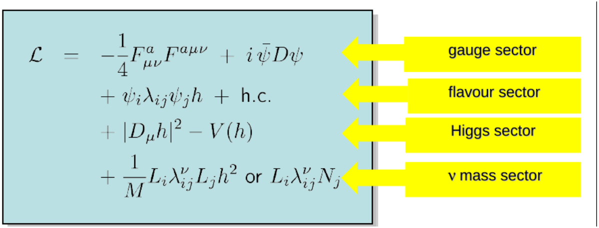
Physics 290e:
Quark Interactions: SM and Beyond
Overview and Introduction

Jan 30, 2019

The (Extended) Standard Model Lagrangian



$$\begin{aligned}\mathcal{L} &= -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}D\psi \\ &+ \psi_i\lambda_{ij}\psi_j h + \text{h.c.} \\ &+ |D_\mu h|^2 - V(h) \\ &+ \frac{1}{M}L_i\lambda^\nu_{ij}L_j h^2 \text{ or } L_i\lambda^\nu_{ij}N_j\end{aligned}$$

gauge sector

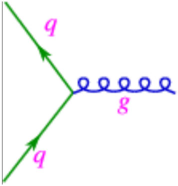
flavour sector

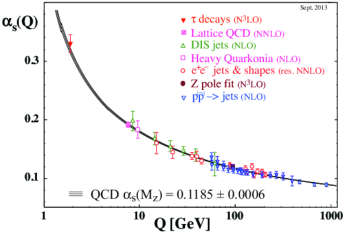
Higgs sector

ν mass sector

- $\mathcal{L} = \mathcal{L}_{QCD} + \mathcal{L}_{EW}$
- Gauge group: $\mathrm{SU}(3) \times \mathrm{SU}(2)_L \times \mathrm{U}(1)$
- Quark are the only fundamental particles that interact with all the gauge fields
  - A unique probe of the SM
- Different gauge fields couple to different quark bases
  - Presence of mass-mixing matrix with wide number of phenomenological implications
- Quarks appear only in bound states (except top)
  - Vast array of measurements that can be used to test consistency with SM

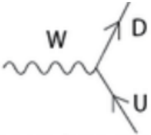
QCD: Quark-Gluon Interactions



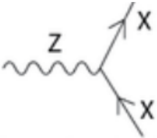


- "Simple" vertex with single coupling (α_S) independent of quark flavor
- Some effects of gluon self-interaction incorporated into running of α_S
  - Strong coupling at low q^2 leads to confinement
  - Rich spectroscopy of hadrons, no free quarks
- Need non-perturbative techniques to include bound-state effects:
  - Lattice QCD
  - Heavy Quark Effective Theory
  - Other resummation techniques
- Such techniques are essential for extraction of CKM and other SM parameters

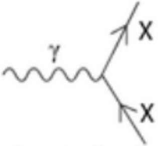
Quark Electroweak Interactions: New Parameters



U is a up-type quark;
D is a down-type quark.



X is any fermion in
the Standard Model.



X is electrically charged.

- Charged current quark interactions are (V-A) ($SU(2)_L$ gauge group) mediated by the $W^{\pm}$
  - Weak basis not the same as mass basis: CKM matrix to map between them
- Neutral current interactions through both $SU(2)_L$ and $U(1)$
  - Both γ and Z are mixtures of the two neutral gauge mediators
  - $\sin\theta_W$ specifies the mixing

Charge Current Electroweak Interactions

- Write hadronic current

$$J^{\mu} = -\frac{g}{\sqrt{2}} \left(\overline{u}\ \overline{c}\ \overline{t}\right) \gamma_{\mu} \frac{(1-\gamma_5)}{2} V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- V_{CKM} gives mixing between strong (mass) and (charged) weak basis
- Often write as

$$V_{CKM} = \begin{pmatrix} V_{ud} & Vus & V_{ub} \\ V_{cd} & Vcs & V_{cb} \\ V_{td} & Vts & V_{tb} \end{pmatrix}$$

- Wolfenstein parameterization:

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

Here λ is the $\approx \sin\theta_C$.

The CKM Matrix (Continued)

- From previous page:

$$\begin{aligned} V_{CKM} &= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \\ &\approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{aligned}$$

- From the explicit form (dropping terms of λ^2 or higher)

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

- Unitarity insures $VV^\dagger = V^\dagger V = 1$. Thus

$$\begin{aligned} \sum_i V_{ij}V_{ik}^* &= \delta_{jk} \text{ column orthogonality} \\ \sum_j V_{ij}V_{kj}^* &= \delta_{ik} \text{ row orthogonality} \end{aligned}$$

- Eg:

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

The Unitarity Triangle

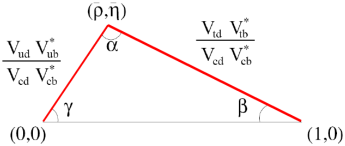
- From previous page

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

- Divide by $|V_{cd}^* V_{cb}|$:

$$\frac{V_{ud}V_{ub}^*}{|V_{cd}^* V_{cb}|} - 1 + \frac{V_{td}V_{tb}^*}{|V_{cd}^* V_{cb}|} = 0$$

- Think of this as a vector equation in the complex plane
- Orient so that base is along x-axis

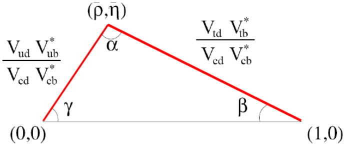


- Also from previous page:

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

The Measurement Game Plan

- Want to test if matrix is unitary
  - Failure of unitarity means new physics
- Make *many* measurements of sides and angles to over-constrain the triange and test that it closes

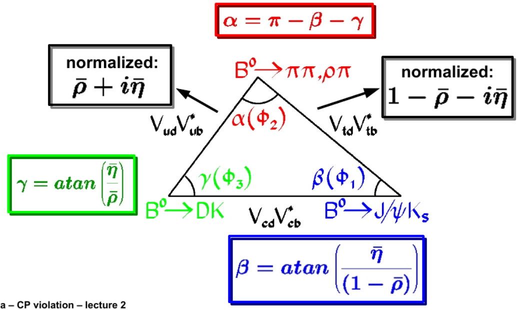


$$\begin{aligned}\alpha &\equiv arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]\\ \beta &\equiv arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]\\ \gamma &\equiv arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]\end{aligned}$$

Examples:

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

many observables
functions of $\bar{\rho}$ and $\bar{\eta}$:
overconstraining



$$\boxed{\alpha = \pi - \beta - \gamma}$$

normalized:
$\bar{\rho} + i\bar{\eta}$

normalized:
$1 - \bar{\rho} - i\bar{\eta}$

$B^0 \rightarrow \pi\pi, \rho\pi$

$\alpha(\phi_2)$

$V_{ud}V_{ub}^*$

$V_{td}V_{tb}^*$

$\gamma(\phi_3)$

$\beta(\phi_1)$

$B^0 \rightarrow DK$

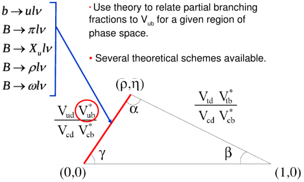
$V_{cd}V_{cb}^*$

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

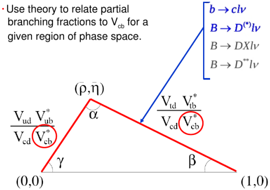
$$\boxed{\gamma = atan\left(\frac{\bar{\eta}}{\bar{\rho}}\right)}$$

$$\boxed{\beta = atan\left(\frac{\bar{\eta}}{(1-\bar{\rho})}\right)}$$

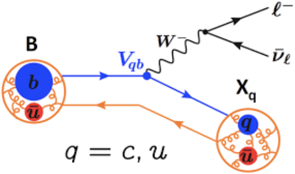
Measuring the Sides (example): B and D Decays



- Use theory to relate partial branching fractions to V_{ub} for a given region of phase space.
- Several theoretical schemes available.



- Use theory to relate partial branching fractions to V_{cb} for a given region of phase space.



- Sides are combinations of magnitudes of CKM matrix elements
- Heavy flavor decays one way to measure these
  - V_{cd} from $D_s \to K\ell\nu$, $D \to \pi\ell\nu$
  - V_{cs} from $D_s^+ \to \mu^+\nu$, $D \to K\ell\nu$
  - V_{cb} from $B \to X_c\ell\nu$ ($X_c \equiv D, D^*$, etc)
  - V_{ub} from $B \to X_d\ell\nu$ ($X_d \equiv \pi, \rho$, etc)
- Requires precise measurement of branching fractions
- Must correct for fact that c or b-quark is bound in a meson
  - Need theory for this

Angle Measurements: Types of CP Violation

- Three different categories
  - Direct CP Violation

$$Prob(B \rightarrow f) \neq Prob(\overline{B} \rightarrow \overline{f})$$

  - Indirect CP Violation (CPV in mixing)

$$Prob(B \rightarrow \overline{B}) \neq Prob(\overline{B} \rightarrow B)$$

  - CP Violation between mixing and decay
- Third category cleanest theoretically since no issues of final state interations
- Always need more than one amplitude to allow interference

The Weinberg Angle θ_W

- We have two couplings: g and g'
- Can always express the ratio as

$$\tan\theta_W = \frac{g}{g'}$$

- Then

$$\begin{aligned}\sin\theta_W &= \frac{g}{\sqrt{g^2+g'^2}} \\ \cos\theta_W &= \frac{g'}{\sqrt{g^2+g'^2}}\end{aligned}$$

- And our LaGrangian becomes:

$$\begin{aligned}\mathcal{L}_{NC} &= -\left[\overline{\chi}\gamma^\mu\left(gI_3(W_3)_\mu + g'B_\mu\frac{Y}{2}\right)\chi\right] \\ &= -\sqrt{g^2+g'2}\left[\overline{\chi}\gamma^\mu\left(\sin\theta_W I_3(W_3)_\mu + \cos\theta_W B_\mu\frac{Y}{2}\right)\chi\right]\end{aligned}$$

- Now we can pick out the piece that couples to charge and identify it with the photon

The photon, the Z and the $W^\pm$

- Define photon field as piece that couples to charge

$$A_\mu = B_\mu \cos\theta_W + (W_3)_\mu \sin\theta_W$$

- The Z is the orthogonal combination

$$Z_\mu = -B_\mu \sin\theta_W + (W_3)_\mu \cos\theta_W$$

- Because photon couples to charge, we can relate e to the couplings and θ_W:

$$e = g\sin\theta_W = g' \cos\theta_W$$

- The $W^\pm$ bosons are

$$W^\pm = \frac{W_1 \pm iW_2}{\sqrt{2}}$$

  and their coupling remains g. Using standard conventions

$$\frac{g^2}{8} = \frac{G_F M_W^2}{\sqrt{2}}$$

- $\sin\theta_W$ is a parameter to be measured (many different techniques)

$$\sin^2\theta_W \sim 0.23$$

The Quark Quantum Numbers

- Follow same prescription as for the leptons
- W_μ coupling is left handed: $\gamma_\mu(1-\gamma^5)/2$, B coupling is left-right symmetric: γ_μ
  - Left handed weak isodoublets, right handed weak isosinglets
  - Y value for multiplets chosen to enforce $Q = I_3 + Y/2$

fermion	Q	I_3^L	Y_L	Y_R
ν_ℓ	0	$\frac{1}{2}$	-1	-
ℓ	-1	$-\frac{1}{2}$	-1	-2
u, c, t	$+\frac{2}{3}$	$+\frac{1}{2}$	$+\frac{1}{3}$	$+\frac{4}{3}$
d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	$+\frac{1}{3}$	$-\frac{2}{3}$

Predicted Z Couplings to Fermions

- The Z current specified by

$$Z_\mu = -B_\mu \sin\theta_W + (W_3)_\mu \cos\theta_W$$

- Together with the LaGrangian from page 18 this gives (with some math)

$$J^Z_\mu = J^3_\mu - \sin^2\theta_W j^{EM}_\mu$$

- The neutral weak coupling is NOT (V-A) but rather $C_V \gamma_\mu + C_A \gamma_m u(1-\gamma^5)$
- Values of C_V and C_A can be calculated from $\sin^2\theta_W$
- Weak NC vector and axial vector couplings are:

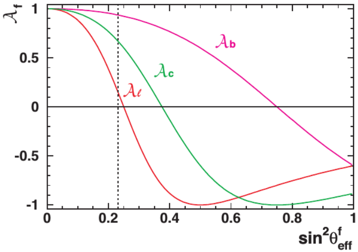
f	Q_f	C_A	C_V
ν	0	$\frac{1}{2}$	$\frac{1}{2}$
e	-1	$-\frac{1}{2}$	$-\frac{1}{2} + 2\sin^2\theta_W$
u	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$
d	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$

Forward-Backward Asymmetry

- Angular distribution in QED: $1 + \cos^2\theta$
- Here θ is angle between ingoing e^- direction and outgoing fermion f direction
- Parity violating weak interactions add a $\cos\theta$ term
- Can see this effect either by measuring angular distribution or integrating over positive and negative $\cos\theta$

  Both have been done
- The integrated quantity

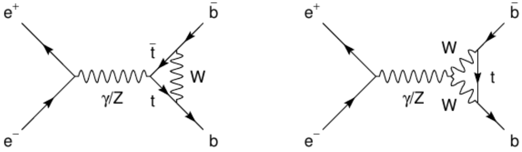
$$A_{FB} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



- Different asymmetries for leptons, for u-type and for d-type quarks
- Note: e^+e^- channel has t-channel Feynman diagram

Measuring the Quark Couplings at LEP

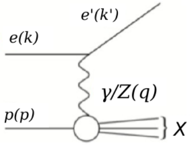
- Asymmetry measurements require distinguishing f and $\overline{f}$
- No clean way to do this for light quarks
  - Can try to measure jet charge, but large systematic uncertainties
  - We saw results from later HERA measurements on page 6
- Variety of techniques possible for "tagging" bottom and charm ("Heavy Flavor")
  - Some distinguish q and $\overline{q}$ while others don't
- Want to determine
  - $A_{FB}^{b,c}$: Different τ_3 for b and c leads to different couplings
  - R_b and R_c: Sensitive to couplings but also in case of R_b to Zbb vertex



Hera: DIS at large Q^2

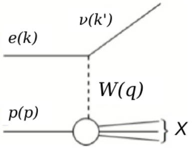
Neutral current scattering

$ep \rightarrow e'X$

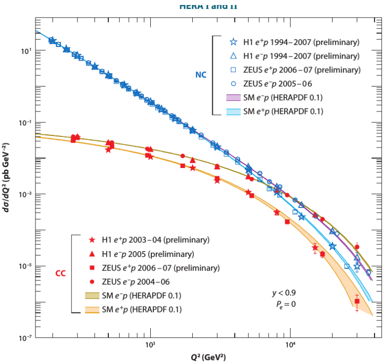


Charged current scatterin

$ep \rightarrow \nu_e X$

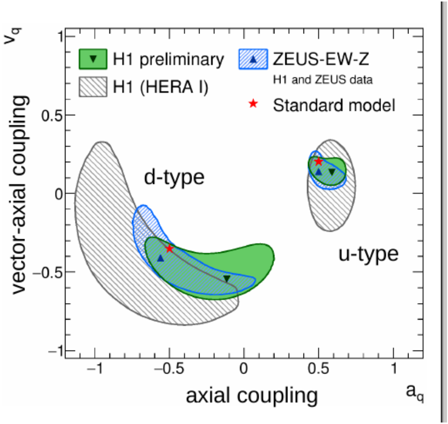


- Electron-proton collider
    - e^+ and e^-: $E_e = 27.6$ GeV
    - $E_p = 920$ GeV
    - Unpolarized running 1993-2000
    - Longitudinally polarized leptons
- Fits to high statistics data to determine EW parameters
- Leave vector and axial vector couplings of e, u-quarks and d-quarks free
- Constrain SM parameters
- Global PDF fits

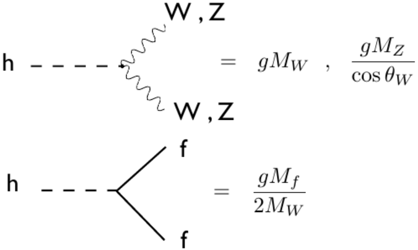


Measurements of NC couplings of quarks

- Axial and vector couplings determined by weak I_3 and Y
- Same equations as for leptons, but different numbers
- These couplings measured well at LEP, SLC
- HERA provides an alternative method



Quark Interactions with the Higgs: Yukawa Couplings



$$= gM_W \quad , \quad \frac{gM_Z}{\cos\theta_W}$$

$$= \frac{gM_f}{2M_W}$$

- Coupling to W^+W^- and ZZ defined by $\mathcal{L}$
- Coupling to fermions with strength that depends on fermion mass
  - These are known as the Yukawa couplings
- Current LHC measurements provide strong constraints on the W and Z and τ couplings to the Higgs, but how about the quark Yukawas?
  - Indirect constraints on Ht coupling from ggF (top loop)
  - First observation of ttH production in 2018
  - First observation of $H \to b\bar{b}$ in 2018
  - Only limits on first and second generation quarks so far

BSM Physics: Searches for FCNC Interactions

- In SM, GIM mechanism suppresses FCNC
    - Unitarity of CKM matrix means FCNC only possible due to differences between quark masses
    - This is why, eg $BR(K_L^0 \to \mu^+\mu^-) = 6.8 \times 10^{-9}$
- FCNC possible for BSM interactions
    - Because SM rate small, possible to see small BSM couplings if they exist
- Searches possible in many modes, eg:
    - $t \to Zq$
    - $b \to s\gamma$ or $s\ell^+\ell^-$

BSM Physics: Are Quarks Composite?

- To the best of our knowledge quarks, like leptons, are point-like particles
  - But, people used to think nuclei, and later nucleons were point-like
- Whenever the energy of our beam increases, we can probe smaller distances
- Analog of the Rutherford experiment
  - Look for an excess of events at large angle and/or high transverse momentum
- Best constraints today from LHE due to large $\hat{s}$

BSM Physics: New Interactions

- Many BSM models extend the SM Gauge group (embedding the “old” physics in the new)
- Resulting theory has additional force mediators (typically with large mass)
- These mediators can have color, flavor, lepton number
  - New interactions forbidden in SM appear
    - Rate often low due to high mass of mediator
- New particles can also appear
  - Eg: Leptoquarks with both lepton and baryon number
  - If kinematically allowed, can be seen at invariant mass peak in jet-lepton spectrum
  - Below threshold, non-resonance phenomena possible

Conclusions

- Precise measurements of quark couplings a rich field of research
  - Inconsistencies among measurements would indicate presence of new particles or interactions
- Significant ongoing work to constrain CKM matrix
  - Is the single phase in CKM the only source of CP violation in quark sector?
- Searches for suppressed or forbidden processes allows us to constrain (or see) new physics
  - It's easier to see a small cross section process if the background is zero or tiny
- Many theories developed to explain the as-yet-unexplained introduce such interaction.

  We hope such theories may explain:
  - What is the source of the matter-antimatter asymmetry in the Universe?
  - What is Dark Matter?
  - Are the SM interactions unified at a high mass scale?
  - What about gravity?