Unraveling

the Mystery of Flavor

Fermilab Colloquium
February 23, 2000

Adam Falk
Johns Hopkins

Recent events in the physics of FLAVOR . . .

1. $\frac{\varepsilon'}{\varepsilon}$ in $K \to \pi\pi$

KTeV

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = [28.0 \pm 4.1] \times 10^{-4}$$

NA48

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = [18.5 \pm 7.3] \times 10^{-4}$$

2. CP violating asymmetry in $B \to J/\psi\, K_s$

CDF

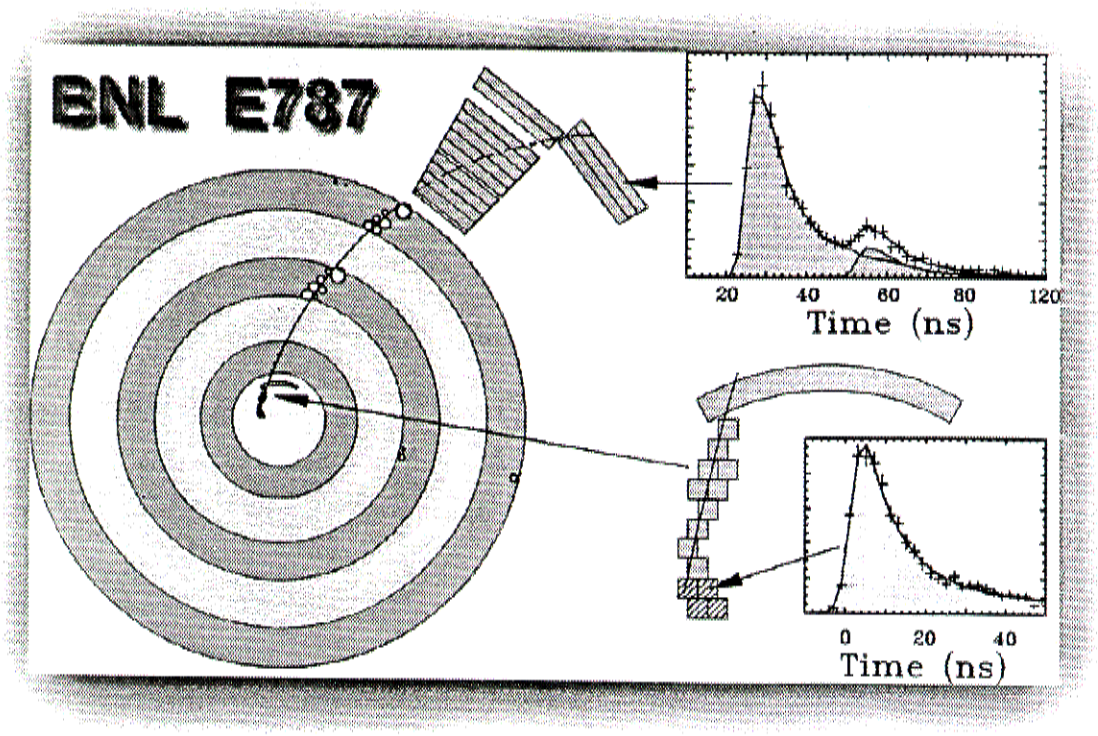
$$\sin 2\beta = 0.79^{+0.41}_{-0.44}$$

$0 \le \sin 2\beta \le 1$ at 93% c.l.

3. Observation of $K^+ \to \pi^+ \nu \bar{\nu}$

E787

$$Br = 1.5^{+3.4}_{-1.2} \times 10^{-10}$$



4. B Factory startups

Asymmetric (SLAC, KEK)

BaBar at PEP-II

BELLE at KEK-B

Symmetric (Cornell)

CLEO-III at CESR

Physics results in 2000

Hadronic fixed target (DESY)

HERA-B at HERA

Issues for this talk ...

- How do these events fit together?

- What does this mean for particle physics?

- What is the path for the future?

- Why do "low-energy" high-energy physics in the next decade?

Particle Physics at $\mu \lesssim 10$ GeV

Quarks	u	c	
	d	s	b
Leptons	ν_e	ν_μ	ν_τ
	e	μ	τ

Gauge Interactions $\quad \underbrace{SU(3)}_{\text{gluon}} \times \underbrace{U(1)}_{\text{photon}}$

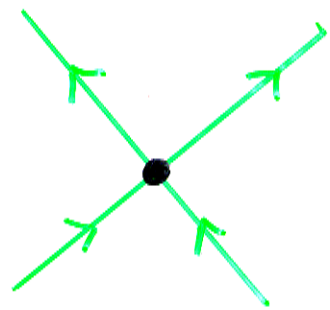
Fermion masses

- Gauge interactions, mass terms are

RENORMALIZABLE

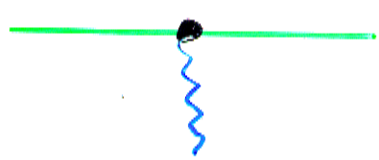
All flavor-changing processes mediated by NONRENORMALIZABLE interactions...

e.g. • Dimension 6



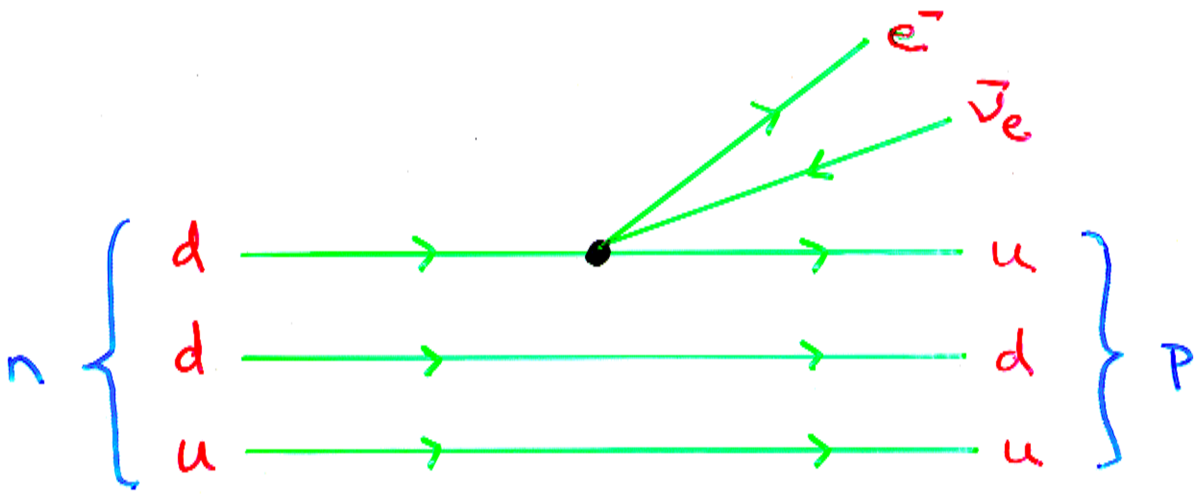
$$\frac{1}{M^2}\,\bar{\Psi}_1\,\Gamma\,\Psi_2\;\bar{\Psi}_3\,\Gamma\,\Psi_4$$

• Dimension 5



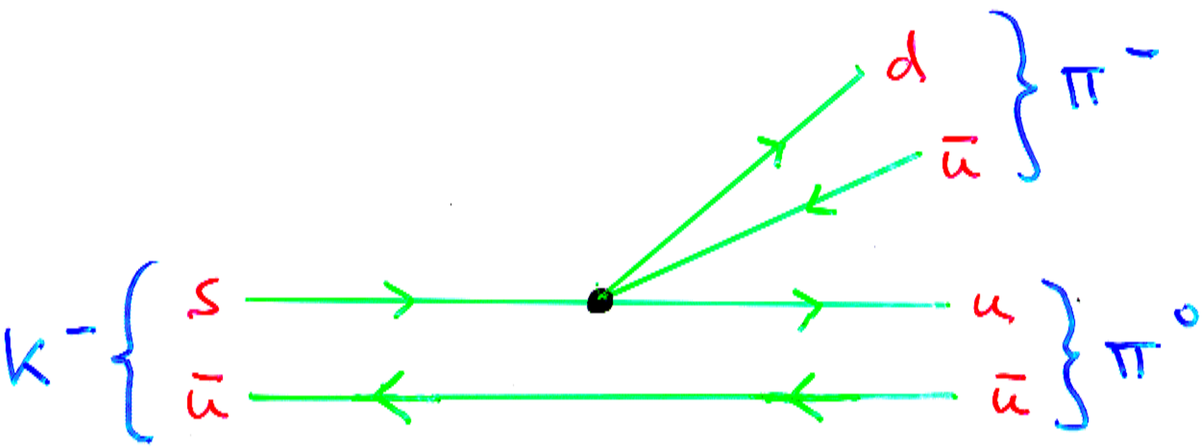
$$\frac{1}{M}\,\bar{\Psi}_1\,\sigma_{\mu\nu}\,\Psi_2\,F^{\mu\nu}$$

$$n \to p \; e^- \; \bar{\nu}_e$$



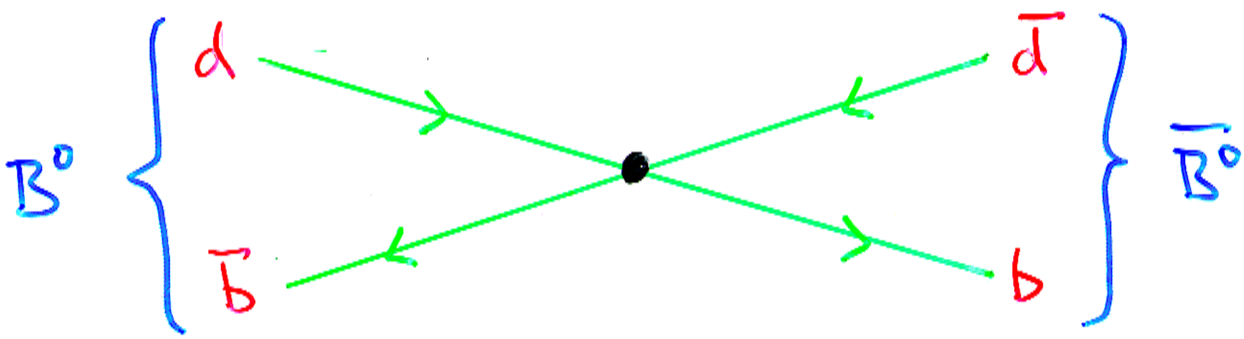
$$\boxed{\bar{u}\,\gamma^\mu(1-\gamma^5)\,d\;\bar{e}\,\gamma_\mu(1-\gamma^5)\,\nu_e}$$

$$K^- \to \pi^- \pi^0$$



$$\boxed{\bar{u}\gamma^\mu(1-\gamma^5)s\,\bar{d}\gamma_\mu(1-\gamma^5)u}$$

$B^0 - \bar{B}^0$ mixing



$$\boxed{\bar{b}\gamma^\mu\gamma^5 d\,\bar{b}\gamma_\mu\gamma^5 d}$$

Hundreds of nonrenormalizable operators at $\mu \lesssim 10$ GeV

Leptons $\quad \bar{\mu}\gamma^{\mu}(1-\gamma^5)\nu_{\mu}\,\bar{\nu}_e\gamma_{\mu}(1-\gamma^5)e$

$\vdots$

Quark-lepton $\quad \bar{u}\gamma^{\mu}(1-\gamma^5)d\,\bar{e}\gamma_{\mu}(1-\gamma^5)\nu_e$

$\bar{c}\gamma^{\mu}b\,\bar{\mu}\gamma_{\mu}\nu_{\mu}$

$\vdots$

Quarks $\quad \bar{d}\gamma^{\mu}\gamma^5 s\,\bar{d}\gamma_{\mu}\gamma^5 s$

$\bar{d}\gamma^{\mu}u\,\bar{c}\gamma_{\mu}s$

$\bar{b}\gamma^{\mu}c\,\bar{u}\gamma_{\mu}d$

$\vdots$

Fermions-gauge fields $\quad \bar{s}\sigma^{\mu\nu}T^a b\,G^a_{\mu\nu}$

$\bar{\mu}\sigma^{\mu\nu}\mu\,F_{\mu\nu}$

$\vdots$

Nonrenormalizable operators

$\longleftrightarrow$ exchange of heavy particles

Physics we know is there (we've seen it!):

a) $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

W^i $\quad B \quad$ γ

3 broken generators $\quad W, Z$

$M_W \simeq 80$ GeV

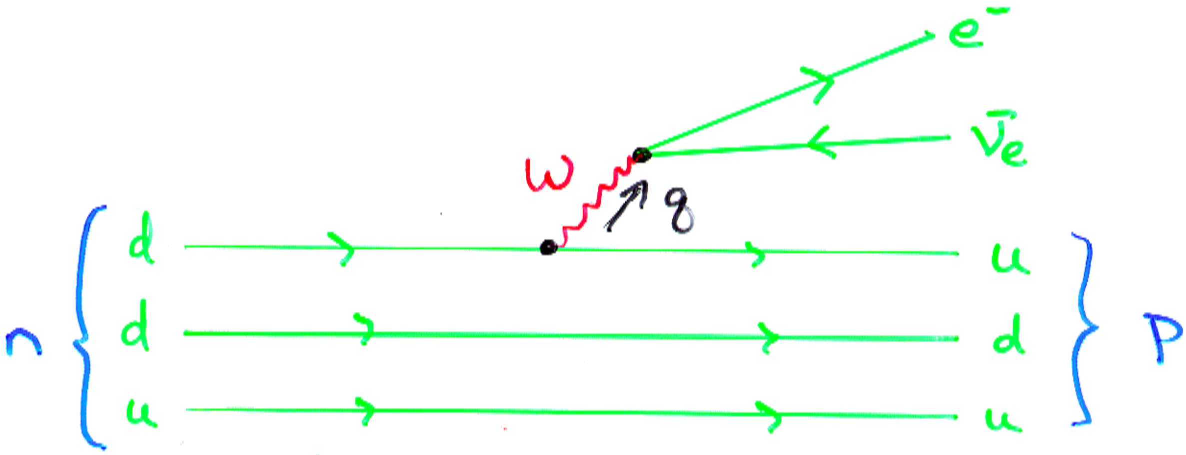
$M_Z \simeq 91$ GeV

b) top quark

$m_t \simeq 175$ GeV

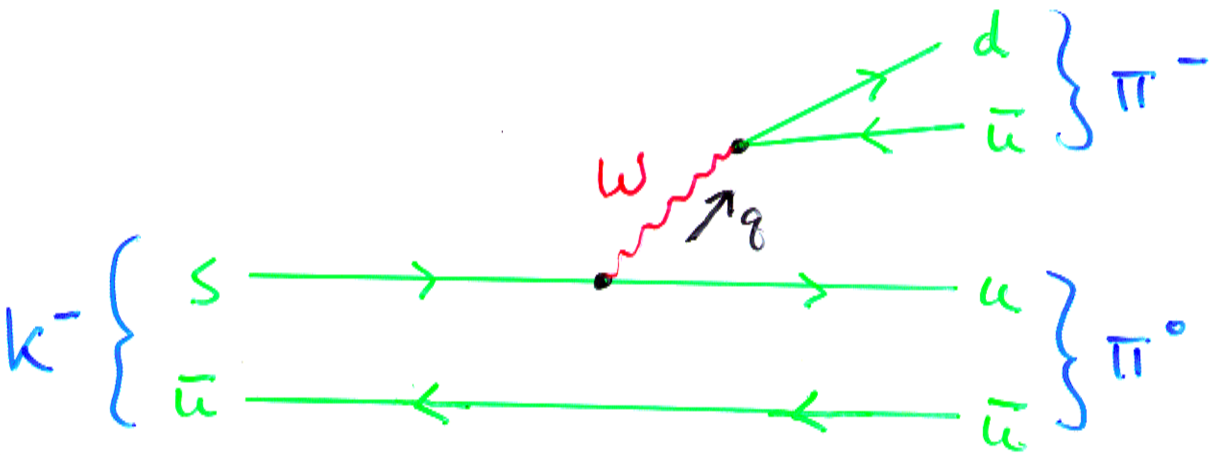
Virtual W, Z, t can generate nonrenormalizable operators at $\mu \lesssim 10$ GeV

$$n \longrightarrow p \; e^- \; \bar{\nu}_e$$



$$\frac{1}{M_W^2 - q^2} \quad \bar{u}\,\gamma^\mu (1-\gamma^5)\, d \;\; \bar{e}\,\gamma_\mu (1-\gamma^5)\, \nu_e$$

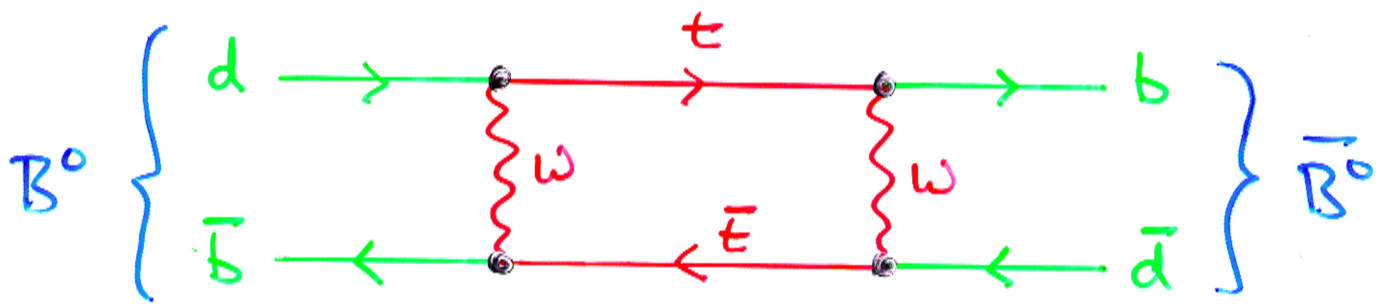
$$K^- \to \pi^- \pi^0$$



$$\frac{1}{M_W^2 - q^2} \; \bar{u}\, \gamma^\mu (1-\gamma_5) s \;\; \bar{d}\, \gamma_\mu (1-\gamma_5) u$$

$+$ QCD radiative corrections

$B^0 - \bar{B}^0$ mixing



$$\frac{1}{M_W^2} f\left(\frac{m_b^2}{m_t^2}, \frac{m_b^2}{M_W^2}\right) \bar{b}\gamma^\mu\gamma^5 d\, \bar{b}\gamma_\mu\gamma^5 d$$

$64,000 Question:

Can virtual W, Z, t exchange account for <u>all</u> flavor-changing nonrenormalizable interactions in the effective field theory at $\mu \lesssim 10$ GeV?

At what level can we see deviations from this simple description?

Are there new particles and interactions in the region $100\ \text{GeV} \lesssim M \lesssim 1\ \text{TeV}$ which couple to flavor?

Popular example: Supersymmetry

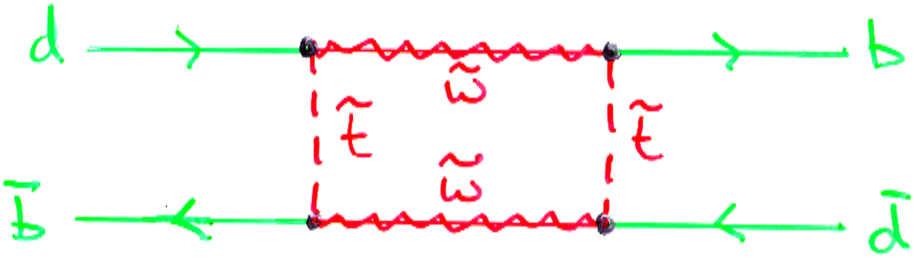
- squarks, sleptons
- gauginos
- charged and neutral Higgs

e.g.

New contributions to effective theory

- change coefficients of existing operators

e.g.

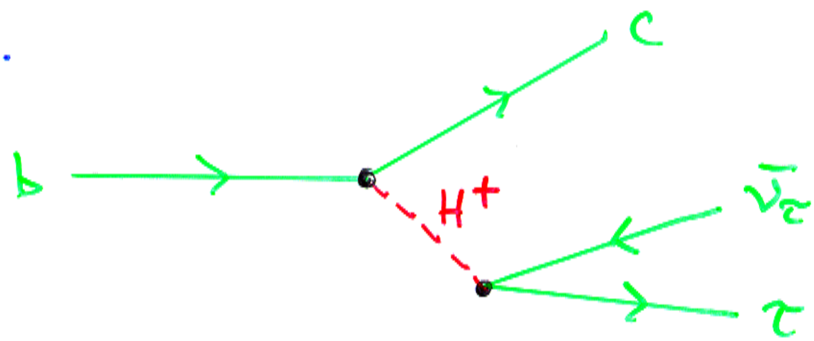


$$\rightarrow \quad \bar{b}\gamma^\mu\gamma^5 d\, \bar{b}\gamma_\mu\gamma^5 d$$

($B-\bar{B}$ mixing)

- introduce new operators

e.g.



$$\rightarrow \quad \bar{c}\, b\, \bar{\tau}\, \nu_\tau$$

(semileptonic B decay)

To look for flavor physics beyond the Standard Model,

we first must understand flavor physics and the breaking of flavor symmetries within the Standard Model

Start with the quarks...

Quarks: representations of $SU(3) \times SU(2) \times U(1)$

	$SU(3)$	$SU(2)$	$U(1)$
Q_L^i :	3	2	$\frac{1}{6}$
$U_R^{i\,*}$:	$\bar{3}$	$-$	$-\frac{2}{3}$
$D_R^{i\,*}$:	$\bar{3}$	$-$	$\frac{1}{3}$

Q_L^i, U_R^{i*}, D_R^{i*} : two-component fermions

$i = 1, 2, 3$: global flavor index

Masses $\longleftrightarrow$ fermion bilinears

$\Rightarrow$ forbidden by gauge invariance

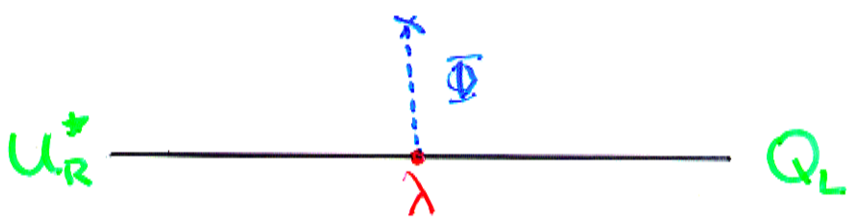
Need "Higgs field" (fundamental or effective/composite)

Φ :	$-$	2	$\frac{1}{2}$

Yukawa couplings

$$\lambda_u^{ij}\, U_R^{i*}\, \Phi\, Q_L^j + \lambda_D^{ij}\, D_R^{i*}\, \tilde{\Phi}\, Q_L^j$$

$SU(2) \times U(1) \to U(1)_{EM}$ $\qquad \langle \Phi \rangle \neq 0$



Fermion mixing $\sim \lambda \langle \Phi \rangle$

$$m \sim \begin{pmatrix} 0 & \lambda\langle\Phi\rangle \\ \lambda\langle\Phi\rangle & 0 \end{pmatrix}$$ (suppressing flavor)

Eigenvalues $\sim$ $\lambda\langle\Phi\rangle$ = "Dirac" mass

For $\lambda \sim \mathcal{O}(1)$, natural size of quark masses is the weak scale, $\sim$ few hundred GeV

True for top, but most λ's are much smaller

The Yukawa couplings λ_u^{ij}, λ_D^{ij}
break the huge flavor symmetry

$$\underset{Q_L^i}{U(3)} \times \underset{u_R^{*i}}{U(3)} \times \underset{D_R^{*i}}{U(3)}$$

down to

$$U(1)_B \qquad \text{baryon number}$$

In the Standard Model, this is where all flavor physics comes from

Quark Sector of Standard Model

Mass basis

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Charged current interactions : $W^\pm$

$$(\bar{u} \ \bar{c} \ \bar{t}) \ \gamma^\mu (1-\gamma_5) \ V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} W_\mu$$

Neutral current interactions : γ, Z

flavor-diagonal (GIM mechanism)

Cabibbo - Kobayashi - Maskawa

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Hierarchy

V_{ud}, V_{cs}, V_{tb}	$\mathcal{O}(1)$
V_{us}, V_{cd}	$\mathcal{O}(10^{-1})$
V_{cb}, V_{ts}	$\mathcal{O}(10^{-2})$
V_{ub}, V_{ts}	$\mathcal{O}(10^{-3})$

V_{CKM} has 4 parameters, including an unremovable complex phase

Wolfenstein parameterization

- exploits observed hierarchy
- approximately unitary

$$V_{CKM} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$\lambda = \sin\theta_c \approx 0.22$ sets hierarchy

A, ρ, η of order 1

$VV^{\dagger} = 1 + \mathcal{O}(\lambda^4)$

(keep higher orders in λ if necessary)

CP Violation

Nonvanishing phase in V_{CKM}

$\Downarrow$

Complex Lagrangian couplings

$\Downarrow$

CP Violation

Purely quantum effect

Observe in interference phenomena

- coefficients of nonrenormalizable operators must be taken to be complex

- CP Violation is naturally present in SM

It is not a mystery!

Phases in Wolfenstein parameterization

$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

V_{ub}, V_{ts} have phases of order one

Other elements have small phases

$$\text{"}1\text{"} = 1 + \mathcal{O}(\lambda^2)$$

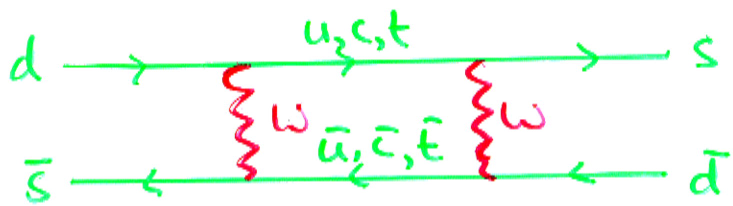
V_{ub}, V_{ts} are $\mathcal{O}(10^{-3})$

$\Rightarrow$ $\cancel{CP}$ is CKM suppressed

- K decays : $\cancel{CP}$ requires virtual t
- B decays : $\cancel{CP}$ requires some coupling to first generation

CP Violation in K System

1) 1964 $\Delta S = 2$ operator



$$\left[A\, V_{cd}^2 V_{cs}^{*2} + B\, V_{td}^2 V_{ts}^{*2} + C\, V_{cd} V_{td} V_{cs}^* V_{ts}^* \right]$$

$$\times \quad \bar{s}\gamma^\mu(1-\gamma^5)d\; \bar{s}\gamma_\mu(1-\gamma^5)d$$

- $\Delta S = 2$ operator $\Rightarrow$ $K^0 - \bar{K}^0$ mixing
- complex coefficient $\Rightarrow$ $\cancel{CP}$ in $K^0 - \bar{K}^0$ mixing

Phenomenological parameter $\varepsilon_K \propto \mathrm{Im}(V_{td} V_{ts}^*)$

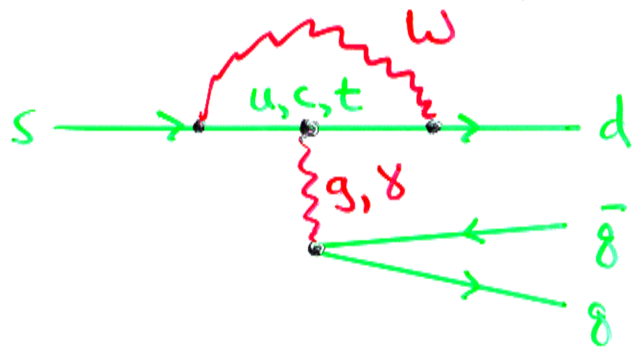
Expt. $|\varepsilon_K| = [2.258 \pm 0.018] \times 10^{-3}$

Predict ε_K ? $\langle \bar{K}^0 | \bar{s}\gamma^\mu(1-\gamma^5)d\, \bar{s}\gamma_\mu(1-\gamma^5)d | K^0 \rangle$

Hadronic uncertainty $\sim 25\%$?

ε_K is at the right level for SM

2) 1999 Confirmation of $\not{CP}$ in $\Delta S=1$ operator



Most important operators

$$Q_6 = \bar{s}_\alpha \gamma^\mu (1-\gamma^5) d_\beta \sum_{u,d,s} \bar{q}_\beta \gamma^\mu (1-\gamma^5) q_\alpha$$

$$Q_8 = \bar{s}_\alpha \gamma^\mu (1-\gamma^5) d_\beta \sum_{u,d,s} e_q \bar{q}_\beta \gamma^\mu (1-\gamma^5) q_\alpha$$

Both Q_6, Q_8 can mediate $K \to \pi\pi$

Complex coefficients $\Rightarrow$ $\not{CP}$ $\Rightarrow$ can mediate $K_L \to \pi\pi$

Phenomenological parameter $\varepsilon' \sim \mathrm{Im}(V_{td} V_{tb}^*)$

Predict ε' : need

$$\langle \pi\pi | Q_6 | K_L \rangle \qquad \Delta I = \tfrac{1}{2}$$

$$\langle \pi\pi | Q_8 | K_L \rangle \qquad \Delta I = \tfrac{1}{2}, \tfrac{3}{2}$$

No symmetry relates $\Delta I = \frac{1}{2}, \frac{3}{2}$ amplitudes

Crude approximation

$$\frac{\varepsilon'}{\varepsilon} = \left[B_6^{(1/2)} - 0.5\, B_8^{(3/2)} \right] \times 10^{-3}$$

B: parameterize hadronic uncertainty

Vacuum insertion ansatz $\quad B_6^{(1/2)} = 1.0$

$$B_8^{(3/2)} = 0.8$$

$\Rightarrow$ predict $\quad \frac{\varepsilon'}{\varepsilon} \simeq 0.7 \times 10^{-3}$

Expt avg. $\quad \frac{\varepsilon'}{\varepsilon} \simeq 2.0 \times 10^{-3}$

Too large? Hadronic uncertainties too large to say this

- CP Violation in K system is at the right level
- Something is correct in SM picture of $\not{CP}$
- Hadronic uncertainties preclude precision tests in the K system

"Paradigm Shift":

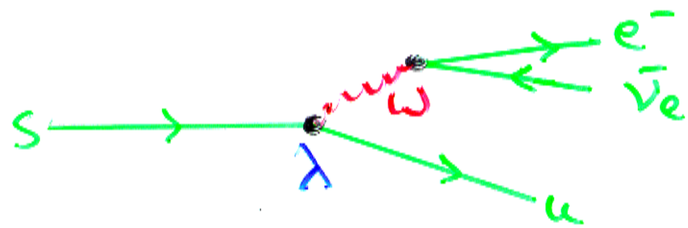
Now that $\not{CP}$ has been observed and accounted for naturally in the SM, it is no longer interesting for its own sake!

But... is the Standard Model the only source of CP Violation?

Explore $\not{CP}$ in as many nonrenormalizable operators as possible

Current constraints on V_{CKM}

1) $\lambda = V_{us}$ $\qquad \bar{u}\gamma^\mu(1-\gamma^5)s\;\bar{e}\gamma_\mu(1-\gamma^5)\nu_e$

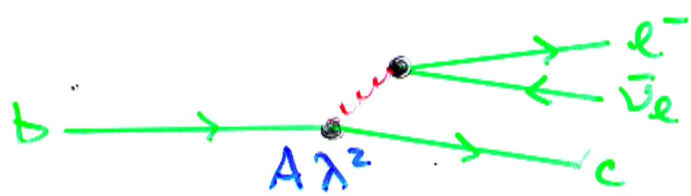


$$K^+ \to \pi^+ e^- \bar{\nu}_e$$

$\langle \pi^+ | \bar{u}\gamma^\mu(1-\gamma^5)s | K^+ \rangle$: chiral perturbation theory (m_s small)

$$\boxed{\lambda = 0.2196 \pm 0.0023}$$

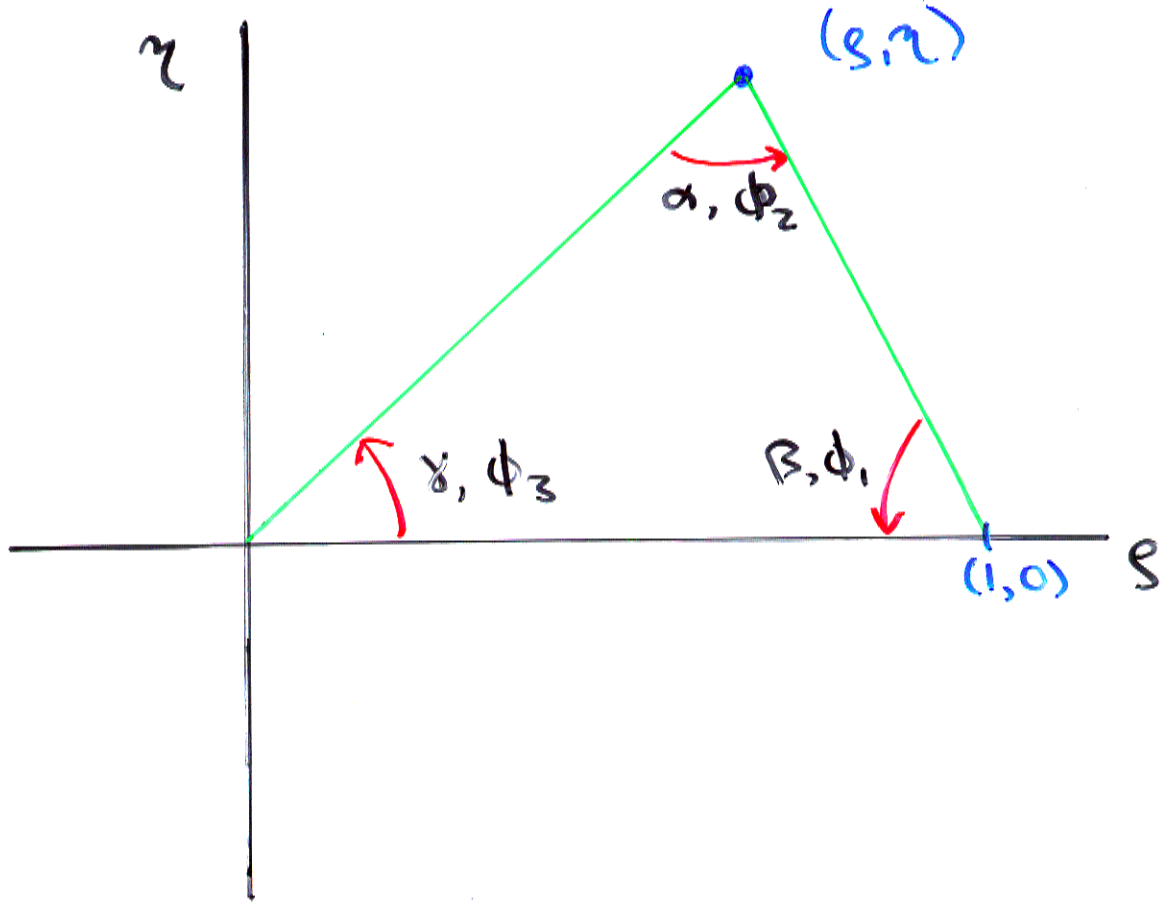
2) $A\lambda^2 = V_{cb}$ $\qquad \bar{c}\gamma^\mu(1-\gamma^5)b\;\bar{\ell}\gamma_\mu(1-\gamma^5)\nu_e$



$B \to D^* \ell\nu$ or $X_c \ell \nu$ $\qquad$ HQET (m_b large)

$$\boxed{A\lambda^2 = 0.039 \pm 0.02 \;\Rightarrow\; A = 0.82 \pm 0.04}$$

ρ, η are most important unknowns



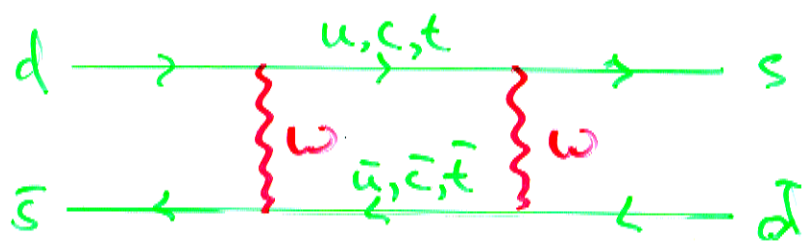
"Unitarity Triangle"

Higher order Wolfenstein $\to$ $(\bar{\rho}, \bar{\eta})$

$$\alpha + \beta + \gamma = \pi = \phi_1 + \phi_2 + \phi_3$$

Constraints on ρ, η

1) ε_K $\boxed{\bar{s}\gamma^\mu(1-\gamma_5)d\,\bar{s}\gamma_\mu(1-\gamma_5)d}$



Combination of λ, A, ρ, η

Uncertainty dominated by

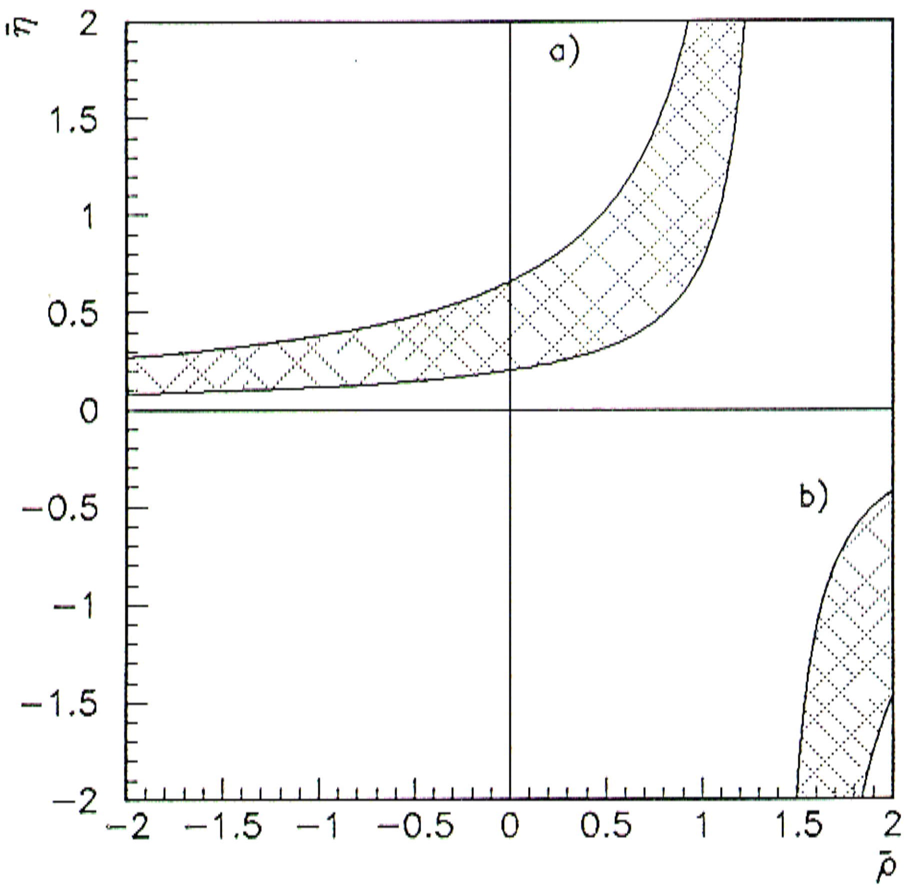
$$\langle \bar{K}^0 | \bar{s}\gamma^\mu(1-\gamma_5)d\,\bar{s}\gamma_\mu(1-\gamma_5)d | K^0 \rangle$$

Lattice : error at 20% level

In (ρ, η) plane, $\varepsilon_K \sim A^4 \rightarrow$ 20% uncertainty

1a) $\frac{\varepsilon'}{\varepsilon}$ No precision constraint

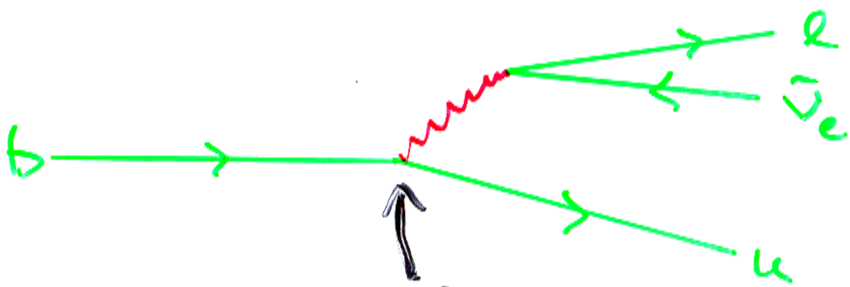
$\varepsilon_K = [2.258 \pm 0.018] \times 10^{-3}$



BaBar Physics Book

2) $$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \lambda^2(\rho^2+\eta^2)$$

$$\boxed{\bar{u}\,\gamma^\mu(1-\gamma^5)\,b\;\bar{\ell}\,\gamma_\mu(1-\gamma^5)\,\nu_e}$$



$A\lambda^3(\rho-i\eta)$

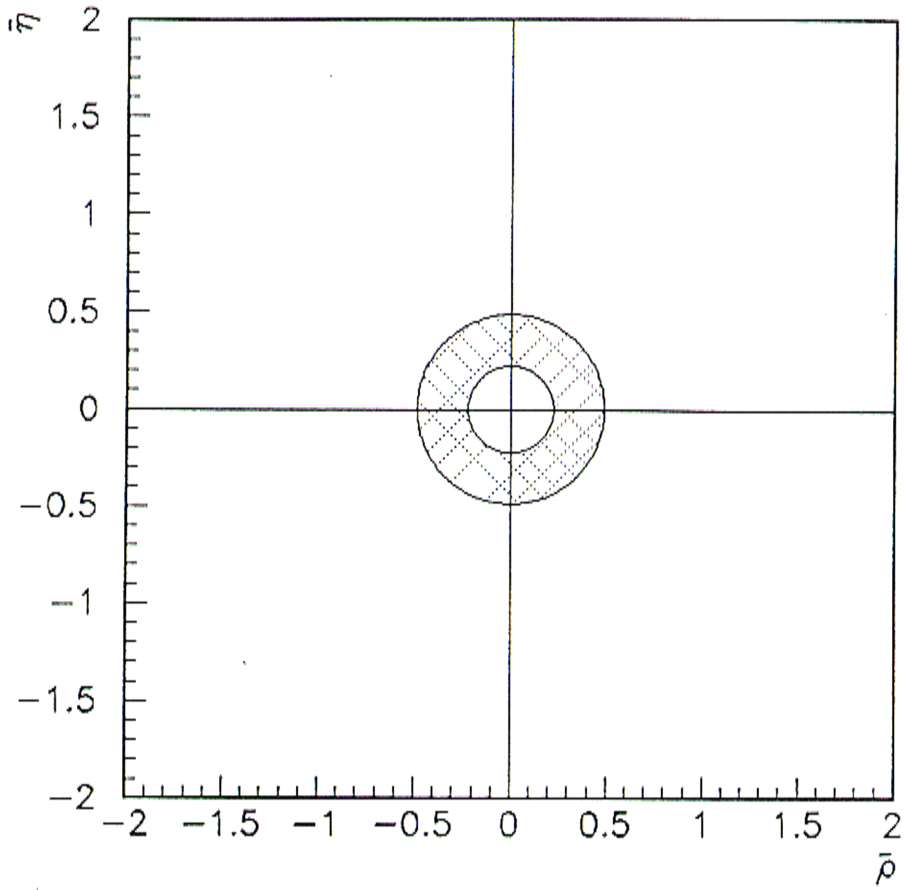
100× background : $b \to c\,\ell\,\bar{\nu}_e$

⇒ Large hadronic uncertainties, hard to quantify meaningfully

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.09 \pm 0.02$$

$$\sqrt{\rho^2+\eta^2} = 0.41 \pm 0.09$$

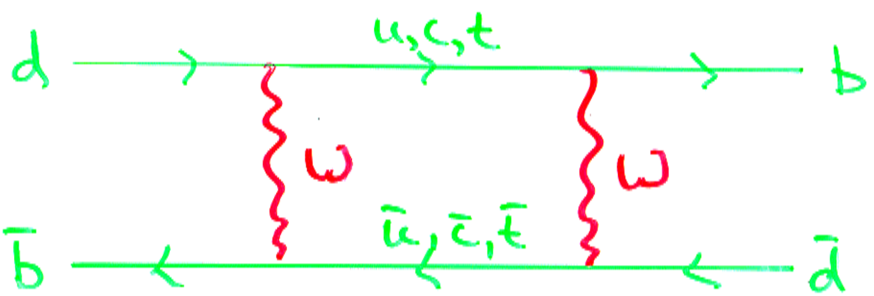
$|V_{ub}| / |V_{cb}|$



BaBar Physics Book

3) ΔM_d $\qquad B^0 - \bar{B}^0$ mixing

$$\boxed{\bar{b}\gamma^\mu(1-\gamma^5)d\,\bar{b}\gamma_\mu(1-\gamma^5)d}$$



dominated by top

$$|V_{td}^* V_{tb}|^2 = A^2\lambda^6\left[(1-\rho)^2+\eta^2\right]$$

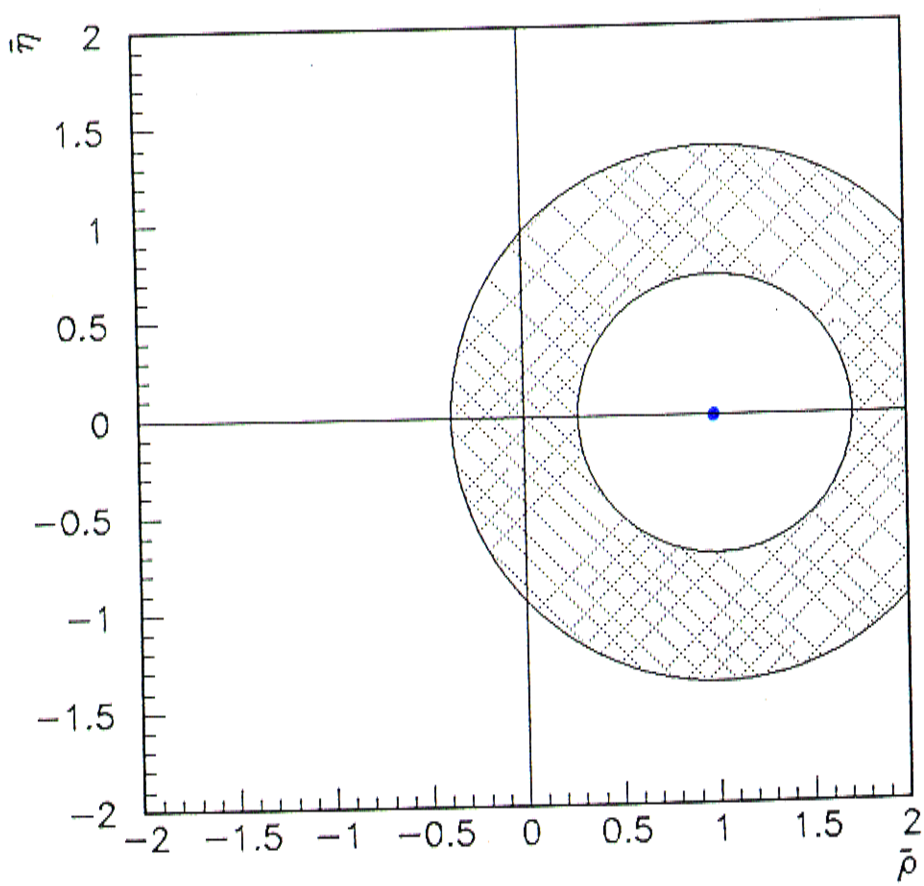
Hadronic uncertainty

$$\langle \bar{B}^0|\,\bar{b}\gamma^\mu(1-\gamma^5)d\,\bar{b}\gamma_\mu(1-\gamma^5)d\,|B^0\rangle$$

Lattice : ~ 20% accuracy ?

Expt. $\Delta M_d = 0.464 \pm 0.018\ \text{ps}^{-1}$

ΔM_d



BaBar Physics Book

3a) ΔM_s $\qquad$ $B_s - \bar{B}_s$ mixing

$$\boxed{\bar{b}\gamma^\mu(1-\gamma^5)s\,\bar{b}\gamma_\mu(1-\gamma^5)s}$$

$$\xi^2 = \frac{\langle \bar{B}^0 | \bar{b}\gamma^\mu(1-\gamma^5)s\,\bar{b}\gamma_\mu(1-\gamma^5)s | B^0\rangle}{\langle \bar{B}_s | \bar{b}\gamma^\mu(1-\gamma^5)d\,\bar{b}\gamma_\mu(1-\gamma^5)d | B_s\rangle}$$

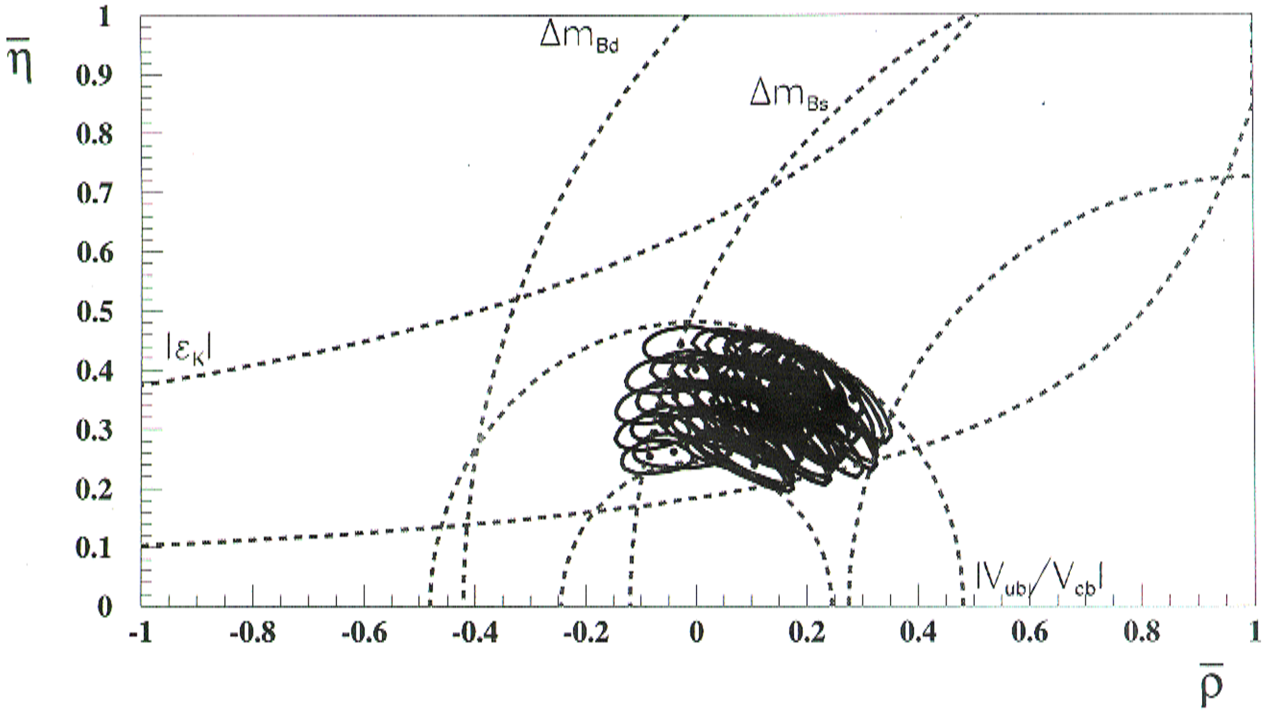
$$= 1 + SU(3) \text{ corrections}$$

$$\xi^2 \frac{\Delta M_d}{\Delta M_s} = \frac{|V_{td}|^2}{|V_{ts}|^2} = (1-\rho)^2 + \eta^2$$

Current limit $\Delta M_s > 14.3\,ps^{-1}$, 95% c.l.

ΔM_s should be measured by CDF at Run II

$\xi = 1.14 \pm 0.13$ $\qquad$ lattice



BaBar Physics Book

Future Scientific Program

Does the Standard Model fully explain flavor physics?

Constrain (ρ, η) independently in

1) K physics : $\Delta S = 1$, $\Delta S = 2$ operators

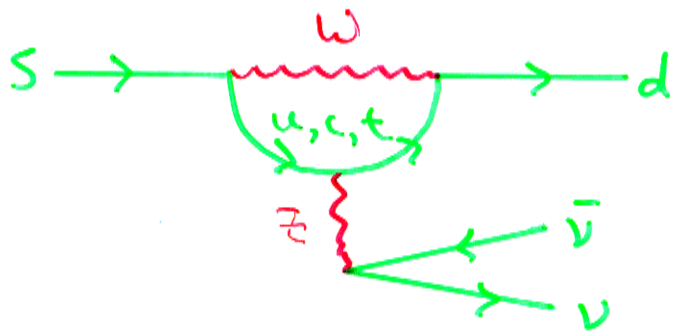
2) B physics : $\Delta B = 1$, $\Delta B = 2$ operators

Measurements must be theoretically clean!

K System

1) $K^\pm \to \pi^\pm \nu \bar{\nu}$ $\qquad\qquad \Delta S = 1$

$$\boxed{\bar{s}\, \gamma^\mu (1-\gamma^5) d \;\; \bar{\nu}\, \gamma_\mu (1-\gamma^5) \nu}$$



dominated by
c, t

Amplitude $\sim$ $a\, V_{ts} V_{td}^* + b\, V_{cs} V_{cd}^*$

$\langle \pi^- | \bar{s}\, \gamma^\mu (1-\gamma^5) d | K^- \rangle$: χPT, known

Constraint on $\eta^2 + (1 - \rho + \delta_c)^2$

$\delta_c = 0.4$, uncertainty $\sim 15\%$
(largely from V_{cb})

2) $K_L \to \pi^0 \nu \bar{\nu}$ $\Delta S = 1$

CP violating

$$a(K_L \to \pi^0 \nu \bar{\nu}) \propto \mathrm{Im}\, a(K^\pm \to \pi^\pm \nu \bar{\nu})$$

$$\mathrm{Im}\left[V_{ts} V_{td}^*\right] = \eta$$

No charm contribution
Theoretically pristine

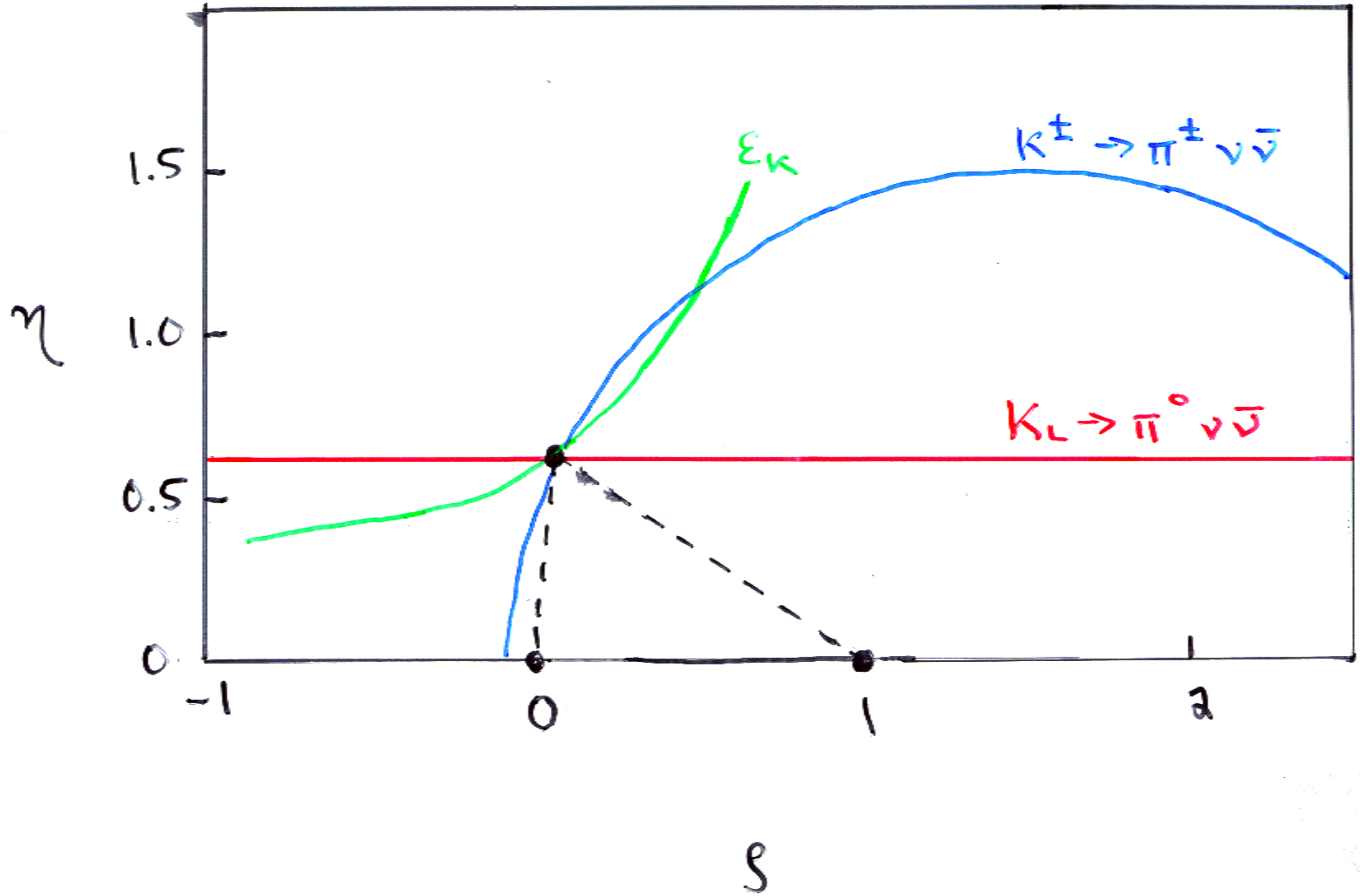
3) ε_K $\Delta S = 2$

Larger uncertainties

~ 20% from hadronic physics

~ 20% from V_{cb}

Constraints from K



Experimental Prospects

$B(K^{\pm} \to \pi^{\pm} \nu \bar{\nu}) \sim 10^{-10}$

1 event at BNL-AGS-E787

Proposals: BNL - next generation E949

Fermilab - CKM

$B(K_L \to \pi^{0} \nu \bar{\nu}) \sim 10^{-11}$

Proposals: BNL - E926

Fermilab - KAMI

$$\boxed{\text{VETOING!!}}$$

B System

- Magnitudes of CKM elements

  $V_{ub}, V_{cb}, \Delta M_s, \Delta M_d, \ldots$

- Phases - angles in Unitarity Triangle

  $\alpha, \beta, \gamma \qquad (\phi_1, \phi_2, \phi_3)$

  Probe $\not{CP}$ directly

  Can be theoretically clean

A few important examples ...

$C\not{P}$ in $B \to J/\psi\ K_s$

Interference between mixing and decay

$$\begin{tikzcd} B^0 \arrow[r, "m_B"] \arrow[dr, "a_{\psi K_s}"'] & \bar{B}^0 \arrow[d, "a^*_{\psi K_s}"] \\ & \psi K_s \end{tikzcd}$$

$m_B = B^0 - \bar{B}^0$ mixing amplitude

$a_{\psi K_s} = B \to \psi K_s$ decay amplitude

$m_K = K^0 - \bar{K}^0$ mixing amplitude

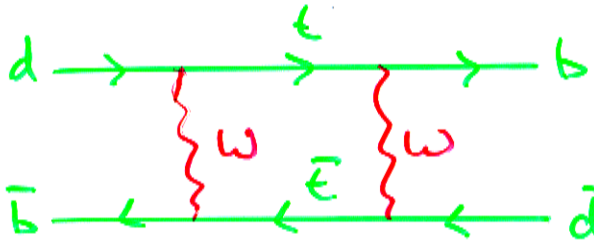
Measure $$\frac{\Gamma(B^0 \to \psi K_s) - \Gamma(\bar{B}^0 \to \psi K_s)}{\Gamma(B^0 \to \psi K_s) + \Gamma(\bar{B}^0 \to \psi K_s)}$$

Asymmetry depends on $\mathrm{Im}\,\lambda_{CP}$, $|\lambda_{CP}| = 1$

$$\arg \lambda_{CP} = \arg m_B + 2 \arg a_{\psi K_s} + \arg m_K + \pi$$

Standard Model

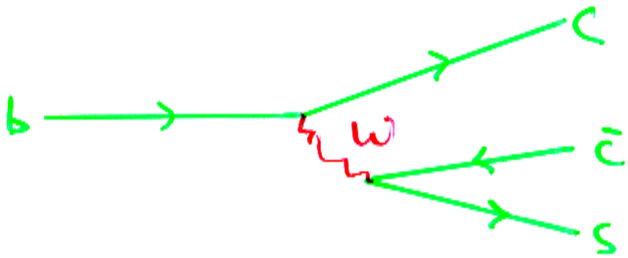
- m_B



$+ \cdots$

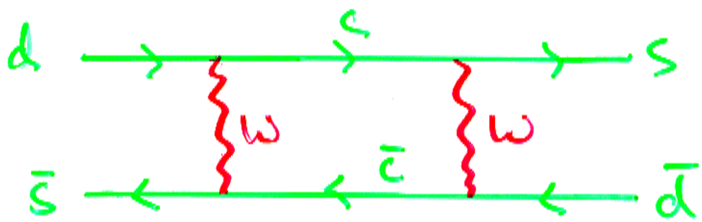
$$\arg m_B = \arg\left(V_{td}^2 V_{tb}^{*2}\right) = -2\beta$$

- $a_{\psi K_S}$



$$\arg a_{\psi K_S} = \arg\left(V_{cb} V_{cs}^*\right) = 0$$

- m_K

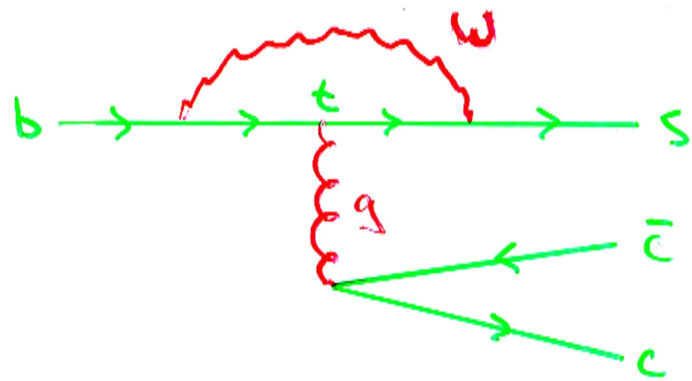


$$\arg m_K = \arg\left(V_{cd}^2 V_{cs}^{*2}\right) = 0$$

$$\Rightarrow \text{Im}\,\lambda_{CP} \simeq \underline{\sin 2\beta} \qquad (B-\bar{B}\text{ mixing})$$

Corrections to $a_{\psi K_s}$ from "penguins"

$a'_{\psi K_s} \sim$

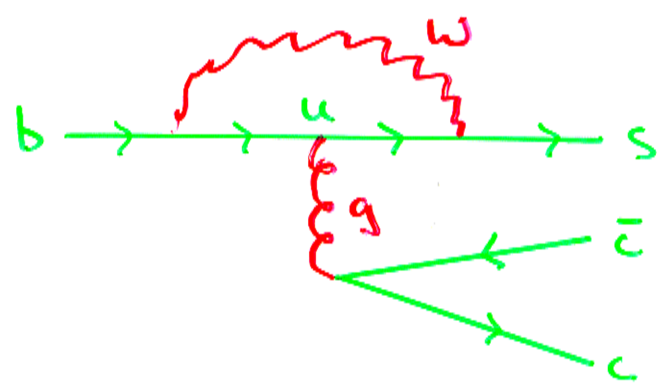


New operator : $\bar{b}\gamma^\mu T^a s\, \bar{c}\gamma_\mu T^a c$

$\arg(a'_{\psi K_s}) = \arg(V_{tb}V_{ts}^*) = O(\lambda^2)$

$\Rightarrow \arg(a_{\psi K_s} + a'_{\psi K_s}) = \arg(a_{\psi K_s}) + O(\lambda^2)$

$a''_{\psi K_s} \sim$



$\arg(a''_{\psi K_s}) = \arg(V_{ub}V_{us}^*) = -\gamma$

But $\dfrac{V_{ub}V_{us}^*}{V_{tb}V_{ts}^*} \simeq \lambda^2$; penguin loop suppression

THEORETICALLY CLEAN

Current constraints on $\sin 2\beta$

Global fit: V_{ub}, ΔM_d, ε_K

$0.4 \lesssim \sin 2\beta \lesssim 0.8$ BaBar Physics Book

$0.65 \lesssim \sin 2\beta \lesssim 0.77$ Parodi, Roudeau, Stocchi

CDF: $\sin 2\beta = 0.79 \, ^{+0.41}_{-0.44}$

$0.00 \leq \sin 2\beta \leq 1.00$ at 93% c.l.

The sign is consistent with K physics!

Eventual accuracy on $\sin 2\beta$?

Expt.	$\delta \sin 2\beta$
BaBar / BELLE D0 / CDF / HERA-B	0.05 – 0.10
BTeV / LHCb ATLAS / CMS	0.01 – 0.02

$B \to \pi\pi$

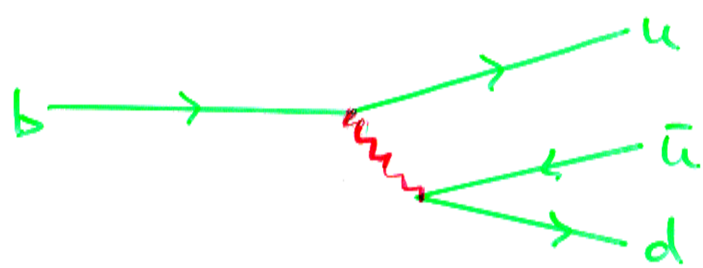
$$\begin{tikzcd} B^0 \arrow[r, "M_B"] \arrow[dr, "a_{\pi\pi}"'] & \bar{B}^0 \arrow[d, "a^*_{\pi\pi}"] \\ & \pi^+\pi^- \end{tikzcd}$$

$$\arg \lambda_{CP} = \arg M_B + 2 \arg a_{\pi\pi}$$

Standard Model

- $\arg M_B = -2\beta$

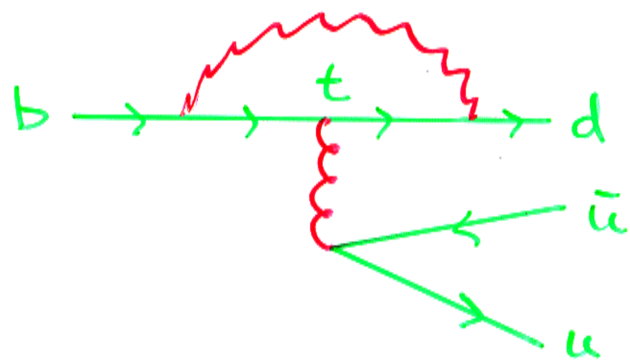
- $a_{\pi\pi}$



$$\arg a_{\pi\pi} = \arg (V_{ub} V^*_{ud}) = -\gamma$$

$$\Rightarrow \text{Im}\, \lambda_{CP} = -\sin(2\beta + 2\gamma) = \underline{\sin 2\alpha}$$

Corrections to $a_{\pi\pi}$ from "penguins"

$a'_{\pi\pi} \sim$ 

$$\arg a'_{\pi\pi} = \arg(V_{tb} V_{td}^*) = \beta$$

Two operators with different phases and matrix elements

$\bar{b}\gamma^\mu(1-\gamma^5)u\,\bar{u}\gamma_\mu(1-\gamma^5)d$ $\quad e^{-i\gamma}$ $\quad |V_{ub}V_{ud}^*| \simeq \lambda^3$

$\bar{b}\gamma^\mu T^a d\,\bar{u}\gamma_\mu T^a u$ $\quad e^{i\beta}$ $\quad |V_{tb}V_{td}^*| \simeq \lambda^3$
$\times$ loop factor

Are penguin matrix elements enhanced, to compensate loop suppression?

- Penguins dominate $B \to K\pi$
- $B \to K\pi$ larger than $B \to \pi\pi$

$$0.2 \lesssim \left|\frac{P}{T}\right| \lesssim 0.5$$

$B \to \pi\pi$ does not measure cleanly the phase of a single operator in the effective theory at $\mu \lesssim 10$ GeV

Solutions ?

Exploit isospin structure

$\bar{b}\gamma^\mu(1-\gamma^5)u\bar{u}\gamma_\mu(1-\gamma^5)d$ $\quad\Delta I = \frac{1}{2}, \frac{3}{2}$

$\bar{b}\gamma^\mu T^a d\bar{u}\gamma_\mu T^a u$ $\quad\Delta I = \frac{1}{2}$

1. Gronau and London — PRL 65, 3381, '90

   Measure $B \to \pi^+\pi^-, \pi^0\pi^0, \pi^\pm\pi^0$

   Problem: $B^0 \to \pi^0\pi^0$ too hard, too rare

2. Quinn and Snyder — PRD 48, 2139, '93

   Measure $B \to (\rho^-\pi^+, \rho^+\pi^-, \rho^0\pi^0) \to \pi^+\pi^-\pi^0$

   Dalitz plot analysis

   Need thousands of events

☆ Can B Factories do this ?

☆ Can BTeV or LHCb ?

Extraction of γ

$$V_{ub} = |V_{ub}| e^{-i\gamma}$$

Direct $\not{CP}$: $b \to u \bar{u} d', u \bar{c} d'$

Requires strong phase, too, which must be extracted from the analysis (δ)

- $B^\pm \longrightarrow (D^0, \bar{D}^0) K^\pm \to f_i K^\pm \quad i = 1, 2$

  Triangle construction from rates $\Rightarrow \sin(\gamma \pm \delta)$
  Total BR $\sim 10^{-7}$: statistics ?

- $B_s \to D_s K^\pm$

  Rate asymmetry, theoretically clean
  BTeV or LHCb

- $B \to K\pi$

  Combinations of rates
  Additional assumptions – rescattering effects, penguin contributions, SU(3), factorization

  Careful !

V_{ub} from $b \to u \ell \bar{\nu}_e$

$$\boxed{\bar{u}\, \gamma^\mu (1-\gamma^5)\, b \;\; \bar{\ell}\, \gamma_\mu (1-\gamma^5)\, \nu_e}$$

Background from $b \to c \ell \bar{\nu}_e$

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} \lesssim 0.01$$

Kinematic cuts in $B \to X_u \ell \nu$

$$\left.\begin{array}{l} \bullet\ E_\ell \gtrsim 2.3 \text{ GeV} \\ \bullet\ M(x) \lesssim 1.8 \text{ GeV} \end{array}\right\} \text{exclude charm}$$

Theory
- $\Gamma(B \to X_u \ell \nu)$ model-independent

  $\delta m_b = 100$ MeV $\to$ uncertainty $\sim 10\%$

- $\Gamma(B \to X_u \ell \nu)\Big|_{\text{severe kinematical restriction}}$ needed

  $\Rightarrow$ dependence on $|\vec{p}_b|$ in B

$\Rightarrow$ Irreducible model-dependence

a) Recent LEP average from $B \to X_u \ell \nu$

$$|V_{ub}| = 4.05^{+0.62}_{-0.74}$$

or $$\left|\frac{V_{ub}}{V_{cb}}\right| = 0.104^{+0.153}_{-0.183}$$ (~15% error)

- Uses $M(X)$ and E_ℓ to reject $b \to c \ell \nu$
- Very dependent on B meson model
  - → typically, two-parameter fit to $\psi(\vec{p}_b)$

  but spectrum depends on all details of $\psi(\vec{p}_b)$

⇒ Error estimate is EXTREMELY SOFT

b) Recent CLEO average from $B \to \rho \ell \nu$

$$|V_{ub}| = 3.25^{+0.61}_{-0.64}$$ (~ 20% error)

- $\langle \rho | \bar{u} \gamma^\mu (1-\gamma^5) b | B \rangle$ from models

⇒ Error estimate is EXTREMELY SOFT

V_{ub} is very important constraint on ρ, η

Prospects . . .

1) $B \to X_u \ell\nu$
   - loosen kinematic cuts ?
   - q^2 spectrum may be better behaved theoretically (Bauer, Ligeti, Luke)

2) $B \to \rho \ell\nu$
   - need $\langle \rho | \bar{u} \gamma^\mu (1-\gamma_5) b | B \rangle$

     - lattice ($\vec{p}_\rho \simeq 0$ region)
     - heavy quark symmetry $\Leftrightarrow$ $D \to K^* \ell\nu$ (size of corrections ?)
     - models (QCD sum rules, quark models)

3) Inclusive nonleptonic decays
   - $b \to u\bar{c}s$
   - theoretically clean, experimentally "challenging" (AF, Petrov; Chay, AF, Luke, Petrov)

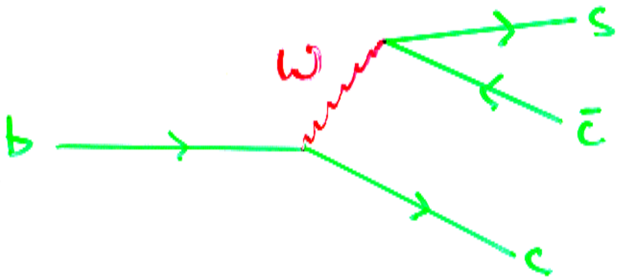
Strategies for testing Standard Model

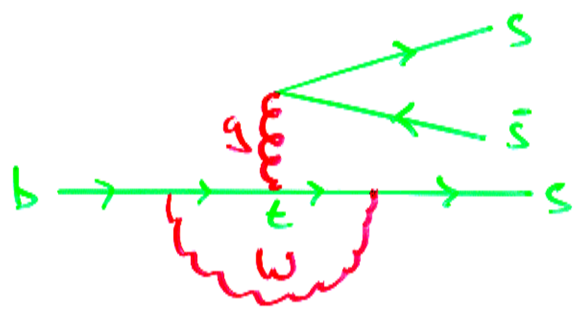
1) $B \to \psi K_s$ vs. $B \to \phi K_s$

Grossman, Worah, PLB395, 241, '97

SM : both measure phase of $B - \bar{B}$ mixing

Decay amplitudes :





$B \to \psi K_s$	$B \to \phi K_s$
λ^2, tree	λ^2, loop
$\boxed{\bar{c}\gamma^\mu(1-\gamma^5)b\,\bar{s}\gamma_\mu(1-\gamma^5)c}$	$\boxed{\bar{s}\gamma^\mu T^a b\,\bar{s}\gamma_\mu T^a s}$

New physics more important in $\bar{s}\gamma^\mu T^a b\,\bar{s}\gamma_\mu T^a s$?

Compare "$\sin 2\beta$" from $B \to \psi K_s$ and $B \to \phi K_s$

2) New physics in B-$\bar{B}$ mixing

Grossman, Nir, Worah, PLB 407, 307, '97

$B \to \psi K_s$ $\qquad \arg M_B + \underbrace{2\arg A(B\to\psi K_s)}_{\emptyset \text{ in SM}} + \arg M_K$

$B \to \pi\pi(\pi)$ $\qquad \arg M_B + \underbrace{2\arg A(B\to\pi\pi)}_{-2\delta \text{ in SM}}$

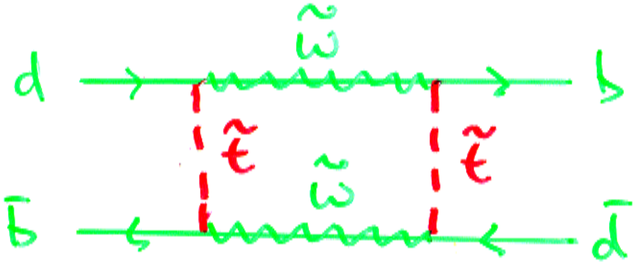
a) Compare $\Rightarrow$ extract γ, independent of M_B

b) Measure $\frac{|V_{ub}|^2}{|V_{cb}|^2}$ from $b \to u l \nu$ $\Rightarrow$ $\rho^2 + \eta^2$

(a) + (b) fixes $\rho, \eta \Rightarrow$ fixes β

Then compare this β to $\arg M_B$ from $B \to \psi K_s$

Sensitive to



Future Program - Expt. and Theory

K Physics

1) ε_K : need better V_{cb}
   need better hadronic matrix elements

2) $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

$!

3) $K^0 \rightarrow \pi^0 \nu \bar{\nu}$

B Physics

	constrains	do it where?
1) $B \to \psi K_s$	β	B Factories CDF, DØ BTeV, LHCb LHC expts.
2) $B \to X_u \ell \nu$	$\rho^2 + \eta^2$	B Factories
3) ΔM_s (w/ ΔM_d)	$\eta^2 + (1-\rho)^2$	CDF
4) $B \to \rho\pi$	$\beta + \gamma$ (α)	B Factories? BTeV, LHCb?
5) $B_s \to D_s K$	γ	BTeV, LHCb
6) $B \to DK$	γ	B Factories? BTeV, LHCb?

. . . and many other modes . . .

Important roles for

- B Factory expts. : BaBar, BELLE, CLEO-III
- CDF/DØ at Run II ; HERA-B
- Hadronic B expts. : BTeV, LHCb

A few concluding remarks about the quark sector...

- Every measurement of a new operator is significant. "Redundancy" is essential!

- One theoretically clean measurement is worth ten dirty ones. But dirty ones help!

- We are not simply...
  - measuring (ρ, η)
  - measuring (α, β, γ)
  - looking for $\not{CP}$ in the B system

  We are trying to learn as much as possible about the physics of flavor

- When new phenomena are seen at Run II or LHC, "low energy" physics will be crucial in helping us understand what the new phenomena are, and what they are <u>not</u>!

Lepton Flavor

Lepton quantum numbers

	SU(3)	SU(2)	U(1)
$L_L^i = \begin{pmatrix} \nu_L^i \\ E_L^i \end{pmatrix}$	-	2	$-\frac{1}{2}$
E_R^{i*}	-	-	1

Masses forbidden by gauge invariance

"Higgs":

Φ	-	2	$\frac{1}{2}$

Yukawa couplings $\quad \lambda_L^{ij} E_R^{i*} \tilde{\Phi} L_L^j$

$$\langle \tilde{\Phi} \rangle \sim \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$\Rightarrow$ masses for charged leptons

No other Yukawas $\Rightarrow$ charged-current interactions can be diagonalized

Neutrino masses would require coupling of the form

$$\lambda N \Phi L_L$$

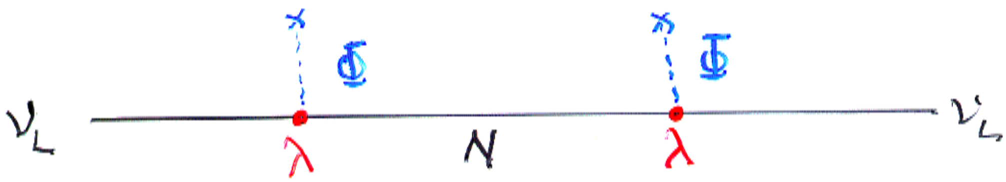
N = new fermion, $SU(3) \times SU(2) \times U(1)$ singlet

There is no reason for an SM gauge singlet fermion to be light. This is, in every sense, physics beyond the Standard Model!

Suppose there is new physics at a scale M

$M \sim M_{GUT} \sim 10^{16}$ GeV?

Naturally, $m_N \sim M \rightarrow N$ only appears <u>virtually</u>



So $m_\nu \sim \lambda\langle\Phi\rangle \cdot \frac{1}{m_N} \cdot \lambda\langle\Phi\rangle \sim \frac{M_{weak}^2}{M}$

Or maybe new physics is more complicated...

$$\frac{1}{M}\left(\Phi L_L\right)^2 \rightarrow \frac{M_{weak}^2}{M}\nu_L\nu_L$$

In either case, it is natural to expect:

- Majorana masses for neutrinos (no light right-handed state)
- $m_\nu \sim \frac{M_{weak}^2}{M} \times (\text{Yukawa couplings})^2$

For $M \sim M_{GUT}$, charged lepton Yukawas,

$$m_\nu \sim \underset{\lambda_e}{10^{-11}\,eV} \;-\; \underset{\lambda_\tau}{10^{-6}\,eV} \;-\; \underset{1}{10^{-3}\,eV}$$

- Even if N is light (how?), you can't observe it directly (but then ν_L's would be heavier)

Majorana masses $\Rightarrow$ CKM matrix for leptons

Tiny masses — use weak eigenstates

$\Downarrow$

Observable phenomenon is neutrino mixing

$$\nu_1 \longrightarrow (\nu_2, \nu_3, N)$$

$\uparrow$ if N light

Direct bounds on ν masses:

ν state	endpoint spectrum of
$m(\nu_e) \lesssim 3\,\text{eV}$	${}^3H \to {}^3He + e^- + \bar{\nu}_e$
$m(\nu_\mu) \lesssim 170\,\text{keV}$	$\pi^+ \to \mu^+ + \nu_\mu$
$m(\nu_\tau) \lesssim 18\,\text{MeV}$	$\tau \to 5\pi + \nu_\tau$

Evidence for Oscillations

1) Solar ν problem

some ν_e missing

Δm^2 : 10^{-9} — 10^{-4} eV^2

$\sin 2\theta$: ~ 1 small or ~ 1

vacuum osc. MSW (matter)

2) Atmospheric ν problem

$\downarrow$ cosmic rays

$\downarrow \pi^+$

$\downarrow \mu^+ + \nu_\mu$

$\downarrow e^+ + \bar{\nu}_\mu + \nu_\mu + \nu_e$

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \simeq 2:1$$

ν_μ missing, after passing through earth

Δm^2 : $10^{-4} - 10^{-3}$ eV^2

$\sin 2\theta$: close to 1

Current paradigm:

$\nu_e \to \nu_\mu$ solar (large or small mixing)

$\nu_\mu \to \nu_\tau$ (or N) atmosphere (maximal mixing)

ν_τ ——— $10^{-2} - 10^{0}$ eV

ν_e, ν_μ ═══ $10^{-4} - 10^{-2}$ eV

Mixing matrix might look like

$$U \simeq \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}}_{\text{maximal}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}}_{\cancel{CP}} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

No need for small mixing angle. s_{12}

Fly in the ointment ...

LSND $\bar{\nu}_\mu \to \bar{\nu}_e$

$$\Delta m^2 \sim 10^{-1} - 10^{0}\ \mathrm{eV}^2$$

- No confirmation from KARMEN
- To be checked definitively by MiniBooNE

Why is LSND trouble?

3 Δm^2's in 3-ν system

$\Downarrow$

Δm^2's must sum to zero

$\Downarrow$

not possible w/ solar, atmospheric, LSND

LSND requires (w/ other two) a light N!

This is really beyond the Standard Model!

Issues for the future

$\nu_\mu \rightarrow$ what? at $\Delta m^2 \sim 10^{-3}\,eV^2$

MINOS, K2K : confirmation of disappearance, in an accelerator experiment

$\nu_\mu \rightarrow A\,\nu_e + B\,\nu_\tau + C\,N$

N ← anything else!

$|A|^2 + |B|^2 + |C|^2 = 1$ in some units

$|A|^2$ highly constrained ($\lesssim 10^{-2}$) by reactor experiments (e.g. CHOOZ)

$\dfrac{|B|^2}{|C|^2}$ information from $\dfrac{NC}{CC}$ at SuperK

($B=0$, $C=1$) is highly disfavored (ruled out soon?)

Observation of a few ν_τ's (via τ appearance) would rule out ($B=0$, $C=1$). Too late?

Observation of ~100 ν_τ's would measure $\dfrac{|B|^2}{|C|^2}$

This is the goal worth pursuing!

Which solution to the solar neutrino problem is right?

vacuum oscillations?

MSW (matter) oscillations?

the sun? Not likely!

Superkamiokande: lower thresholds
→ better spectrum information

SNO: neutral and charged currents
→ sensitive to ν_μ's

Borexino: low threshold
sensitive to $E_\nu = 862$ keV from ^{7}Be,
which is suppressed in MSW

ν Factory based on μ storage ring !?

Huge flux = high sensitivity

- at $\Delta m^2 \sim 10^{-3}\, eV^2$
  - see ν_τ's
  - measure $|A|^2 \propto |U_{e3}|^2$, which is small

    what is a physics-driven goal?

- $\cancel{CP}$ in ν oscillations need not be CKM suppressed

Measure, e.g., $\dfrac{(\nu_e \to \nu_\mu) - (\bar{\nu}_e \to \bar{\nu}_\mu)}{(\nu_e \to \nu_\mu) + (\bar{\nu}_e \to \bar{\nu}_\mu)}$

Experimental ν physics is entering its

Golden Age

SuperK
SNO
Borexino
K2K
MINOS
MiniBooNE
⋮

CERN → Gran Sasso
⋮

ν Factory

Finally....

I could have given a very different colloquium, and asked the crucial question:

What is the high-energy physics that breaks the flavor symmetries of the Standard Model?

Personally, I like this question more!

But before we can successfully speculate about high energies, we must unravel the mystery of flavor in our low-energy domain.