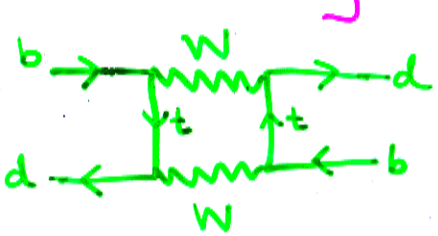
SEMILEPTONIC AND RARE b-HADRON DECAYS AT FERMILAB

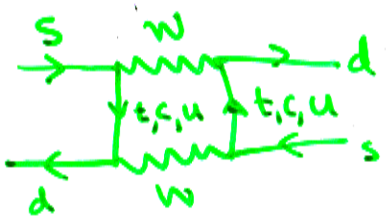
Over next few years much of HEP program devoted to testing CKM sector of Standard model.

DESPERATELY SEEKING THE UNITARITY TRIANGLE

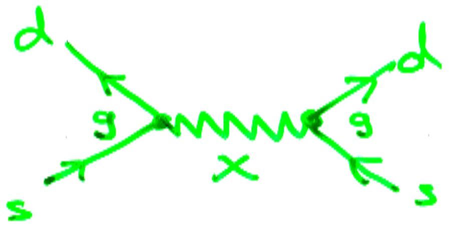
Processes that only occur at one loop level in standard model are particularly sensitive to contributions from new physics (i.e. not standard model physics)

Eg. "Second order Weak" $K^0-\bar{K}^0$ and $B^0-\bar{B}^0$ Mixing





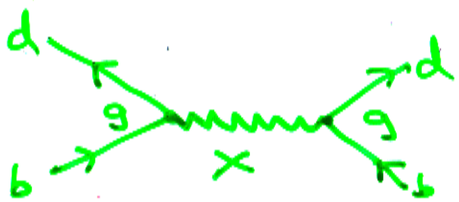
Suppose exchange of very heavy boson X with mass M_X is responsible for a fraction f of measured value of ε



$$f|\varepsilon| \sim \left|\frac{\mathrm{Im}\,M_{12}}{\underbrace{\Delta m_{LS}}_{3.5\times10^{-15}\,\mathrm{GeV}}}\right| \sim \left|\frac{g^2 \overbrace{\Lambda_{QCD}}^{0.3\,\mathrm{GeV}}{}^3}{M_X^2\,\Delta m_{LS}}\right|$$

$$\Rightarrow M_X \sim 6\times10^{7}\,(g/\sqrt{f})\,\mathrm{GeV}$$

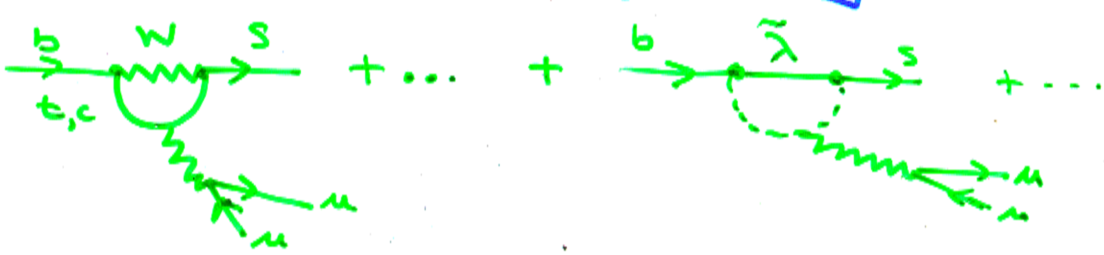
Similarly for B^0–$\bar{B}^0$ mixing



$$f\,\underbrace{\Delta m_{Bd}}_{3.1\times10^{-13}\,\mathrm{GeV}} \sim \frac{g^2\Lambda_{QCD}^3}{M_X^2}$$

$$\Rightarrow M_X \sim 3\times10^{5}\,(g/\sqrt{f})\,\mathrm{GeV}$$

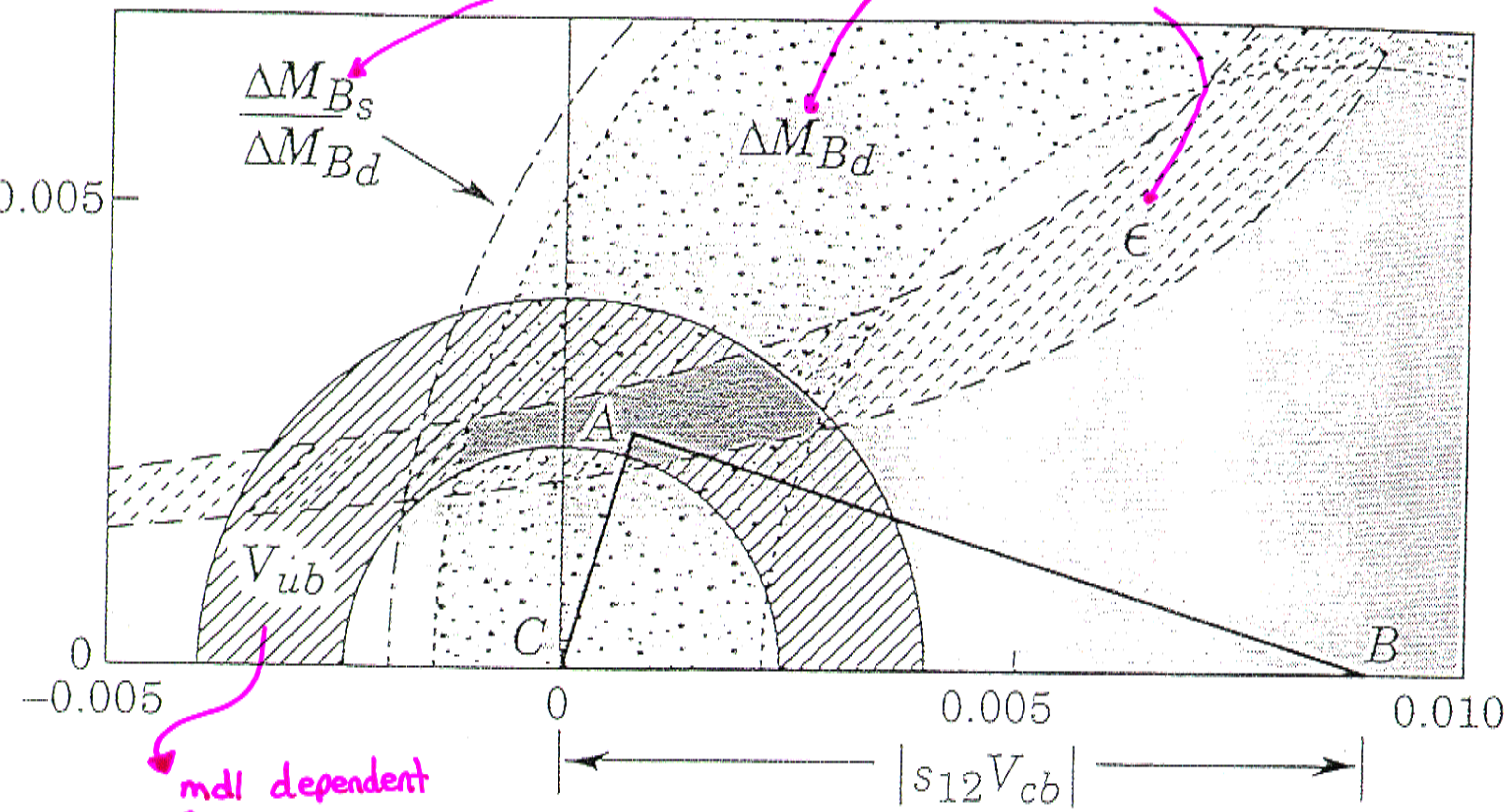
Or new particles not too much heavier than W can occur in loops. Happens, for example, in low energy supersymmetry E.g. $\bar{B}\to X_s\mu^+\mu^-$



$1 \curvearrowright V_{ud}V_{ub}^* + \overset{\sim -s_{12}}{V_{cd}} V_{cb}^* + V_{td} \overset{\sim 1}{V_{tb}^*} = 0$: Unitarity of CKM

$\Rightarrow$ $V_{ub}^* + V_{td} = s_{12} V_{cb}^*$: Unitarity triangle!

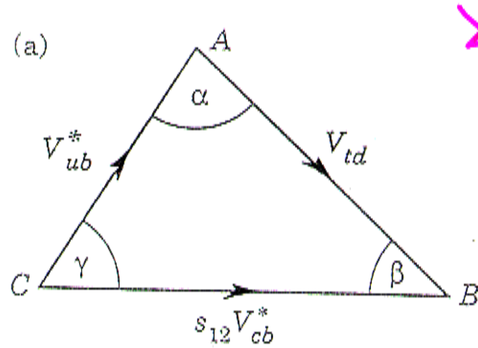
lattice QCD evaluation of matrix elements of four quark operators



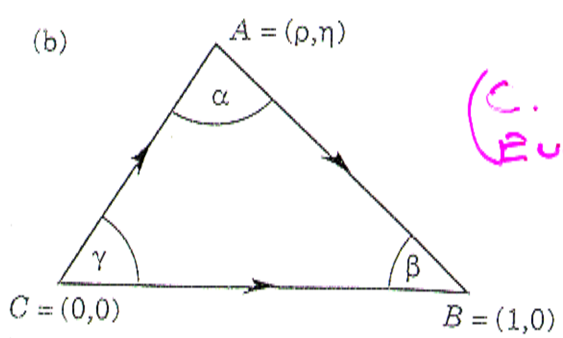
mdl dependent from endpoint and exclusive semileptonic B decay

Inclusive B semileptonic decay and $B \to D^{(*)} e \bar{\nu}_e$ decay. The $1/m_{b,c}$ expansion and quark hadron duality.

(a)



(b)



(C. Caso et. al. PDG Euro. Phys. J. C3 (1998) 1)

I Λ_b Semileptonic Decay

(Note $\bar{B} \to \Lambda_c e^- X$ branching ratio $< 3 \cdot 10^{-3}$)

Inclusive $\Lambda_b \to X_c e \bar{\nu}_e$ and exclusive $\Lambda_b \to \Lambda_c e \bar{\nu}_e$ decays provide an interesting testing ground for ideas used in $\bar{B}$ decay to determine $|V_{cb}|$.

(a) $\Lambda_b \to \Lambda_c e \bar{\nu}_e$

Hadronic matrix element of weak current written in terms of Lorentz Scalar Form Factors

$$\langle \Lambda_c(p', s') | \bar{c} \gamma^\nu b | \Lambda_b(p, s) \rangle$$

$$= \bar{u}(p', s') [f_1 \gamma^\nu + f_2 v^\nu + f_3 v'^\nu] u(p, s)$$

$$\langle \Lambda_c(p', s') | \bar{c} \gamma^\nu \gamma_5 b | \Lambda_b(p, s) \rangle$$

$$= \bar{u}(p', s') [g_1 \gamma^\nu + g_2 v^\nu + g_3 v'^\nu] \gamma_5 u(p, s)$$

where four-velocities defined by:

$$p = m_{\Lambda_b} v \quad , \quad p' = m_{\Lambda_c} v'$$

Prediction for form factors using heavy quark spin-flavor symmetry and $1/m_{b,c}$ expansion

Define: $w = v \cdot v'$. Including order $\frac{\Lambda_{QCD}}{m_{c,b}}$ terms
(H. Georgi et. al. Phys. Lett. B252 (1990) 456)

$$f_1 = \left(1 + \left[\frac{\bar{\Lambda}'}{2m_c} + \frac{\bar{\Lambda}'}{2m_b}\right]\right) S(w)$$

$$f_2 = -\frac{\bar{\Lambda}'}{2m_c}\left[\frac{2}{1+w}\right] S(w)$$

$$f_3 = -\frac{\bar{\Lambda}'}{2m_b}\left[\frac{2}{1+w}\right] S(w)$$

$$g_1 = \left(1 - \left[\frac{\bar{\Lambda}'}{2m_c} + \frac{\bar{\Lambda}'}{2m_b}\right]\left[\frac{1-w}{1+w}\right]\right) S(w)$$

$$g_2 = -\frac{\bar{\Lambda}'}{2m_c}\left[\frac{2}{1+w}\right] S(w)$$

$$g_3 = \frac{\bar{\Lambda}'}{2m_b}\left[\frac{2}{1+w}\right] S(w)$$

where $S(1) = 1$. No order $\Lambda_{QCD}/m_{c,b}$ corrections at zero recoil.

In Large N_c limit heavy baryon Λ_Q consists

of heavy quark Q bound to mean field of $N_c - 1$ light quarks. Leading order potential harmonic. (E. Jenkins et. al. Nucl. Phys. B396 (1993) 38)

$$\bar{\Lambda}' = m_{\Lambda_Q} - m_Q = M_N$$

$$S(1) = 1 - \frac{3}{64}\left(\frac{m_N}{m_c}\right)^2 + \ldots$$

Parameter $\bar{\Lambda}'$ related to analogous quantity for mesons. Mass formula:

$$m_{\Lambda_b} = m_b + \bar{\Lambda}' - \frac{\lambda_1'}{2m_b} + \dots \quad \leftarrow 5{,}624 \pm 9\,\mathrm{MeV}$$

$$m_{\Lambda_c} = m_c + \bar{\Lambda}' - \frac{\lambda_1'}{2m_c} + \dots \quad \leftarrow 2{,}285\,\mathrm{MeV}$$

$$\bar{m}_B = \frac{m_B + 3m_{B^*}}{4} = m_b + \bar{\Lambda} - \frac{\lambda_1}{2m_b} + \dots \quad \leftarrow 5{,}313\,\mathrm{MeV}$$

$$\bar{m}_D = \frac{m_D + 3m_{D^*}}{4} = m_c + \bar{\Lambda} - \frac{\lambda_1}{2m_c} + \dots \quad \leftarrow 1{,}975\,\mathrm{MeV}$$

These imply

$$\underbrace{(m_{\Lambda_b} - m_{\Lambda_c}) - (\bar{m}_B - \bar{m}_D)}_{\text{very small so } \lambda_1' \simeq \lambda_1} = \left(\frac{1}{2m_c} - \frac{1}{2m_b}\right)(\lambda_1' - \lambda_1) + \dots$$

$$\bar{\Lambda}' - \bar{\Lambda} = m_{\Lambda_b} - \bar{m}_B - \frac{(\lambda_1' - \lambda_1)}{2m_b} + \dots$$

$$\simeq (311 \pm 9)\,\mathrm{MeV} + \dots$$

In addition perturbative QCD corrections. $\bar{\Lambda}'$ not a physical quantity and perturbative QCD correction not "well behaved". Eliminate $\bar{\Lambda}'$ for a physical quantity then new perturbative series for form factors better behaved. Suggestion Upsilon expansion (A. Hoang et. al. Phys. Rev. Lett 82 (1999) 277.)

$$\bar{\Lambda}' \simeq m_{\Lambda_b} - \bar{m}_B - \left[\frac{m_\Upsilon}{2} - \bar{m}_B\right] = m_{\Lambda_b} - \frac{m_\Upsilon}{2} = 894\,\mathrm{MeV}$$

(b) $\Lambda_b \to X_c e \bar{\nu}_e$

Differential decay distributions available

using OPE and $1/m_b$ expansion. Eg.
(Bigi et. al. Phys. Rev. Lett 71 (1993) 496; Manohar and Wise, Phys. Rev. D49 (1994) 1310; B. Blok et. al. Phys. Rev. D49 (1994) 3356.)

$$\frac{\Gamma(\Lambda_b \to X_c e \bar{\nu}_e)}{\Gamma(\bar{B} \to X_c e \bar{\nu}_e)} = 1 + \frac{(\lambda_1' - \lambda_1)}{2m_b^2} - \frac{3\lambda_2}{2m_b^2} g\left(\frac{m_c^2}{m_b^2}\right)$$

measured $B^* - B$ mass splitting

where $\lambda_2 \simeq 0.12 \text{ GeV}^2$ and

$$g(\rho) = \left[\frac{3 - 8\rho + 24\rho^2 - 24\rho^3 + 5\rho^4 + 12\rho^2 \ln\rho}{1 - 8\rho + 8\rho^3 - \rho^4 - 12\rho^2 \ln\rho}\right],$$

$$g\left(\frac{m_c^2}{m_b^2}\right) \simeq 4.2,$$

Using near equality of λ_1 and λ_1'

$$\frac{\Gamma(\Lambda_b \to X_c e \bar{\nu}_e)}{\Gamma(\bar{B} \to X_c e \bar{\nu}_e)} \simeq 1 - 0.03.$$

Given unexpected large difference between Λ_b and B lifetimes it would be interesting to test expected equality of semileptonic Λ_b and B rates (not branching ratios!).

Experiment: $Br(\Lambda_b \to \Lambda_c X \ell^- \bar{\nu}_e) = (9.0^{+3.1}_{-3.8})\%$
$Br(\bar{B} \to X \ell^- \bar{\nu}_e) = (10.4 \pm 0.8)\%$
$\tau_{B^0} = (1.56 \pm 0.04) \times 10^{-12}\text{s}$, $\tau_{B^\pm} = (1.65 \pm 0.04) \times 10^{-12}\text{s}$
$\tau_{\Lambda_b} = (1.24 \pm 0.08) \times 10^{-12}\text{s}$

not a real measurement of this depends on production.

(II) $\bar{B} \to K^* \ell \bar{\ell}$

Short distance part involves $B \to K^*$ matrix element of weak current

$\bar{s}\gamma_\mu(1-\gamma_5)b$ ← assumes standard model (and a smaller contribution ← at large invariant lepton pair mass from $\bar{s}\sigma_{\mu\nu}(1+\gamma_5)b$)

Parametrize in terms of Lorentz Scalar form factors

$$\langle V(p',\varepsilon)|\bar{q}\gamma_\mu Q|H(p)\rangle = i g^{(H\to V)} \varepsilon_{\mu\nu\lambda\sigma}\varepsilon^{*\nu}(p+p')^\lambda(p-p')^\sigma$$

$$\langle V(p',\varepsilon)|\bar{q}\gamma_\mu\gamma_5 Q|H(p)\rangle = f^{(H\to V)}\varepsilon^*_\mu$$
$$+ a_+^{(H\to V)}(\varepsilon^*\cdot p)(p+p')_\mu + a_-^{(H\to V)}(\varepsilon^*\cdot p)(p-p')_\mu$$

Once $|V_{ub}|$ is known use $\bar{B}\to\rho e\bar{\nu}_e$ to determine form factors for $V=\rho$. SU(3) then gives that these are the same as form factors for $V=K^*$. So can predict short distance part of decay rate for $\bar{B}\to K^*\ell\bar{\ell}$.

But how large are SU(3) violations?

Experimental evidence they are small

For $D\to K^* \bar{e}\nu_e$ form factors measured
(E.M. Aitala et.al. E791 Coll. Phys. Rev. Lett. 80 (1998) 1393)

$$f^{(D\to K^*)}(y) = \frac{(1.9\pm 0.1)\,\mathrm{GeV}}{1+0.63(y-1)}$$

$$a_+^{(D\to K^*)}(y) = \frac{-(0.18\pm 0.03)\,\mathrm{GeV}^{-1}}{1+0.63(y-1)}$$

$$g^{(D\to K^*)}(y) = -\frac{(0.49\pm 0.04)\,\mathrm{GeV}^{-1}}{1+0.96(y-1)}$$

$$q^2 = (p'-p)^2 = m_H^2 + m_V^2 - 2m_H m_V y$$

Note for $D\to K^*\bar{e}\nu_e$, $1<y\lesssim 1.3$, while for $\bar{B}\to\rho e\bar{\nu}_e$, $1<y\lesssim 3.5$. Assume SU(3)

$$f^{(D\to K^*)}(y) = f^{(D\to\rho)}(y),\quad \text{etc}$$

then predict: (Z. Ligeti et.al, Phys. Lett. B240 (1998) 359)

$$\mathrm{Br}(D\to\rho^0\bar{l}\nu_e) = 0.044\,\mathrm{Br}(D\to\bar{K}^{*0}\bar{l}\nu_e)$$

$\frac{|V_{cd}/V_{cs}|^2}{2} \simeq 0.026$
plus about factor of two enhancement from greater phase space

Experiment
[0.047 ± 0.013]
(E.M. Aitala et.al, Phys. Rev. Lett. B397 (1997) 325)

Heavy quark symmetry relates SU(3) violations in $\bar{B}$ decay to those in D decay. So they expected to also be small for relating $\bar{B}\to\rho e\bar{\nu}_e$ to $\bar{B}\to K^* e\bar{\nu}_e$. turn argument around & have method to get $|V_{ub}|$