HOUSEKEEPING:
- SEE SCHEDULE ONLINE, LET ME KNOW IF YOU SWAP SLOTS
- THIS SEMESTER: JOINT MTGS ONCE A MONTH w/ hep-ex
  ↳ TO COMPLEMENT FRIDAY JOINT MEETINGS

TODAY: 30 MIN THEORY SUMMARY by flip
30 MIN EXP. SUMMARY by WALTER VIA SKYPE

→ this is a **DISCUSSION**, PLEASE ASK (& ANSWER) QUESTIONS

THE BASICS : def (PDG):

0: charge (em)

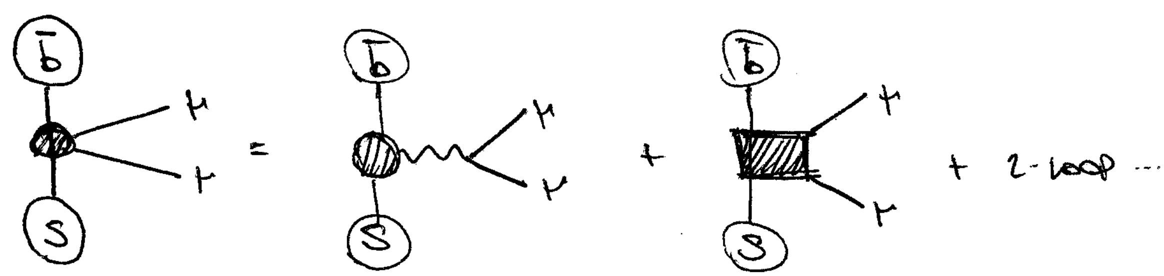
$$\boxed{\begin{array}{l} B^0_d \equiv \bar{b}d \\ B^0_s \equiv \bar{b}s \end{array}}$$

("B meson")
("B_s meson")

- PSEUDOSCALAR MESONS
- $m_b \gg m_d, m_s$ ⋯→ (HQET) ←⋯ but irrelevant for this decay

FLAVORFUL : CARRIES −1 bottom charge, +1 strange charge } but B^0 is charge neutral

DECAYS WILL ~~[crossed out]~~ INVOLVE FLAVOR-CHANGING NEUTRAL CURRENT
↳ but we know FCNCs NOT ALLOWED IN SM @ tree level



PENGUINS BOXES

A POINT ABOUT PENGUINS:

HOPE: NP IN LOOPS APPEARING AS A DEVIATION FROM SM.

WANT: FCNC. DRAW THE EXT FERMION LINE:

IF YOU WANT TO BE ARGUMENTATIVE, YOU'D ARGUE THAT THIS PENGUIN NEEDS 'LEGS' (as H does for $B_s \to \mu\mu$). BUT YOU CAN SEE THAT THE *PHYSICS* IS ALREADY IN THE γ EMISSION.

BIG PIC: the $\mu\mu$ is THERE TO MAKE UP FOR THE $\Delta p \sim m_b - m_s$.

A very RARE DECAY:

$B_{s,d} \to \mu\mu$ IS ONE OF THE REMAINING STRONGHOLDS OF THE SM. FLAVOR SECTOR.

will discuss shortly ⟶ IT IS BOTH THEORETICALLY INTERESTING (BSM)

also nice: CLEAN SIG, THY UNCERTAINTY ENCODED IN f_B & HAS YET TO BE DISCOVERED (… CDF ?)

the SM BRANCHING RATIO FOR $B_{s,d} \to \mu\mu$ IS SUPPRESSED BY

- LOOP $\sim (4\pi)^{-2}$
- GIM $\sim V_{ib}^* V_{js} \; \Delta m_{u_i}/M_W$
- MASS INS. $\sim m_\mu$ } B^0 IS A PSEUDOSCALAR
  - → LEPTONS MUST HAVE SAME HELICITY
  - → BUT IN SM, WEAK CURRENT ONLY COUPLES TO LEFT CHIRALITY

$$Br(B_s \to \mu\mu)_{SM} \approx 4 \times 10^{-9}$$ ← I DUNNO, MAYBE IT'S 3×10^{-9} … I DON'T REALLY CARE. DO YOU?

$$Br(B_d \to \mu\mu)_{SM} \approx 2 \times 10^{-10}$$

EFFECTIVE THEORY REMINDER

$$\mathcal{M} = \langle \mathcal{H}_{eff} \rangle = \sum_i c_i \langle \mathcal{O}_i \rangle$$

WILSON COEFFICIENTS ENCODES UV THEORY (dof w/ $m > M_W$) INCLUDES RUNNING FROM HI SCALE TO M_W

EFFECTIVE OPERATOR ENCODES IR DOF (OPERATOR ASSUMED TO BE @ LOW SCALE; IN GENERAL ONE MUST INCLUDE $\mathcal{O}$ MIXING EFFECTS INTO THE c_i)

<u>ASSUMPTION</u>: OPERATORS FACTORIZE INTO ~~[illegible]~~ QUARK & LEPTON PIECES. OTHERWISE BARYON / LEPTON # VIOLATION (such $\mathcal{O}$s should have negligible wilson coefficients)

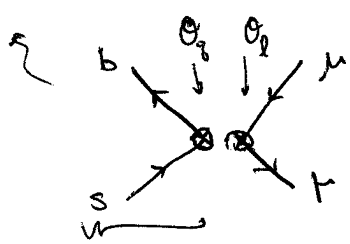
$$\mathcal{O}^V_{XY} = \bar{b}\gamma^\mu P_X s \otimes \bar{\mu}\gamma_\mu P_Y \mu \quad \text{vector}$$

$$\mathcal{O}^S_{XY} = \bar{b} P_X s \otimes \bar{\mu} P_Y \mu \quad \text{scalar}$$

$$\mathcal{O}^T_X = \bar{b}\sigma^{\mu\nu} P_X s \otimes \bar{\mu}\sigma^{\mu\nu} P_Y \mu \quad \text{tensor}$$

note: OTHER PEOPLE PARAMETERIZE IN TERMS OF V, A, S, P, T.

$$P_{L,R} = \tfrac{1}{2}(1 \mp \gamma^5)$$



HADRONIC SHIT

$$\langle \mu\bar{\mu} | H_{eff} | B_s^0(p)\rangle = \sum_i C_i \underbrace{\langle \mu\bar{\mu}|O_\ell^i|0\rangle}_{\text{EASY}} \underbrace{\langle 0|O_q^i|B_s^0(p)\rangle}_{\text{CONTAINS QCD EFFECTS!}}$$

THE $\langle 0|O_q|B\rangle$ MATRIX ELEMENT IS NON-PERTURBATIVE & IS PARAMETERIZED BY A <u>DECAY CONSTANT</u>

BY LORENTZ INVARIANCE

ALL HADRONIC THY UNCER

$$\langle 0|\bar{b}\gamma^\mu P_{L,R}\, s|B_s^0(p)\rangle = \mp \frac{i}{2} p^\mu f_{B_s}$$

$\mp$ CORRESPONDS TO $P_{L,R} = \frac{1}{2}(1\mp\gamma^5)$
[ONLY γ^5 CONTRIBUTES $\leftrightarrow$ PSEUDOSCALAR]

from this, contract w/ p_μ to obtain scalar matrix element

$$\langle 0|\bar{b}P_{L,R}\, s|B_s^0(p)\rangle = \pm\frac{i}{2}\frac{M_{B_s} f_{B_s}}{m_b+m_s}$$

can also note that the <u>scalar</u> makes no contribution

CHECK: $p_\mu \langle 0|\bar{b}\gamma^\mu P_{L,R}\, s|B\rangle = \langle 0|\bar{b}(\not{p}_b+\not{p}_s)P_{L,R}\, s|B\rangle$ $(1-P_L)$

$= -m_b\langle 0|\bar{b}P_{L,R}|B\rangle + m_s\langle 0|\bar{b}P_{R,L}\, s|B\rangle$

$= -(m_b+m_s)\langle 0|\bar{b}P_{L,R}\, s|B\rangle + m_s \underbrace{\cancel{\langle 0|\bar{b}s|B\rangle}}_{\text{PSEUDOSCALAR}} \to 0$

FINALLY: $\langle 0|\bar{b}\sigma^{\mu\nu}P_{L,R}\, s|B_s^0(p)\rangle = 0$

by LORENTZ: CAN'T FORM ANTISYM. TENSOR OUT OF ONLY p^μ.

IT IS NOT ESPECIALLY ILLUMINATING TO GO OVER PARTICULAR DIAGRAMS, BUT IT IS WORTH MENTIONING THAT THE PHOTON PENGUIN VANISHES BY THE WARD IDENTITY:

$$\langle \mu\bar{\mu}|\bar{\mu}\gamma^\mu P_{L,R}\,\mu|0\rangle\langle 0|\bar{b}\gamma_\mu P_{L,R}\, s|B\rangle \sim p_\mu\langle \mu\bar{\mu}|\bar{\mu}\gamma^\mu P_{L,R}\,\mu|0\rangle$$

$$= 0.$$

NOW YOU CAN JUST PLUG & CHUG

$$Br(B_s^0 \to \mu \bar{F}) = \frac{\tau_B}{16\pi} \frac{|\mathcal{M}|^2}{M_B} \sqrt{1 - \left(\frac{m_\mu + m_F}{M_B}\right)^2} \sqrt{1 - \left(\frac{m_\mu - m_F}{M_B}\right)^2}$$

CONTAINS WILSON COEFFICIENTS

IF YOU WANT TO GEN. TO $B \to \ell \bar{\ell}'$

PARAMETRICALLY :

RUNNING top mass

$$Br(B_s^0 \to \mu\mu) = 3.5 \times 10^{-9} \left[\frac{\tau_{B_s}}{1.6\,ps}\right] \left[\frac{f_{B_s}}{210\ \text{MeV}}\right]^2 \left[\frac{|V_{ts}|}{0.040}\right]^2 \left[\frac{\overline{m}_t(m_t)}{170\ \text{GeV}}\right]^{3/2}$$

BUCHALLA & BURAS NUCL PHYS B400 225 (1993)

that's all I want to say about the SM.

BSM : 2HDM (TWO HIGGS DOUBLET MODEL) ← eg. SUSY (MSSM)

GENERIC 2HDM ARE VERY CONSTRAINED BY FLAVOR SINCE THEY INDUCE FCNC @ TREE LEVEL

↳ IF H_u COUPLES TO BOTH u_R & d_R THEN CANNOT DIAGONALIZE

WHAT WE REALLY CARE ABOUT

SO: TYPICALLY HAVE TO IMPOSE SYMMETRIES TO KILL FCNC

TYPE II 2HDM : H_u COUPLES ONLY TO u_R
H_d " d_R

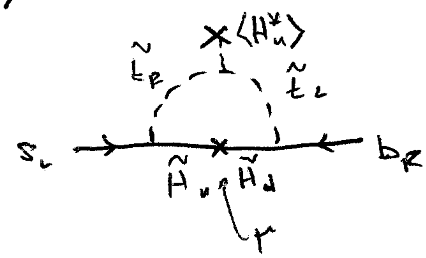
$$\mathcal{L} = y_u \bar{Q} H_u u_R + y_d \bar{Q} H_d d_R$$

Remark: 2HDM REQ BY MSSM, this is the natural set up.
↳ ANOMALY CANCELLATION & HOLOMORPHY of W

✓ eg $\mu H_u H_d$ ⟶ HAS TO BE THERE FOR EWSB

BUT : $\cancel{\text{SUSY}}$ TERMS BREAK THIS STRUCTURE (even HOLOMORPHIC PRT.)

eg :



COUPLES H_u to b_R !

[SEE KANE, KOLDA, LENNON '03]

SO, AFTER EWSB:

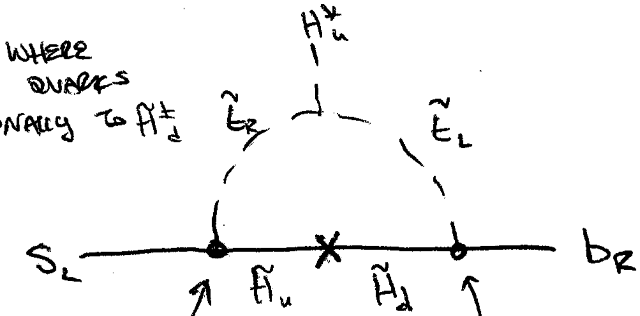
(IGNORE 1ST GENERATION FOR SIMPLICITY)

$$\mathcal{L}^{\text{1-loop}}_{\text{mass}} \supset \begin{pmatrix} \bar{s}_R & \bar{b}_R \end{pmatrix} \begin{pmatrix} m_s & 0 \\ y_b \varepsilon v_u & m_b \end{pmatrix} \begin{pmatrix} s_L \\ b_L \end{pmatrix}$$

INDUCED BY LOOP DIAGRAM

ε INCLUDES $y_t V_{ts}$ & KINEMATIC (LOOP) FACTORS

IN BASIS WHERE DOWN-TYPE QUARKS COUPLE DIAGONALLY TO $H_d^\pm$



LOOP LEVEL FLAVOR CHANGE + WRONG-HIGGS COUPLING. THE SIGNIFICANCE OF THE LATTER IS THIS

$y_t V_{ts} \subset \varepsilon$ OFF DIAG.

y_b COUPLING, DIAGONAL

[ALSO: $\tilde{g}$ DIAGRAMS w/ δ^{23} INS.]

YUHSIN IS AN EXPERT

DIAGONALIZE 1-LOOP MASS MATRIX

ROTATE BY AN ANGLE

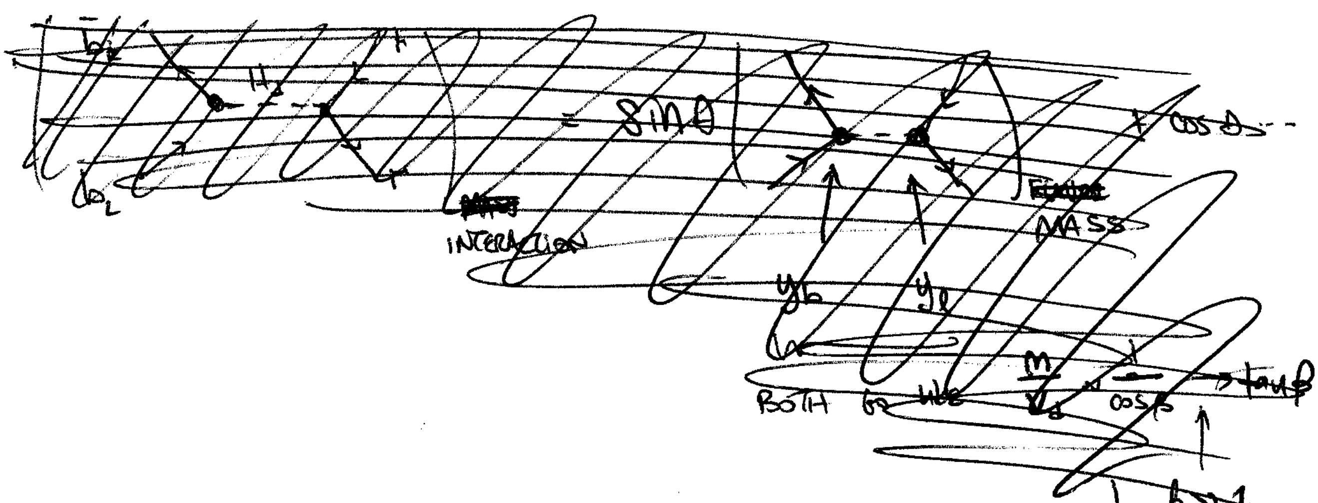
$$\boxed{\sin\theta} \simeq y_b \varepsilon v_u / m_b = \varepsilon \frac{v_u}{v_d} = \boxed{\varepsilon \tan\beta}$$

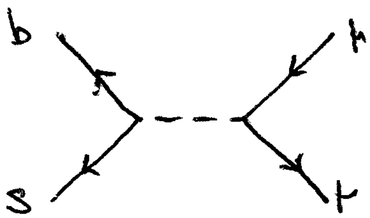
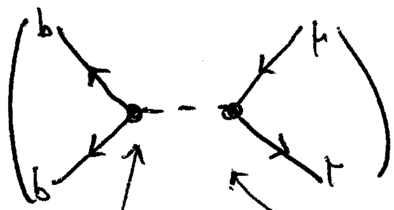
the flavor → mass rotation in our toy 2 flavor case

$m_b = y_b v_d$

PARAMETER of 2HDM CAN OVERCOME LOOP SUPPRESSION

tan β DEPENDENCE:



 $= \sin\theta \Big($  $\Big) + \cos\theta \, (-)$

$y_b \sim \frac{m_b}{v_d} \sim \frac{1}{\cos\beta}$

$y_\ell \sim \frac{m_\ell}{v_d} \sim \frac{1}{\cos\beta}$

$$\sim \sin\theta \, \frac{1}{\cos^2\beta} \xrightarrow{\tan\beta \gg 1} \boxed{\tan^3\beta}$$

LARGE ENHANCEMENT

Remark: large $\tan\beta$ favored by $SO(10)$ GUT

↳ want to make $y_t \approx y_b$ @ GUT SCALE

CONNECTIONS TO OTHER OBSERVABLES

& HINTS FOR MODEL BUILDING

- FLEISCHER, SERRA, TUNING (2010)

Main source of systematic uncertainty

WANT TO BEAT THIS DOWN.

$$\frac{Br(B_s \to \mu\mu)}{Br(B_q \to X)} = \frac{f_q}{f_s} \frac{\epsilon_X}{\epsilon_{\mu\mu}} \frac{N_{\mu\mu}}{N_X}$$

DECAY CONST — DET. EFF. — # EVENTS

LHCb EXTRACTS $B_s \to \mu\mu$ BY NORMALIZING w.r.t.

$$B_q \to X = \begin{array}{l} B^+_u \to (J/\psi) K^+ \\ B^0_d \to K^+\pi^- \\ B^0_d \to (J/\psi) K^{*0} \end{array}$$

PROPOSE: NEW WAY TO OBTAIN f_d/f_s @ LHCb:

PICK: $B_s \to X_1$ & $B_d \to X_2$

SUCH THAT

1. RATIO of BRANCHING RATIOS EASY TO MEASURE @ LHCb
   $\longrightarrow$ decay into 2 charged particles

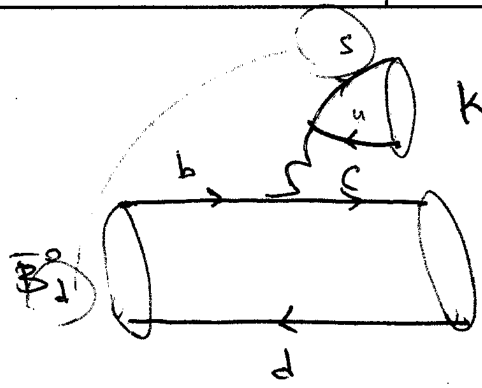
2. DECAYS ROBUST AGAINST NP CONTRIB.
   $\longrightarrow$ no penguins (WANT: free-level)

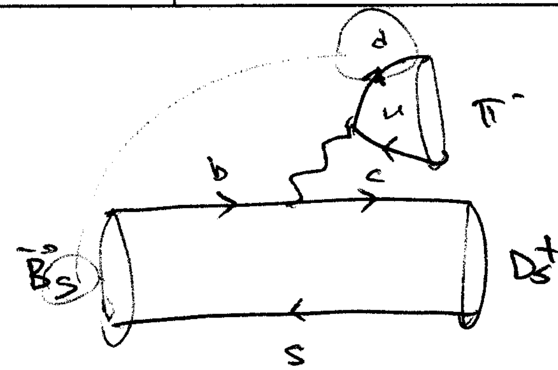
3. RATIO of Br's THEORETICALLY WELL UNDERSTOOD

$$\Rightarrow \bar{B}^0_s \to D^+_s \pi^-$$

$$\bar{B}^0_d \to D^+ K^-$$

{CHARMED MESON}





RELATED BY U-SPIN $\subset SU(3)_F$
NO EXCHANGE TOPOLOGIES $\Rightarrow$ $B_{\underline{d}}$ MUST GO TO $(u\underline{s}) = K^-$
$B_{\underline{s}}$ ——"—— $(u,\underline{d}) = \pi^-$

UP TO U-SPIN BREAKING EFFECTS

CLAIM: CAN INCREASE NP REACH BY A FACTOR OF 2.

- <u>RELATION TO $B_s - \bar{B}_s$ MIXING</u>

GOLOWICH, HEWETT, PAKVASA, PETROV (2009)
" , YEGHIYAN (2010)

ALSO: ALOK, SANKAR '07
BURAS hep-ph/0303060

<u>IDEA</u>: WRITE OUT eff $\mathcal{L}$ FOR q & ℓ SECTORS.
MUST ASSUME A CLASS OF NP MODEL
(eg INTERMEDIATE VECTOR, FCNC HIGGS, ...)
COMPARE B_s MIXING CONSTRAINT TO $B \to \mu\mu$

eg. Z' w/ FCNC

$$\Delta M_{B_s}^{(Z')} \sim (\text{factors}) \frac{g^2_{Z' sb}}{M^2_{Z'}} \Rightarrow \frac{g^2_{Z' sb}}{M^2_{Z'}} < 2.5 \times 10^{-11} \frac{1}{\text{GeV}^2}$$

$$Br^{(Z')}(B_s \to \mu\mu) \sim (\text{factors}) \frac{g^2_{Z' sb}}{M^2_{Z'}} \Rightarrow Br(B_s \to \mu\mu) < .25 \times 10^{-9}$$

$$\left(\frac{\text{TeV}}{M_{Z'}}\right)^2$$

REMARKS: THIS STRATEGY IS MOTIVATED BY A STUDY BY THE AUTHORS CONNECTING D MIXING W/ $D \to \mu\mu$.

D SECTOR: IF ALL / MOST OF MIXING FROM NP, CAN OFTEN PREDICT $D \to \mu\mu$ BECAUSE AMPLITUDES CAN HAVE SAME PARAMETERS

SM MIXING HAS LARGE THY UNCERTAINTIES & MANY NP MODELS CAN PRODUCE THE OBS. MIXING.

B SECTOR: VERY DIFFERENT!
SM MIXING AGREES W/ OBS VALUE

CAN ALSO HAVE INTERFERENCE WHICH MAKES $B_r < B_r^{SM}$

$$\frac{\Delta M_{B_s}^{NP}}{\Delta M_{B_s}^{SM}} \leq 20\%$$

↳ STRONG CONSTRAINT IN SOME NP MODELS!

OTHER OBSERVABLES: $\varepsilon_K - S_{\psi K_S}$ TENSION

SM 2β

& $|V_{ub}|$ PROBLEM

$Br(B^+ \to \tau^+ \nu)$

$S_{K\phi}$, $K^+ \to \pi^+ \nu\bar{\nu}$

$K_L \to \pi^0 \nu\nu$

↳ ALL CORRELATED. SOME HINTS @ DISAGREEMENT W/ EACH OTHER