Why are we here? I was here in '93/2001 (528g) enjoyed both.

Friendships/people still in the field.

Atmosphere cool, Tom, mountains learn something / start by new

Ask questions - get paid!

What I'd like to explain in these lectures:

- Flavor physics (FCNC + CPV) sensitive probes of short dist. physics (SM + BSM)
- Has taught us a lot in the past
- But there is plenty of room for NP [or more]
- Interesting to explore and will be done order (5) of magnitude better than today

1) Experimental precision

- LHCb, NA62, more

2) Theoretical uncertainties

- Concentrate on electrons only are they clean

3) Expected deviations

- Flavor specific TeV-scale NP (long lived)
- Masses range from vanishing - detectable
- Viable TeV-scale NP nothing is pretty hard not easy (grape seed)

4) What can we learn from measurements? Complementary

Outline:

1) Flavor in SM, testing SM - mixing and CPV pretty close
   - Examples of clean info on DD phys.; NP in mixing maybe

2) What's left from 2nd: strong int., Heavy quark sym. bits
   - OP & inclusive decays. [same hadronic phys IS tractable!]

3) Flavor at the TeV scale: operators -> lepton flavor
   - Top physics, MFV, SUG and flavor bits
What is particle physics?

- What are the elementary d.o.f.?
- How do they interact? Gravity?
- What is the vacuum?
- Symmetry breaking

SM of particle physics + SM of cosmology; still lots we do not understand

NP must exist: DM

Baryon asymmetry

N(baryon) / N(photon) \( \propto 10^{-9} \) \( \Rightarrow \) at \( t \lesssim 10^6 \) after Big Bang

\( \frac{N_u-N_d}{N_u+N_d} \sim 10^{-9} \) \( (T > 160 \text{ eV}) \)

in thermal equilibrium

- B violating interactions
- C & CP violation
- Deviation from thermal eq.

SM contains these, but too small CPV, dev. They (\( 10^{-20} \))

What is the microscopic origin of CPV?

How precisely can we test it?

(What sectors of the SM/BSM?)

There must be CPV beyond SM! (caveats)

Maybe flavor diagonal (EDMs), maybe leptogenesis...

Almost all extensions of the SM do have new sources of CPV
What is flavor physics? Breaking $Q(d,e,l,\mu,\tau)^R$

How the 3 generations differ?

→ very different answers possible in SM/BSM

interesting to explore.

In SM - it all comes from Higgs couplings
we do not even know if there is a Higgs, but there is a condensate with appropriate quantum no's.

$$L_{\text{kin}} = \frac{1}{2} \sum_{\text{groups}} (\bar{f} f)^2 + \sum_{Q,i} \bar{Q}_i \gamma^\mu Q_i$$

Parameters: 7, 9, 95

always CP conserving... neglecting $f\bar{f}$ - also not understood

$$L_{\text{Higgs}} = (\partial \phi)^2 + \mu^2 \phi^+ \phi - \lambda (\phi^\dagger \phi)^2$$

Parameters: $\mu, \lambda, \frac{\mu^2}{\lambda}$

CP Cons. in SM, but CPV possible w/ extended sector

$$L_{\text{ Yuk.}} = -\frac{1}{2} Y_i^\dagger A_{ij} Q_i \phi^+ + \frac{1}{2} Y_i^\dagger A_{ii} Q_i \phi^+ \phi - (\text{Higgs})$$

Diagonalize:

$$Y_{ij}^\dagger = v_{ij}^L, M_{ij}^R$$

$U_{ij}$

which are in the same $SU(2)_L$ doublet

$$\begin{pmatrix} U_{ij}^+ \chi_i \end{pmatrix} = \begin{pmatrix} v_{ij}^L \chi_i \end{pmatrix}$$

CC int. change phases

$\text{AdS}_6$ and general $U(6)$ symm.

CPV related to unremovable phases

$$X_{ij} \phi^+ \phi_{ij} + X_{ij} \phi_{ij}$$

If there is a basis that $X_{ij} = X_{ji}$, then

$\phi$ is conserved

(\text{does not change the coefficients})
SM flavor structure

Neutral currents \( \gamma \rightarrow \mu^+\mu^- \) no free level \( W^+\gamma \) lead to GIM! (need to add c)

FCNCs at loop level \( \tilde{\mu} \rightarrow \tilde{e} \tilde{e} \) could be used to predict \( \mu \) before discovery (Gounaris, Lee)

\[ \alpha \left( \frac{\mu_i}{\mu_2} \right) = \text{susy} + \text{V} \text{V}^* + \text{V} \text{V}^* \text{V} \text{V}^* \]

FCNCs are suppressed, directly probe differences of generations!

Flavor was instrumental figuring out \( L \), may also crucial for \( R \)

1st

- Counting flavor params (SM) = 6 quarks

\( (2 \times 8 \text{ couplings}) - (26 \text{ broken sym}) = 10 \text{ phys. params} \)

\( X_k, \chi \)

- \( 6 \text{ mass} + 3 \text{ mix} + 1 \text{ phase} \)

\( \gamma \) to p. 20

- Neutrinos: \( \Delta y = -\gamma_i \bar{\nu}_i \phi \bar{\nu}_i \), \( \Delta y = \frac{\nu_i \nu_i}{M} \)

\( (18 + 12 \text{ couplings}) - (18 \text{ broken sym}) = 12 \text{ phys. params} \)

\( \gamma \) completely, 6 mass \( + 3 \text{ mix} + 1 \text{ phase} \)

2nd

- CKM matrix

\[ \left( \begin{array}{ccc} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{array} \right) \]

\[ \left( \begin{array}{c} 1 \\ -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{array} \right) \]

\[ \left( \begin{array}{c} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \\ 0 \end{array} \right) \]

\[ \left( \begin{array}{c} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \\ 0 \end{array} \right) \]

Convenient language to compare measurements
Why should we care...?

- The low energy / EFT viewpoint
  At K/D/B scale anything that changes flavor is a local interaction (doesn't matter if SM or NP)
  In SM few parameters
  determine lots of processes
  - strong suppression
  - correlations between dozens of OPE's that NP may not respect
  - dozens of operators, some absent in SM (LOR)
  But also "undesired" things, eq. \( \theta \neq 0 \)

- The New Physics flavor problem
  TeV scale (hierarchy problem) \( \ll \) flavor & CP
  Cannot write down OPE's w/ \( O(1) \) coeffs & \( \Lambda \)-TeV scale
  \[ \left( \frac{\delta d}{\Lambda} \right)^2 \Rightarrow A \sim 10 \text{ TeV} \]
  \[ \left( \frac{\delta d}{\Lambda} \right)^2 \Rightarrow A \sim 10^2 \text{ TeV} \]
  \[ \left( \frac{\delta s}{\Lambda} \right)^2 \Rightarrow A \sim 10^2 \text{ TeV} \]
  \[ \Delta M_W \quad \text{In radon, CPV, etc} \quad \Delta M_{\nu} \quad \Delta M_{\nu s} \]
  TeV-scale NP models typically have new sources of flavor & CP violation.
K-K mixing gives $5 \times 10^{-15}$ eV vs $3.4 \times 10^{-17}$ eV

$\Delta m^2 = \frac{g_4^2 |\langle \bar{V}qV \rangle|^2}{16 \pi^2 m_B^2}$

Strong suppressions:
loop, CKM, GIM $<\langle \bar{q}l \gamma_5 q \rangle^K |K> = \frac{2}{3} m_B^2 B_K$

NP (assumed tree level)

$\frac{\Delta m^{(x)}}{\Delta m^{(exp)}} \approx \frac{2 m_B}{m^2} \Delta m_K \rightarrow m_K > 3 \times 10^{-3}$ eV

Less SM suppressions in B mixing => weaker bound

Bound is relevant for LHC even if $g < 10^{-2}$ (loop)

B-se - even less SM suppr => in many models one $E_6$ bound is the strongest since so are SM suppressions

K bound built into NP models since 70's - otherwise dead on arrival.

How else can we get clean info?

E6 fit with O(1) KM phase - only CPV 1964-1999

E6 notoriously hard to calculate
cannot prove, nor rule out that it is 50% NP!

$\Delta m^{(x)} = \frac{2 m_B}{m^2} \Delta m_K$

\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \text{ and } K^0 \rightarrow \pi^0 \nu \bar{\nu} \]

3 events: $Br(K \rightarrow \pi^+ \nu \bar{\nu}) = (1.7 \pm 1) \times 10^{-7}$

SM uncertainty $= 5\%$ (3\%?) for $K^+$, less for $K^0$

CERN NA62 aim: $100 K^+$ events

$\Delta$-PARCLE (KOTO) $K^0$
maybe Fermilab later? (project X2)

DB mixing: only observed in 2007, interesting to constrain NP, maybe 3rd lecture
Why B-Physics?

Theory: top loops not GIM & CKM exp. Exp: N(4S) clean source, large & clean CPV possible. Long B lifetime (ΔM/F → Ω(1)/Δt_π^0)

Some hadronic physics is understandable (m_c >> m_q)

Model independent

Formalism:

|B_{K,L}^0⟩ = P |B^0⟩ + P Q |B^0⟩ (B_{K,L}^0) = |B^0⟩ \pm (i M_{cL} + i M_{cL}) + |B^0⟩

\frac{1}{2} (|B^0⟩ + (B^0⟩) = (1 - \frac{1}{2} \Gamma) (|B^0⟩ + (B^0⟩))

CPT: M_{12} = M_{21}, P_M = P_M

M_{12} dominated by intermediate top quarks \rightarrow short dist. decays

ΔM = M_{M1} - M_{M2} (left)

ΔΓ = P_{M1} - M_{M2} (so that \approx M_{B^0})

Final states in B^0 \& B^0 decay

Solution simplifies in \( |P_{MK}| < |M_{12}| \) limit (\( |M_{K}| \approx |M_{12}| \))

ΔM = 2M_{12} \pm ... \quad \frac{q}{r} = \frac{M_{12}^2}{M_{12}^2} (1 - \frac{1}{2} \Gamma \frac{P_{M1} - P_{M2}}{P_{M1}})

= -2M_{12} \cos β + \text{need later, leading } |V_{s}| - 1

SM: B_d \left( \frac{q}{r} \right) = \frac{V_{ud}^* V_{td}}{V_{cd}^* V_{td}} = -2Z + \text{(conv.)}

B_s \left( \frac{q}{r} \right) = \frac{V_{us}^* V_{ts}}{V_{cd}^* V_{td}} = -2Z + \text{(conv.)}

ΔΓ: B_d \left( \frac{q}{r} \right) = \frac{B(0^+)}{B(0^+)} \frac{8π}{9} \frac{1}{2}|V_{td}^2| \left( \frac{M_s}{M_d} \right)^2 \text{ OPE }\text{ form. inc. in top decay}

Hadr. uncertainties in ΔM and esp. A_1/P_1 but not in arg (q/r)

1/f of uncertainty

10/f of uncertainty
Direct CP violation

- can occur in $M^+$, $M^0$ decay, also kaon decays
- simplest in some sense
  \[ \sum u \rightarrow \text{weak phases} \]
  \[ \sum d \rightarrow \text{strong phases} \]
  \[ A^+ = \langle 81 | H | B \rangle = \sum A_u e^\pm \]
  \[ \bar{A}^- = \langle 8 | H | B \rangle = \sum A_u e^{\pm} \]

due to CP invariance of QED. IF $A^+ \neq \bar{A}^-$ CPV

Unambiguously established by E13 at 1999

\[ E_{13} = \frac{1}{3} \left( \frac{\langle \pi^0 \pi^- \pi^+ \rangle}{\langle \pi^+ \pi^- \pi^- \rangle} - \frac{\langle \pi^0 \pi^- \pi^- \rangle}{\langle \pi^0 \pi^+ \pi^- \rangle} \right) \approx 10^{-5} \]

\[ \Delta \Gamma(B \rightarrow K^+\pi^-) - \Delta \Gamma(B \rightarrow K^-\pi^+) \]

\[ A_{K^+\pi^-} = \frac{\Delta \Gamma(B \rightarrow K^+\pi^-)}{\Delta \Gamma(B \rightarrow K^-\pi^+)} \approx 0.1 \] (Huge effect!)

Needs at least two contributions with different strong & weak phases.

Cannot - in general - calculate hadronic weak decays

Except special cases. Claims/problems in $m_K >> m_{\pi}$.

"K+T puzzle" \[ A_{K^+\pi^-} - A_{K^+\pi^+} = 0.15 \pm 0.03 \] (55)

Clean cases: amplitudes with one weak phase dominate

\[ \rightarrow b \rightarrow \ell^- X \text{ but not } b \rightarrow \ell^+ X \text{ (ratio of } A/\bar{A} = 1:0) \]

\[ \rightarrow \text{CP eigenstates, in some cases } |\frac{A}{\bar{A}}| = 1 + \text{small} \]
CPV in mixing - DØ dimuon asymmetry

\[ \frac{P_{\mu\mu}}{P_{\pi\pi}} \]

If CP were conserved \[ |\text{BR}(B_\mu)\rangle \sim |B_\pi\rangle \] and \( \arg M_{\mu} = \arg M_{\pi} \). Please cancel then \( \frac{P_\mu}{P_\pi} = 1 \) and \( \arg M_{\mu} = \arg M_{\pi} \).

CPV is \( \frac{2}{P} \) e.g. \( \langle B_\mu | B_\pi \rangle \rangle = \frac{|P|^2 - |Q|^2 + 0}{2} \)

\[ \frac{P_{\mu\mu} - P_{\pi\pi}}{P_{\mu\mu} + P_{\pi\pi}} = \frac{2 - 2|P|^2}{2 + 2|P|^2} = \frac{1 - |P|^2}{1 + |P|^2} = \text{Im} \frac{M_{\mu}}{M_{\pi}} \rightarrow \text{time-dep. interference in } B \rightarrow \text{reac.}

SM: \[ \left| \frac{\Gamma_{\nu\pi}}{\Gamma_{\nu\pi}} \right| = O(\frac{m_{\nu}}{m_{\pi}}) \] and \[ \arg \left( \frac{\Gamma_{\nu\pi}}{\Gamma_{\nu\pi}} \right) = O(\frac{m_{\nu}}{m_{\pi}}) \]

Valid beyond SM if we say that \( |\text{BR}| \) near SM tested by CDF but phase of \( \frac{\Gamma_{\nu\pi}}{\Gamma_{\nu\pi}} \) can still change from NA.

1st suppression generic, second available still.

\[ \otimes \]

DØ: \[ \Gamma(B \rightarrow \mu^+ \mu^-) - \Gamma(B \rightarrow \pi^+ \pi^-) = \Gamma_{RS}^+ \Gamma_{WS} - \Gamma_{RS}^+ \Gamma_{WS} + \Gamma_{RS}^- \Gamma_{WS}^+ - \Gamma_{WS}^- \Gamma_{RS}^+ = \]

\[ \Gamma_{RS}^+ = \sum \left[ \lambda(B \rightarrow B) \Gamma_{RS} \right] + \sum \left[ \Gamma_{RS} (B \rightarrow B) \right] \]

\[ \Gamma_{RS}^- = \sum \left[ \lambda(B \rightarrow B) \Gamma_{RS} \right] + \sum \left[ \Gamma_{RS} (B \rightarrow B) \right] \]

assuming no direct CPV \( \Gamma_{\nu\pi} = \Gamma_{\nu\pi} \) and using the fact also \( \sum \lambda(B \rightarrow B) = \sum \lambda(B \rightarrow B) \)

\[ \Rightarrow \Gamma_{RS}^+ = \Gamma_{RS}^- \] and it drops out.

\[ \text{Observe the rest as a combination of } A_{\rho} \text{ & } A_{\rho} \]

Moral: SM very small, uncertainty substantial, but no hope could clearly see new physics!

\[ \frac{\Gamma_{\mu\mu}}{\Gamma_{\pi\pi}} \]

if \( m_{\mu} = m_{\pi} \), and \( \arg M_{\mu} = \arg M_{\pi} \).
CPV in interference of decay w/o uniting

\[ \Gamma(B^0 \rightarrow f) - \Gamma(B^0 \rightarrow \bar{f}) = \frac{2}{1 + \frac{1}{2} \lambda^2} \sin(\text{unit}) \]

\[ A_{\text{CPV}} = \frac{\Gamma(B^0 \rightarrow f) - \Gamma(B^0 \rightarrow \bar{f})}{1 + \frac{1}{2} \lambda^2} \]

Especially simple if \( |\lambda| = 1 \)

\[ \frac{|A|}{|\bar{A}|} = 1 \] so need \( |\lambda| = 1 \)

\[ \Rightarrow \sin(\text{unit}) = 0 \]

Automatic if one weak phase dominates

Hadronic physics drops out!!

\[ A_{\text{CPV}} = \frac{2}{1 + \frac{1}{2} \lambda^2} \sin(\text{phasediff in above f}) \sin(\text{unit}) \]

\[ \frac{A_{\text{CPV}}}{|\bar{A}| / |A|} = \frac{2}{1 + \frac{1}{2} \lambda^2} \]

The celebrated \( B \rightarrow 4 \nu s \):

\[ \frac{A_{\text{CPV}}}{|\bar{A}| / |A|} = \text{most estimates give few } \times 10^{-3} \]

\( \sin(2\beta) = 0.678 \pm 0.20 \) a 3\% uncertainty!

→ Consistent w/ earlier constraints from Eu, W, E89

→ CPV is \( O(1) \) just suppressed in K decay by small flavor viol.

→ Many models w/ approximate CP, etc., etc.

\[ \lambda = \frac{(2)(\bar{A})}{F(B^0 A \bar{A})} \rightarrow \text{CP is } O(1) \quad \text{just suppressed in K decay by small flavor viol.} \]

\[ \lambda = \frac{(2)(\bar{A})}{F(B^0 A \bar{A})} \]
\(B_5 \rightarrow 4\phi - \text{u25 limit from Tevatron}

"Gold-plated" LHCB measurement

\(b \rightarrow c\bar{c}5\) in \(B_5\) decay, theory same as for \(B \rightarrow K\bar{K}\)

except: \(c\bar{c}\) final state - combination of \(L = 0, 1, 2\)

\(L = 0, 2\) are CP\(^+\); \(L = 1\) is CP\(^-\) - Gates need to be measured

Need (time dependent) angular analysis to eliminate dependence on amplitude ratio (uncalculable)

\(\sin 2B_5 = -\sin 2\phi_s = 0.036\)

- current limits much larger.
- Would mean that NP/SM likely different in \(B_5\) vs \(B\) mix

\(Penguin\ modes : B_5 \rightarrow \phi K_5\) \((B_5 \rightarrow \phi\phi)\)

\[\overline{\Phi_{K_5}} = \left(\overline{\Phi_{K_5}} | H_B \right) = \sum_{q=e,\mu,\tau} \overline{V_{cq}} V_{ct}^* P_q\]

\[\overline{A_{\phi K_5}} = V_{cb} V_{ct}^* (P_+ - P_-) + V_{ub} V_{us} (P_u - P_s)\]

\[\frac{A}{A} = 1 + x^2 (\text{no additional suppression})\]

- without additional inputs on amplitudes

At present \(S_{\Phi K_5} = 0.57 \pm 0.17\) - Belle and Babar quite inconsistent

\(S_{\phi\phi} = 0.59 \pm 0.07\) - large enhancement of rate, hence small error

interesting to reduce the uncertainties by many-fold

before hadronic physics becomes problematic

Comparing \(S_{\Phi K_5}\) w/ \(S_{\phi\phi}\) tests the penguin amplitude in the latter and bounds NP in it
L & Χ more complicated - need many measurements to eliminate dependence on hadronic physics

X - isospin analysis. ZT in I = 0 or 2 state
B's: I = 1/2, Χ is 1/2 and 3/2 but penguin is only 1/2
want to isolate CP asym in tree decay which is 1/2 + 3/2
so CPV to I = 2 final state would be free of penguin

\( \text{TREE LEVEL} \)

\( \Theta \) - \( B^+ \rightarrow D^0 K^+ \rightarrow K^+ \eta \)

using several modes, can extract hadronic + phase. 
ultimate tree uncertainty is very small - always small & limited.

\( W \) - \( B_s \rightarrow D^\pm K^\pm \) another special mode for LHCb
(may not be the best \( S \), but clean & different)

\( B_s \rightarrow D_s^- K^- : A_1 \)
\( B_s \rightarrow D_s^+ K^+ : A_2 \)

\( \frac{A_{D_s K^-}}{A_{D_s K^+}} = \frac{A_1 (V_{us} V_{cs}^*)}{A_2 (V_{us} V_{cs}^*)} \)
\( \frac{A_{D_s K^+}}{A_{D_s K^-}} = \frac{A_2 V_{ub} V_{cs}^*}{A_1 V_{ub} V_{cs}^*} \)

Clean info by measuring hadronic amplitudes including their strong phases (effectively...).
New physics in $B\bar{B}$ mixing?

Large class of models: $3\times3$ CKM mix unitary
- tree-level decays SM dominated

Rec., NP in mixing: $M_{12} = M^S_{12} (1 + \text{i} h_d e^{2i\Delta\phi}) = \text{Re} \cdot M^S_{12} e^{\text{i} \Delta\phi}$

$\rightarrow$ tree-level constraints unaffected: $|\text{Re}/\text{Im}|$, $\chi_1^2 (\chi_{1-3})$

$\rightarrow$ $B\bar{B}$ mixing dependent observables

$\Delta M^B = \chi (\Delta M^S)$

$S_{4\text{mes}} = \sin (2\beta + 2\theta)$

$S_{4\text{mix}} = \sin (2\beta - 2\delta)$

$S_{5\text{q}} = \sin (2\beta - 2\delta)$

Because of tension (20%)
- between (Re) and $\Delta M^B$
- best fit point is away from $h_d = 0$ (SM)

$\rightarrow$ 20% NP contribution still allowed
- for $2\theta_d = 0$ (mod 2$\pi$) even Barger (MFV later...)
- Same is true in $B \rightarrow X_s \gamma$ and most FCNC processes
- Before B factories NP in $B\bar{B}$ mixing could still be an order of magnitude off the SM.

$\chi^2$: $h_d = 0$

- Weak phase is dominant source of CPV in FC processes
- CPV in SM is $\mathcal{O}(1)$ just screened in $K$ decays
- Measurements probe $\gg 1$ TeV, only statistics limited
- NP in most FCNCs can be $\mathcal{O}(0.2 \times 5\delta)$
- Emerging MFV paradigm - NP must leave
- similar suppressions as the SM flavor structure

Did not know most of this 10 years ago!
Future: lots of clean measurements get better
Of course, for theorists, the money is in making less clean ones better...
or devise new observables (below Bells in economy)

LHCb:
- $B_s \rightarrow 4\phi$ (mixing phase)
- $\phi\phi$ (penguins)
- $B_s \rightarrow \rho^+\rho^-$
- $B \rightarrow K^*\ell^+\ell^-$
- $8$ from $B\rightarrow D\bar{K}, B_s\rightarrow D_sK$
- $A_{52}$

Super-B
- $4Ks$ (reference)
- $B \rightarrow \phi\ell_3 s, 4\ell_3 s$

CPV: $D-D$ mixing
- $V_{cb}, V_{ub},$ inclusive
- $8$ from many modes
- $A_{52}, S_{12}$
- $b \rightarrow s\nu\nu, B\rightarrow \tau\nu$ etc
- $\tan\beta$, etc

Complementary to one another & won't hit "phase wall"

2HDM:
- $H_u, H_d$ to $\tan\beta$
- $t, \tau$ to $\tau$
Dealing with strong interactions

\[ \Delta S(\mu) = \frac{\Delta S(A)}{\mu^2 \ln \Lambda^2}, \quad B_0 = 11 - \frac{2}{3} \mu \]

Solutions: Symmetries in some limits (Higgs, chiral)

OPE - some processes determined by short distance

Lattice QCD (like the bullet - limited cases, too)

1. \( B \to 4k_s \) and \( \sin \theta_B \) (yesterday)

\[ \langle 4k_s | 4k_s | B \rangle = -\langle 4k_s | 4k_s | B^0 \rangle (1 + \mathcal{O}(\Lambda R^2)) \]

2. \( V_{ub} \) from \( B \to \Delta \ell v \)

\[ P = |V_{ub}|^2 \text{ (known)} (1 + \mathcal{O}(|V_{ub}|^2)) \]

3. \( B \to X_s \ell \bar{\nu} \): separate physics at \( m_\pi, \mu \gg \mu \)

\( \mu^2 \text{ loop matching} / \mu^2 \text{ loop QCD} \); \( \Delta \ell \ell \) terms etc.

\[ P(B \to X_s \ell \bar{\nu}) = \text{(known)} (1 + \mathcal{O}(|V_{ub}|^2)) \]

Maybe the most complex calculation done

\( \mathcal{O} \) Not enough to know expansion parameters, need experimental guidance how well it works!

from 100MeV to 700GeV \( \mu \approx 26 GeV \) all O(1)

Strong int. model indep \( \equiv \) uncertainties suppressed by small parameters
Heavy quark symmetry

$m_b \gg m_c \gg m_u$: quark is like a static color source with fixed $O(1)$ that's not changed by interactions with "broad nuclei" ($q\bar{q}$, $q\bar{q}$, $q\bar{q}$)

→ spin interactions subleading
→ changing $m_b$ subleading ($\Delta m_b$) → $SU(2)_L$ spin-flavor symmetry

Similar to atomic physics ($m_e \ll m_u$)

- flavor sym: isotopes similar chemistry ($\gamma$ independent)
- spin sym: hyperfine levels near degenerate ($\Delta \approx 0$) subleading

Predictions - spectroscopy (simplest in a sense)

\[ f = S \bar{q} + S \bar{c} \]

Total angular mom. of

\[ S_i \perp 4L \] → [SU(4) of h.q.]

\[ [S_i \perp 4L] = 0 \]

\[ S_{q \bar{c}} = 0 \]

→ can classify states according to spin of l.d.o.f.

\[ f_+ = S_q \pm \frac{1}{2} \text{ doublet} \text{ } \& \text{ } HQS \]

\[ S_q = \frac{3}{2} \]

\[ S_{\bar{c}} = \frac{1}{2} \]

\[ \Delta \approx 0 \]

\[ B^0 \text{ (2.46)} \]

\[ D^0 \text{ (2.42)} \]

\[ \Theta(1) \text{ splitting} \]

\[ \delta(1.8) \text{ (600)} \]

\[ B^0 \text{ (5.32)} \]

\[ B^+ \text{ (5.88)} \]

\[ \frac{m_{B^+} - m_B}{m_{B^+} - m_B} = \frac{m_{\pi^+}}{m_{\pi^0}} \approx \sqrt{2} \]

→ so $m_{\pi^+} - m_{\pi^0}$ independent of $m_{B^+} - m_B$

A puzzle: $m_{B_s}^2 - m_B^2 = 0.496 \text{ GeV}^2 \quad m_{\tau}^2 - m_{\mu}^2 = 0.55$

$m_{B_s}^2 - m_{\pi^0}^2 = 0.50 \text{ GeV}^2 \quad m_{\pi}^2 - m_{\mu}^2 = 0.57$

$m_{B_s}^2 - m_{\pi^0}^2 = 0.54 \text{ GeV}^2$

$m_{B_s}^2 - m_{\pi^0}^2 = 0.58 \text{ GeV}^2$

something went wrong on mass HRS

Not only important if prediction works, but why? Also how it breaks down!!!
HQET

heavy quarks almost on-shell in heavy-light meson
\[ P = m_0^2 + k^2 \quad (k = 0) \Rightarrow m_0^2 = 1 \]
\[ m_0^2 = m_0^2 + 2m_0v \cdot k + k^2 \]

Propagator:
\[ \frac{i}{P_0 - m_0^2 + i m_0 v \cdot k + k^2} = \frac{-i}{2v \cdot k} \]

in heavy quark rest frame \( \frac{1}{2} (1 + \gamma_0) = \frac{1}{2} (1 + \gamma_0^0) \) projects on particle (rather than anti-particle) components

Define:
\[ Q_a(x) = \sum \max \left( \frac{1}{2} \frac{Q(x)}{2} \right) \]

Project out large momentum component

\[ \tilde{Q}_a(x) = \sum \max \left( \frac{1}{2} \frac{Q(x)}{2} \right) \]

\[ \sum \max \left( \frac{1}{2} \frac{Q(x)}{2} \right) \]

Semi-leptonic \( B \to D_{u,d} \) decay

ground state \( B \bar{q} \) mesons related by HQS

can write as a "superfield" \( \chi(x) = \frac{1 + \gamma_0}{2} \left[ \Phi(x) + i \chi_0(x) \right] \)

... satisfies \( P^+ L^+ = M \) & right transform under Lorentz+HQS

HQET:
\[ \langle M_{\mu} \rangle = \Phi(x) \rightarrow \langle M_{\mu} \rangle = \Phi(x) \]

\[ F(x) = \Phi(x) \chi_0(x) \quad \Phi(x) \]

\[ \Phi(x) = \Phi^0(x) \Phi(x) \quad \]

\[ F(x,y) = \Phi^0(x) \Phi(y) \quad \]

\[ \Phi(x) = \Phi^0(x) \Phi(x) \quad \]

Only possible scale = "recoil" Isgur-Wise function
\[ \Phi(x) = \Phi^0(x) \Phi(x) \quad \]

In full QCD, there are 6 form factors all \( \Phi(x) \Phi(x) \)

\[ \Phi(\pi)_{\mu} \Phi(\pi)_{\mu} \]

\[ \Phi(\pi)_{\mu} \Phi(\pi)_{\mu} \]

\[ \Phi(\pi)_{\mu} \Phi(\pi)_{\mu} \]
Heavy quark expansion

Inclusive: sum over hadronic final states, subject to constraints determined by short dist physics, decay: S.D. - calculable

Hadronization: nonpert. But prob. to hadronize = 1

Use optical theorem + operator product exp. into "multipole expansion" - expand forward scattering amplitude in $k/u_k$

$$ 0 = -\frac{\alpha}{v^2} \Im \langle \sigma (\sigma)\rangle (\sigma) \mu = \overline{\sigma} \times \tau \cdot \rho_\mu$$

$$ \Gamma (B \to X_c \ell \nu) = \sum_{X_c} \int d^4p \left| \langle X_c \ell \nu | 0 | B \rangle \right|^2$$

$$ = \sum_{X_c} \int d^4p \left| \langle X_c \ell \nu | 0 | B \rangle \right|^2$$

$$ W^{\mu \nu} = 2 \pi i \delta^4 (p_B - p_1 - p_2) \langle B | \bar{\ell} c (x) | X_c \ell \nu \rangle$$

$$ = -\frac{i}{\pi} \Im \langle T^{\mu \nu} \rangle = -\frac{i}{\pi} \int d^4x \langle B | T^{\mu \nu} | X_c \ell \nu \rangle$$

Expand time ordered product in local operators

Operators of the form $\bar{B} \mathcal{G}_{\mu \nu} \ldots \bar{B}$

Can use HQS to organize operators (reduce #)

$\Rightarrow$ dim-4 operator vanishes $\Rightarrow$ no $V_{ud}$ correction

$\Rightarrow$ spectator first matters at dim-6 ($\bar{V}_{ud} \bar{V}_{us}$)

Leading order $\langle B | \bar{\ell} c (x) | X_c \ell \nu \rangle \approx 2m_B v^5$ get free quark states

$\Rightarrow$ $\bar{V}_{ud} \bar{V}_{us}$ inclusive

$\Rightarrow$ gets more complicated for $W_1$, $B \to X_{cd}$, etc
- No time to talk about SCET - started with $B \to X_s \ell^+\ell^-$, jet-like final states... $\Rightarrow$ jet physics

- Nonleptonic decays - inclusive - OPE in the physics

\textit{Results:} factorization proven in $B \to D^{(*)+}\pi^-$

\textit{Genuinely new:} color suppressed decays:

- Strong phase in $B \to D\pi$ and $B \to D^*\pi$: isospin triangle sense

\[ \frac{\text{BR}(B^- \to D^{(*)+}\pi^-)}{\text{BR}(B^0 \to D^{(*)+}\pi^-)} = 1 + \delta(N_{\chi\rho}) \quad \text{order } 30\% \text{ cmv.} \]

\[ \frac{1}{\sin^2\theta} \frac{\text{BR}(B^0 \to D^{(*)+}\pi^-)}{\text{BR}(B^- \to D^{(*)+}\pi^-)} = 1 + \delta(N_{\chi\rho}) \quad \text{works pretty well} \]

$B: I = \frac{1}{2}$ ($M = 0, 1$) $\delta_{	ext{fit}} = \frac{1}{2} + \frac{3}{2}$

$A_{2/2}, A_{1/2} - 3$ observables.

\[ \text{Ask?} \]

- Charmless nonleptonic - very active field.

\textit{Important/ongoing progress:}

- Data stimulated lots of developments
- Theorists could impact CLEO measurements done

\textit{Expect synergy to continue...}
3rd Lecture

LHC will find Higgs, or what's responsible for EWSB
Hopefully more than a Higgs (hierarchy problem)

Flavor will likely remain important for understanding
what the results are, and what they are not
(even if superficially unrelated to flavor)

Eq. 1) \( A_{pp \rightarrow t \bar{t}} \) from CDF (3.25)

1st attempt
S-channel\[ \begin{array}{c}
\text{\( t \)} \\
\text{\( \gamma \)} \\
\text{\( \gamma \)}
\end{array} \]
can be flavor diagonal
but not flavor universal (dijets)
...doesn't work well

2nd attempt
\[ \begin{array}{c}
\text{\( t \)} \\
\text{\( u \)} \\
\text{\( u \)}
\end{array} \]
\( t/u \) channel
flavor violation - need to suppress
dijet signals - flavor conservation
can solve both at once
(no models without any issues...)

Eq. 2) \( W^{\pm} W^{\mp} \) anomaly

- need a new particle couple to \( q \bar{q} \)
- why no \( Z^0 / Z^\prime \) excesses?
- "bold" models: \( Z^0 (cs) \) \( \rightarrow \) new
diagonal production \( (104.4520) \)

flavor violating explanation
even observable does not seem to care about it

The LHC will only give limited info on flavor (ATLAS+CMS)
\( (t \bar{t}) + (some \ b) + (other \ jets) \)
\( \leftrightarrow \) easier? \( \leftrightarrow \) harder?

The LHC is a top factory - strong coupling to \( t \) \( \leftrightarrow \) EWSB
Is the 3rd generation different from 1st & 2nd?

Does NP involve new CPV? couple to up/down sector/both?
new flavor violation? modify SM ops? New ans?

Could be that LHC only measures flavor diagonal decays
same more from flavor? Eg. 1 V\( \text{ud} \) and V\( \text{es} \) from B \( \rightarrow \) \( t \) decay
The scale of NP

1) B and L violation (p decay)
\[ \frac{Q_{QL}}{\Lambda^2} \Rightarrow \Lambda > 10^{10} \text{GeV} \]

2) Flavor & CP violation (NP flavor problem)
\[ \frac{Q_{QG}}{\Lambda^2} \Rightarrow \Lambda > 10^{4 \ldots 7} \text{GeV} \]

3) Precision electroweak (little hierarchy prob.)
\[ \frac{(\phi'^\dagger \phi)^2}{\Lambda^2} \Rightarrow \Lambda > \text{few} \times 10^{3} \text{GeV} \]

Flavor & custodial sym. broken already in SM

The dinner is: a unique set of dim-5 terms
\[ \text{dim-5} \Rightarrow \frac{1}{\Lambda} (\Phi^\dagger \Phi)(\bar{\nu} \nu) \Rightarrow \nu \nu, \nu \nu, \nu \nu \]

Majorana masses for \( \nu \)'s

Discovery of new \( \nu \to \) need Dirac \( \nu \)'s (sterile)
need higher dim. Op. \( \approx \) SM or G EFT

All have assumptions; don't know where NP is

SM with \( \mu < 0 \) had lepton flavor conservation
Not the case - no reason to impose on new sectors
If TeV-scale new particles carry lepton \# (sleptons)
then they have their mixing matrices
\[ \begin{pmatrix} A_{e} & A_{\mu} & A_{\tau} \end{pmatrix} \]

\[ \Rightarrow \text{charged lepton flavor violation, } \mu \to e e \]

2 \to 3 e^+ e^- \]
The CDF $A_{T\bar{T}}$ anomaly

Data

2008 CDF $A_{T\bar{T}} = 0.19 \pm 0.07$  
$D\bar{O}$: $0.24 \pm 0.14$

2011 CDF $A_{T\bar{T}} \ (m_{T\bar{T}} > 450 GeV) = 0.97 \pm 0.11$

also 2-lepton 

$$A_{T\bar{T}} = \frac{N(\mu \gamma 2\gamma) - N(\mu \gamma 0)}{\Gamma_{SM}}$$

SM prediction small 

$$\sigma^0 \approx \frac{9}{2} m_{T\bar{T}}$$

and $\frac{d\sigma}{dM_{T\bar{T}}}$ roughly consistent with $SM \approx 7.5$ pb

Uncertainties on tails debated

LHC not yet conclusive $\rightarrow$ will soon be

Models: No bumps $\rightarrow$ s-channel has problems (unless quasi leading)

leading choice: t-channel $\Gamma^T \gg \Gamma^{t\bar{t}}$

interference in spectrum $\Gamma^{t\bar{t}'}$

all models predict enhancement

Dijet Bounds.

Seem like to live below t threshold (connection $\rightarrow$ $W^+W^-$ ?)

Flavor: "unusual" structures $d\bar{d}$ (etc) $\rightarrow$ doublet of new gauge interactions

try to be flavor conserving / MFV

scale triplet particularly nice $\rightarrow$ Eish (dijets)

Signals: $t\bar{t}$ tail; resonance prod, pair prod, $t\bar{t}$, $t\bar{t}jj$

LHC: While $q\bar{q} \rightarrow t\bar{t}$ dominates (Tevatron, $q\bar{q} \rightarrow t\bar{t}$ @ LHC $\rightarrow$ No)

May be easier to see the NP than re-measure $A_{T\bar{T}}$

Ways to try: Large $|y|$ region dominated by $q\bar{q}$

large rapidity $\rightarrow$ ($t\bar{t}$)

Attempts @ LHC to reconstruct $t\bar{t}$

ATLAS - Jets in forward region
FCNC in top decay\(^7\)  
\(t \rightarrow cZ, t \rightarrow cX\)  
Top quark physics is completely uninteresting in the SM, but can probe NP.  

Current bounds few\(\%\), but SM is a 10\(^{-13}\)!  
LHC is a top factory! \(\approx 150\text{pb} @ 7\text{TeV} (800 @ 14\text{TeV})\)  
\[\text{at design: } 1\text{ TeV pair/sec}\]

Indirect bounds from B decays  
\[t \rightarrow cL, t \rightarrow cL\]

ATLAS & CMS expect to get down to \(10^{-5}\) level (100pb\(^{-1}\)).

Can do general operator analysis (before \(SU(2)\times U(1)\) breaking), which could give rise to a signal?  
Expand \(\mathcal{L}\) in \(\frac{\alpha}{\pi}\).  

\[Q_{LL}^u = (\bar{Q}_3 \Gamma^u \bar{Q}_2) (\bar{t}^+ D^0) H \Gamma c\]  
\[Q_{RR}^d = (\bar{t}^R \Gamma d \bar{c}) (\bar{t}^R D^0) H^\dagger\]

\(B_t(t \rightarrow cZ)_{\text{max}} = 3 \times 10^{-7}\)

\(B_s(t \rightarrow cZ)_{\text{max}} = 0.1\)

\(\Gamma_{t \rightarrow cZ} \text{ max} \approx 0.1\).

Several operators constrained more by B decays than top:

\[Q_{LR}^b = (\bar{Q}_2 \Gamma\bar{Q}_3 H) < r \text{ Bsmag gives both} (t \rightarrow cZ)_{\text{max}} = 10^{-7} \text{ and } (t \rightarrow cX)_{\text{max}} = 10^{-2}\]

If top FCNC seen, interesting synergies possible.
**LHC & SUSY**

If the LHC finds something more than a Higgs...
(hopefully sig unexpected, but we can't discuss that; view SUSY as most motivated)

- How is SUSY broken?
- How it is communicated to MSSM?
- Predict/explain/understand soft SUSY breaking terms?

Want to know how new particles interact with SM quarks/leptons

- In SUSY CPV possible in:
  - sneutrino, sleptons couplings
  - flavor diagonal processes (EDM)
  - neutral currents, etc.

MSSM: 44 CPV phases
(CKM + 40 in mixing matrices + 3 CP)

K-R mixing in SUSY here.

Could ease Ee, Eτ, EDM problems if all CPV phases << 1
Flavor and $CP$ violation in SUSY

Superpotential:

$$W = \sum_{i,j} \left( Y_{ij}^u H_u Q_{Li} \bar{U}_{Lj} + Y_{ij}^d H_d Q_{Li} \bar{D}_{Lj} + Y_{ij}^\ell H_d L_{Li} \bar{E}_{Lj} \right) + \mu H_u H_d$$

Soft SUSY breaking terms:

$$\mathcal{L}_{\text{soft}} = -\left( A_{ij}^u H_u \bar{Q}_{Li} \bar{U}_{Lj} + A_{ij}^d H_d \bar{Q}_{Li} \bar{D}_{Lj} + A_{ij}^{\ell} H_d L_{Li} \bar{E}_{Lj} + B H_u H_d \right)$$

$$- \sum_{\text{scalars}} (m_S^2)_{ij} S_i \bar{S}_j - \frac{1}{2} \left( M_1 \bar{B} \bar{B} + M_2 \bar{W} \bar{W} + M_3 \bar{g} \bar{g} \right)$$

3 $Y^f$ Yukawa and 3 $A^f$ matrices — 6×(9 real + 9 imaginary) parameters

5 $m_S^2$ hermitian sfermion mass-squared matrices — 5×(6 real + 3 imag.) param's

Gauge and Higgs sectors: $g_{1,2,3}, \theta_{\text{QCD}}, M_{1,2,3}, m_{h_u,d}^2, \mu, B$ — 11 real + 5 imag.

Parameters: $(95 + 74) - (15 + 30)$ from $U(3)^5 \times U(1)_{\text{PQ}} \times U(1)_R \rightarrow U(1)_B \times U(1)_L$

44 CPV phases: CKM + 3 in $M_1, M_2, \mu$ (set $\mu B^*$, $M_3$ real) + 40 in mixing matrices of fermion-sfermion-gaugino couplings (+80 real param's)

ZL — p. 2/14
K-\bar{K} mixing in SUSY

\[ \frac{\text{Im}(K_{\nu\bar{\nu}})}{\text{Re}(K_{\nu\bar{\nu}})} \sim 10^{-6} \left( \frac{1\text{ TeV}}{\text{At}} \right)^2 (\Delta m^2_{\text{SUSY}}) \]

Classes of models to suppress each terms
- heavy squarks: \( m_{\tilde{q}} \gg 1\text{ TeV} \) (e.g. split SUSY 1st and 2nd gen)
- universality: \( \Delta m^2_{\text{SUSY}} \ll \mu^2 \) (e.g. gauge mediation)
- alignment: \( |(K_{L,R})_{12}| < 1 \) (e.g. horizontal SUSY)

All models incorporate some of this

DB mixing \( \Rightarrow \) if there are 1st two gen. squarks at the TeV scale, some level of degeneracy required.
- Alignment alone cannot do the job (shift everything up)

Hope to get some insights on...

SM
- single source of CPV
- CPV involves all 3 gen. in CC int.
- suppressions by mixing angles
- suppression of FCNC loops
- suppression of chirality flips

NP
- many sources?
- NC? new sectors?
- degeneracies?
- enhancements?
- new operators?

Even if TeV-scale physics unifies loop + GIM
- suppressions, still expect some deviations
Minimally Flavored Violation

Can we get a "lower bound" on flavor physics effects from NP at some scale $\Lambda_N$? What's the "minimal" deviation?

Not reasonable to demand that higher dim op's are flavor invariant and only contain SM fields, not $Y_d$ since $[U(3)]^3 \rightarrow G$ already broken by SM.

$\lambda_{ud} - Y_d \bar{Q}_L \Phi_R = Y_d \bar{Q}_L \Phi_R \quad (\Phi = i\phi_2, \phi_3)$

- Treat $Y_d$ as spurious which transform under $[U(3)]^3 \rightarrow G$ in a way to make SM invariant under $G$ - so that $G$ is broken by "background" values of $Y_d$.

Fields: $Q(3,1,1)$, $\nu_R(1,3,1)$, $\Phi_R(1,1,3)$
Species: $Y_u(3,3,1)$, $Y_d(3,1,3)$

Choose basis: $Y_d = \text{diag}(y_d, y_s, y_c)$, $Y_u = V^{+} \text{diag}(y_u, y_d, y_t)$, $\phi_1 = \text{u} \rightarrow \phi_2$

EFT-like analyses possible:

eg: to get non-diagonal terms, need at least:

$\bar{Q} \Phi_y Y_u \bar{Q}_L$, $\bar{d} \Phi_y Y_d Y_u \bar{Q}_L$, $\bar{d} \Phi_y Y_d Y_u \bar{d}$ (or more insertions of $Y_d$)
Examples of MFV at work

Step 1: \[ A_{\mu \nu} : \frac{X}{\Lambda_{NP}^2} (\bar{\nu}_L \gamma \mu \nu) \]

\[ \bar{\nu}_L (3, 1, 1) \mu \nu (3, 1, 1) \Rightarrow (\bar{\nu}_L \mu \nu) \in (8, 1, 1) \text{ so it must be } \alpha (\bar{\nu}_L \mu \nu)^2 \rightarrow \bar{y}_t^* V_{c}^* V_{ts} \]

\[ \Rightarrow \text{ in MFV: } X \propto \bar{y}_t^* \frac{V_{c}^* V_{ts}}{\Lambda_{NP}^2} \]  

Similarly \[ \bar{y}_t^* \frac{V_{c}^* V_{ts}}{\Lambda_{NP}^2} \]

Step 2: \[ B \rightarrow X \bar{c} \bar{b} : \frac{X}{\Lambda_{NP}^2} (\bar{\nu}_L \gamma \mu \nu F^{\mu \nu} G_R) \]

\[ \bar{\nu}_L \gamma \mu \nu F^{\mu \nu} G_R \text{ not invariant under } (U(3))^3 \]

\[ Q_L \bar{y}_d \bar{c} \text{ is flavor diagonal} \]

\[ Q_L \bar{y}_L \mu \nu F^{\mu \nu} G_R \rightarrow 3 \bar{\nu}_L^* V_{c}^* V_{ts} \bar{y}_t^* \bar{y}_c \bar{b} \]

\[ \Rightarrow \text{ in MFV: } X \propto \frac{y_t^*}{\Lambda_{NP}^2} \frac{y_c^*}{\Lambda_{NP}^2} V_{c}^* V_{ts} \]

As in the SM: - GIM - FCNCs vanish be degeneracy quit

- Need at least two CKM elements
  - one of which must be off diagonal
  - Suppression of chirality flips

In some isolated cases \( \alpha(4) \) deviations from \( S^4 \) cannot yet be ruled out.

If those windows close, MFV may become similar to custodial \( SU(2) \) in guiding BSM model building (some say it's already overdue)

0703.1794

GMFV: what if we cannot expand in \( \bar{y}_L \mu \nu \) (e.g., large \( t \) contributions, etc.) can also be near 1)
MFV Predictions

* spectra: $\varepsilon_{\mu,\nu,\tau} \ll 1$, so approximate $(UE)^3$ remains
  → inded in gauge med. SUSY breaking, the
  first two generation squarks near-degenerate

* mixing: only source is VCKM

\[
V_{\text{CKM}} = \begin{pmatrix}
1 & 0.2 & 0 \\
-0.2 & 1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

New particles decay either to 3rd or non-3rd
generation particles, but not both

---

Explicit studies of NP where MFV can be tested@LHC
In general, easier to rule out then to prove

@ Some subdominant decays may still be substantial
  - complicate reconstruction of edges of kinematic
    distributions (determine) \(\rightarrow\) (Lester?)
  - modify discovery potentials (smear things)

Feng, Mizutani, Papucci

Eg: recent models w/ mixed gauge/gravity mediated
SUSY breaking
  squark flavor – Slepton (5?) flavor may be easier!

As in QCD, already spectrum and branching
rations will contain lots of info.
I did not talk about many of the currently 2-3 o anomalies. In an era of exploding data sets, more interesting (limbo) to see what can/cannot become clearly unquestionable signals.

Lots of measurements have the potential to establish NP - so it's going to be fascinating.

- Flavor is a problem for TeV-scale NP
- Tests of flavor sector will improve an order of mag.
- Exp will continue to motivate theory developments & vice versa
- If new particles are seen we'll want to know as much about their flavor properties as we can possibly find out
- Possible convergence of (S)quark & (S)lepton flavor interplay

- (somehow)

- (FW!)

- (Vexation)