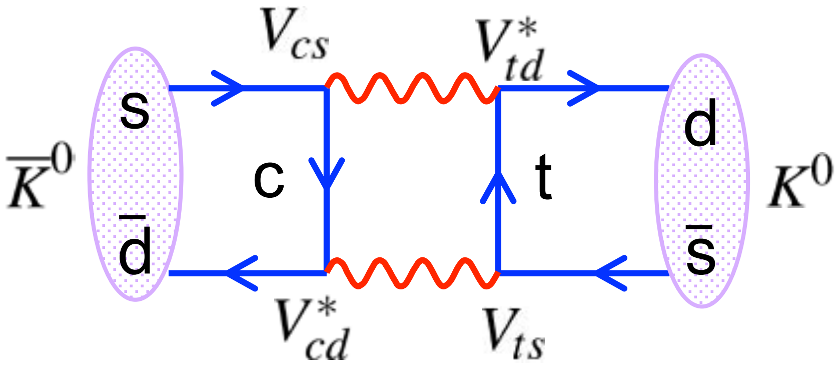
- Calculating $\mathcal{M}$ for this process, we have to consider all possible contributions due to different internal quarks.

To work out which CKM matrix element, follow the quark line *backwards*:
if $t \rightarrow s$: use V_{ts}
if $s \rightarrow t$: then we need V_{st} which doesn't exist, therefore use V^*_{ts}

- For this argument , just consider one contribution:



$$\mathcal{M} \propto V_{cd} V^*_{ts} V_{td} V^*_{cs}$$



$$\mathcal{M}' \propto V_{cs} V^*_{td} V_{ts} V^*_{cd} \propto \mathcal{M}^*$$

$$\Gamma(K^0 \rightarrow \overline{K}^0) - \Gamma(\overline{K}^0 \rightarrow K^0) = \mathcal{M} - \mathcal{M}^* = 2\,\mathcal{I}m(\mathcal{M})$$

- The amount of *CP* violation is related to the imaginary parts of the CKM matrix elements

Cabibbo-Kobayashi-Maskawa Matrix

- The CKM matrix is the source of ***CP*** violation in the Standard Model
- Weak eigenstates are admixture of mass eigenstates, conventionally described using CKM matrix a mixture of the down-type quarks:

weak eigenstates

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

mass eigenstates

- The CKM matrix is unitary, $\boldsymbol{V}_{\mathbf{CKM}}{}^{\dagger}\boldsymbol{V}_{\mathbf{CKM}} = \mathbf{1}$ implies nine “unitarity relations”

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

- The most frequently discussed is (1st row × 3rd column):

$$V^*_{\mathrm{ub}} V_{\mathrm{ud}} + V^*_{\mathrm{cb}} V_{\mathrm{cd}} + V^*_{\mathrm{tb}} V_{\mathrm{td}} = 0$$

The Wolfenstein Parameterisation

- An expansion of the CKM matrix in powers of $\lambda = V_{us} = 0.22$

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

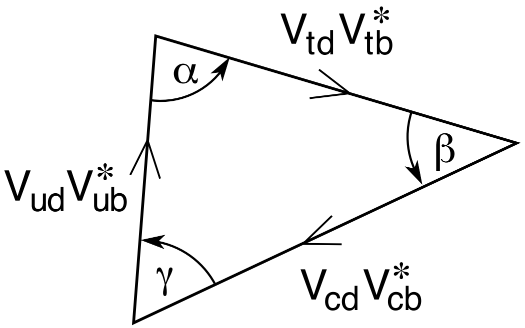
- Parameterisation reflects almost diagonal nature of CKM matrix:
  - ➡The diagonal elements V_{ud}, V_{cs}, V_{tb} are close to **1**
  - ➡Elements V_{us}, $V_{cd} \sim \lambda$ are equal
  - ➡Elements V_{cb}, $V_{ts} \sim \lambda^2$ are equal
  - ➡Elements V_{ub}, $V_{td} \sim \lambda^3$ are very small

- Diagonal structure means down quark mass eigenstate is almost equal to down quark weak eigenstate
  - similarly for strange and bottom mass eigenstates
- Note that the complex phase η only appears in the very small elements, and is thus hard to measure.

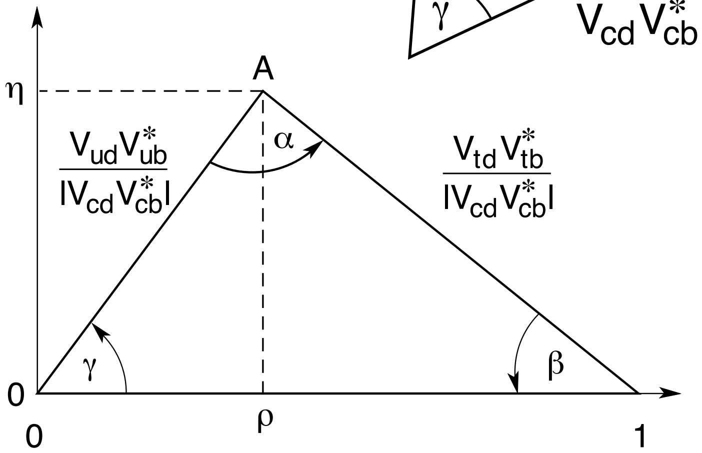
The Unitarity Triangle

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

- Forms a triangle in the complex plane:



- Dividing through by $V_{cd}V_{cb}^*$:



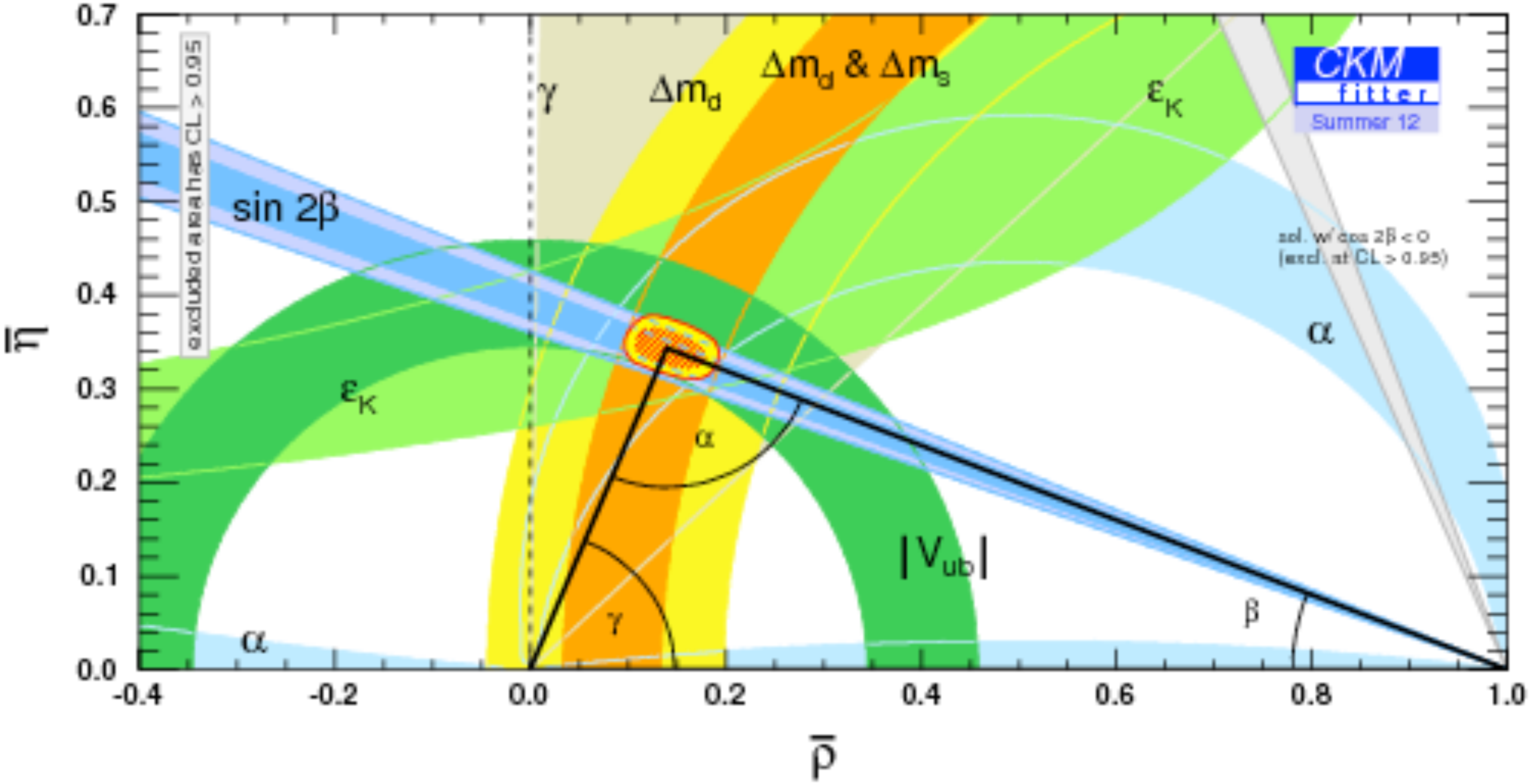
- This **unitarity triangle** is often use to present measurements of ***CP*** violation in **B**-meson decay.
- Lengths and angles of the triangle are:

$$\left|\frac{V_{\mathrm{ud}}V_{\mathrm{ub}}^{*}}{V_{\mathrm{cd}}V_{\mathrm{cb}}^{*}}\right| \qquad \left|\frac{V_{\mathrm{td}}V_{\mathrm{tb}}^{*}}{V_{\mathrm{cd}}V_{\mathrm{cb}}^{*}}\right|$$

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

- Triangle has a finite area only if relative complex phase between CKM elements

“CKM Fit”



- Experimental measurements used to determine lengths and sides of unitarity triangle.
- Determines best values for **η** and **ρ** parameters in Wolfenstein parameterisation.
- Current measurements indicate it is a closed triangle - consistent with only small ***CP*** violation.

Electroweak Unification

- Electroweak Theory was proposed in 1967 by Glashow, Salam & Weinberg. Unifies the electromagnetic and weak forces (Noble prize 1979)
- In 1970 ‘t Hooft and Veltman showed how to renormalise electroweak theory. (Noble prize 1999)

- At high energies ($E \gtrsim m_Z$) the electromagnetic force and the weak force are unified as a single **electroweak force.**
- At low energies ($E \lesssim m_Z$) the manifestations of the electroweak force are separate weak and electromagnetic forces.

- We will see today:
  1. The coupling constants for weak and electromagnetism are unified:

$$e = g_W \sin \theta_W$$

     ➡ Where $\sin\theta_W$ is the **weak mixing angle**

  2. Electroweak Unification predicts the existence of massive W^+ W^- and Z^0 bosons.
     ➡ Relies on Higgs mechanism to “give mass” to the W and Z bosons.

Review from Lecture 7,8: Charged & Neutral Weak Current

- Neutral Current is the exchange of massive *Z*-bosons.
  - ➡Couples to all quarks and all leptons (including neutrinos)
  - ➡No allowed flavour changes!
  - ➡Neutral weak current for fermion, *f*:

$$\frac{g_Z}{2}\bar{u}(f)\gamma^\mu(c_V^f - c_A^f\gamma^5)u(f)$$

c^f_V and c^f_A are constants for fermion flavour, *f*.

Lepton	c^f_V	c^f_A	Quark	c^f_V	c^f_A
ν_e, ν_μ, ν_τ	½	½	**u, c, t**	0.19	½
e, μ, τ	-0.03	−½	**d, s, b**	-0.34	−½

- Charged Current is the exchange of massive *W*-bosons.
  - ➡Couples to all quarks and leptons and changes fermion flavour:
  - ➡Allowed flavour changes are: $e\leftrightarrow\nu_e$, $\mu\leftrightarrow\nu_\mu$, $\tau\leftrightarrow\nu_\tau$, **d'↔u, s'↔c, b'↔t**
  - ➡Acts only on the left-handed components of the fermions: *V−A* structure.

$$g_W\frac{1}{2\sqrt{2}}\bar{u}(\nu_e)\gamma^\mu(1-\gamma^5)u(e^-)$$

Weak Isospin and Hypercharge

- QED couples to electric charge; QCD couples to colour charge...
- Electroweak force couples to two “charges”.
  - **Weak Isospin:** total and third component T, T_3. Depends on **chirality**
  - **Weak Hypercharge,** Y In terms of electric charge Q: $Y = 2\,(Q - T_3)$
    - All right-handed fermions have $T=0$, $T_3=0$
    - All left-handed fermions have $T=½$, $T_3=±½$
    - All left-handed antifermions have $T=0$, $T_3=0$
    - All right-handed antifermions have $T=½$, $T_3(\bar{f})=-T_3(f)$

Lepton	T	T_3	Y	Quark	T	T_3	Y
ν_{eL}, $\nu_{\mu L}$, $\nu_{\tau L}$	½	+½	-1	u_L, c_L, t_L	½	+½	⅓
e_L, μ_L, τ_L	½	−½	-1	d_L, s_L, b_L	½	− ½	⅓
ν_R	0	0	0	u_R, c_R, t_R	0	0	4/3
e_R, μ_R, τ_R	0	0	-2	d_R, s_R, b_R	0	0	−⅔