UNCOVERING THE WEAK INTERACTION

J. Rosner – Cronin Fest – September 8, 2006

From beta decay to giant air showers: 110 years in 30 minutes

Pauli's proposal of the neutrino (Dec. 4, 1930) is about 9 months older than Jim

Jim has been on the front line of uncovering the nature of the weak interaction

"Uncovering": Weak interactions often overlaid with the strong:

Nuclear beta-decay: $0 \to 0$ ("Fermi") transitions especially simple to describe

Parity violation: A key role was played by Dalitz's "phase space plots"

Nucleon axial-vector coupling: Related to strong-interaction parameters

Strange particle decays: S–P wave interference in nonleptonic hyperon decays; $\surd$
$K_{\mu 3}$ vs. K_{e3}; simple pattern of semileptonic hyperon beta-decays (Cabibbo) $\surd$

CP-violating amplitude in neutral kaon decays: Interpretation of its phase

Current algebra: essential features of quarks without needing to believe in them.

Charm and its role in unifying the weak and electromagnetic interactions $\surd$

The Kobayashi-Maskawa theory of CP violation; tests using B mesons $\surd$

NONLEPTONIC HYPERON DECAYS

Sorting out such decays as $\Sigma^+ \to \pi^+ n$, $\Sigma^+ \to \pi^0 p$, and $\Sigma^- \to \pi^- n$ [R. L. Cool, B. Cork, J. W. Cronin, and W. A. Wenzel, Phys. Rev. **114**, 912 (1959)] and $\Lambda \to \pi^- p$ [J. W. Cronin and O. E. Overseth, Phys. Rev. **129**, 1795 (1963)].

Context: M. Gell-Mann + A. H. Rosenfeld, Ann. Rev. Nucl. Sci. **7**, 407–478 (1957)

Parity violation had been seen in polarized Λ decays: up-down asymmetry of protons in $\Lambda \to \pi^- p$ produced in $\pi^- p \to \Lambda K^0$. Did it occur in Σ decays?

Amplitude for $(J = 1/2) \to (J = 0) + (J = 1/2)$: S-wave ("$s$," parity-violating) or P-wave ("p," parity-conserving). Decays are fully characterized by

$$\Gamma \sim |s|^2+|p|^2,\ \alpha \equiv 2\mathrm{Re}(sp^*)/(|s|^2+|p|^2),\ \beta \equiv 2\mathrm{Im}(sp^*)/(|s|^2+|p|^2)$$

$$\gamma \equiv (|s|^2 - |p|^2)/(|s|^2 + |p|^2)\ ,\quad \alpha^2 + \beta^2 + \gamma^2 = 1\ .$$ β: T-violating

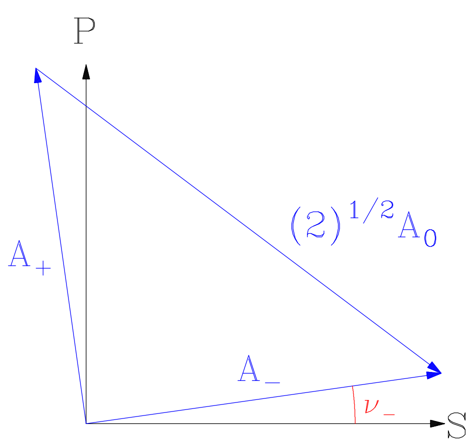
Measure $\alpha\mathcal{P}$ ($\mathcal{P}$ = hyperon polarization) via asymmetry with respect to plane formed by incident beam and recoiling hyperon, e.g. in $\pi^- p \to \Sigma^- K^+$ or $\pi^+ p \to \Sigma^+ K^+$.

Found $\alpha(\Sigma^+ \to \pi^0 p)\mathcal{P}(\Sigma^+) = 0.70 \pm 0.30$, with $\alpha(\Sigma^+ \to \pi^+ n)\mathcal{P}(\Sigma^+) = 0.02 \pm 0.07$ for initial beam momentum 1 GeV/c, and $\alpha(\Sigma^- \to n\pi^-)\mathcal{P}(\Sigma^-)$ consistent with 0 at beam momenta 1 and 1.1 GeV/c. Parity violation is large in $\Sigma^+ \to \pi^0 p$.

$\Sigma \to \pi N$ INTERPRETATION

Observations: (1) Rates for all three $\Sigma \to \pi N$ decays are nearly equal;
(2) Nonleptonic weak interaction greatly favors $\Delta I = 1/2$ over $\Delta I = 3/2$

$\Delta I = 1/2$ rule implies $A_+ + \sqrt{2}A_0 = A_-$ (subscript = pion charge), so amplitudes $A_\pm$ and $\sqrt{2}A_0$ form an isosceles right triangle



Can show $\alpha^- = -\alpha^+ = \sin 2\nu_-$; $\alpha^0 = \pm\cos 2\nu_-$

$\pm$: Triangle could have been drawn reflected about A_-

In context of equal rates for all $\Sigma \to \pi N$ decays and $\Delta I = 1/2$ rule, interpreted data to imply $\alpha^+ = -\alpha^- \le \pm(0.03 \pm 0.11), \alpha^0 = \pm(0.99 \pm 0.01)$

2006: $\alpha^+ = 0.068 \pm 0.013$, $\alpha^- = -0.068 \pm 0.008$, $\alpha^0 = -0.980^{+0.017}_{-0.015}$

MEASUREMENT OF (α, β) IN $\Lambda \to \pi^- p$

Only $\alpha\mathcal{P}$ from up-down asymmetry; for α need p polarization in $\Lambda \to \pi^- p$

Cronin and Overseth: $\mathcal{P}(p)$ from scattering in carbon plates $\Rightarrow \alpha = 0.62 \pm 0.07$ (present: 0.642 ± 0.013); $\beta = 0.18 \pm 0.24$ (present: $\tan^{-1}(\beta/\alpha) = (8 \pm 4)^\circ$)

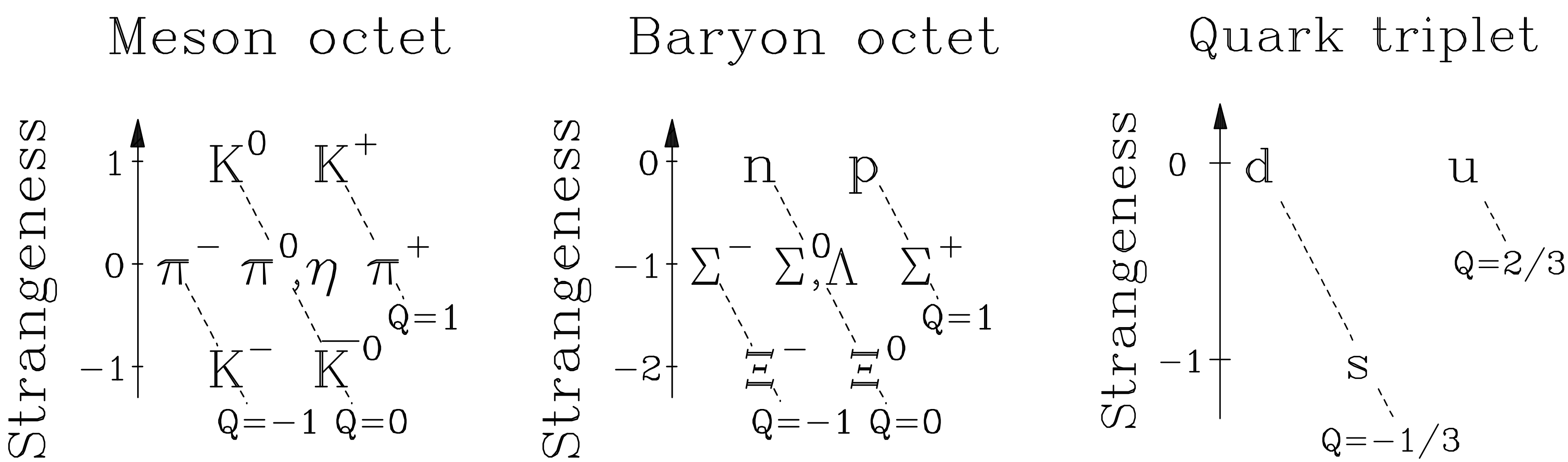
Found $|p/s|$ small; with hypernuclei info. implied odd relative $K\Lambda N$ parity

STRANGE PARTICLE SEMILEPTONIC DECAYS

Strangeness-changing $|\Delta S| = 1$ weak decays suppressed in comparison with $\Delta S = 0$

Gell-Mann and Lévy (1960) proposed a weak current taking $p \leftrightarrow n\cos\theta + \Lambda\sin\theta$

Cabibbo generalized this; in quark language $u \leftrightarrow d\cos\theta + s\sin\theta$



Implies $\Delta S = \Delta Q$ in weak semileptonic decays and successfully describes $n \to pe^-\bar{\nu}_e$, $\Lambda \to pe^-\bar{\nu}_e$, $\Sigma^- \to \Lambda e^-\bar{\nu}_e$, $\Sigma^- \to ne^-\bar{\nu}_e$, $\Xi^- \to (\Sigma^0,\Lambda)e^-\bar{\nu}_e$, $\Xi^0 \to \Sigma^+e^-\bar{\nu}_e$, $K^- \to \pi^0e^-\bar{\nu}_e$, $\bar{K}^0 \to \pi^+e^-\nu_e$, and other semileptonic decays.

Latest average (including key Chicago measurement): $\sin\theta = 0.2257 \pm 0.0021$

WEAK LEPTONIC, HADRONIC CURRENTS

Fermi interaction (including parity violation) described by a Hamiltonian density

$$\mathcal{H}_W = (G_F/\sqrt{2})(J^{\rm lepton} + J^{\rm hadron})_\alpha(J^{\dagger\ \rm lepton} + J^{\dagger\ \rm hadron})^\alpha$$

Since 1962 it was known that each lepton e^-, μ^- had its own neutrino ν_e, ν_μ

Weak charge-changing current $J_\alpha^{\rm lepton} = \bar\nu_e\gamma_\alpha(1-\gamma_5)e + \bar\nu_\mu\gamma_\alpha(1-\gamma_5)\mu$

Weak leptonic current satisfies *current commutation relations*: $Q^{(-)} = Q^{(+)\dagger}$

$$Q^{(+)} \equiv (1/2)\int d^3x J_0^{\rm lepton},\ Q_3 \equiv (1/2)[Q^{(+)}, Q^{(-)}],\ [Q_3, Q^{(\pm)}] = \pm Q^{(\pm)}$$

These are just the commutation relations of SU(2), with $Q^{(\pm)}$ acting as a "raising operator," and serve to normalize the leptonic current

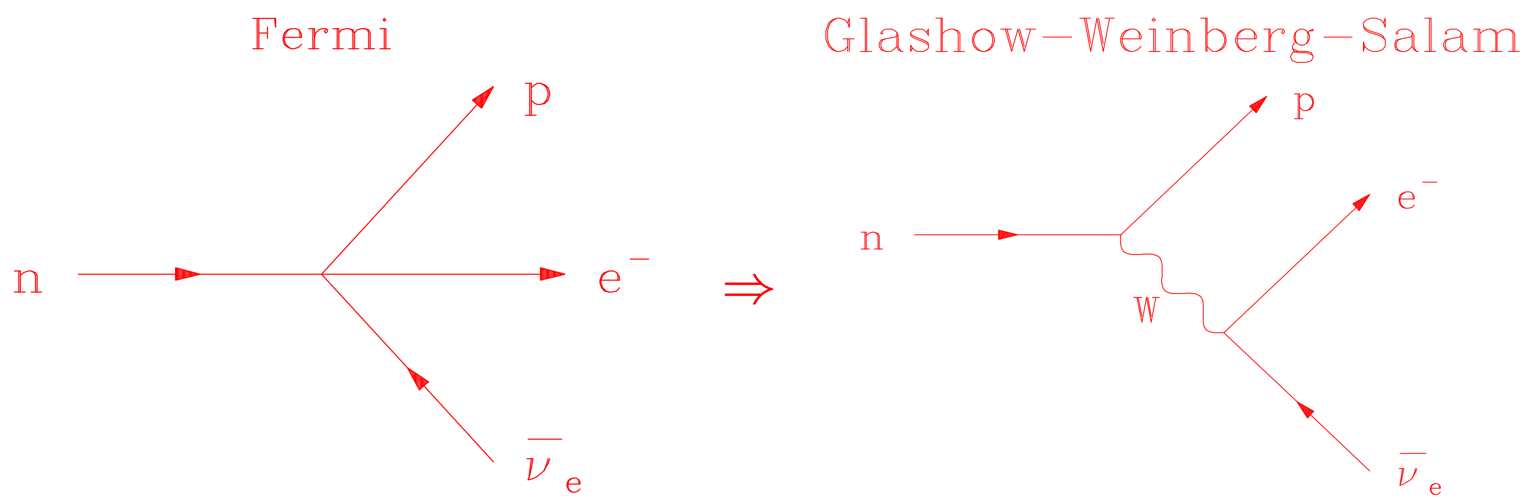
Gell-Mann (1962) proposed similar commutation relations [for SU(3) and vector, axial currents] to normalize the weak currents of *hadrons*

With $J_\alpha^{\rm hadron} = \bar u\gamma_\alpha(1-\gamma_5)(d\cos\theta + s\sin\theta)$, $Q_3^{\rm hadron}$ has terms inducing $s \leftrightarrow d$

Harmless if Q_3 doesn't couple to anything. Glashow-Weinberg-Salam electroweak unification said it *does*, hence Weinberg's title "A Theory of Leptons"

FROM FERMI TO ELECTROWEAK THEORY

Many proposals that weak interactions were due to exchange of an intermediate boson: Yukawa, Klein, Schwinger, . . ., to avoid singular 4-fermion interaction



Charged W's would be members $(W_1 \pm iW_2)/\sqrt{2}$ of an SU(2) triplet.

Photon could not be the neutral member; its coupling doesn't violate parity.

Glashow: Extension to SU(2) $\times$ U(1) $\rightarrow$ additional neutral boson Z $(M_Z > M_W)$

Photon and Z are then orthogonal mixtures of W_3 and the U(1) boson B

Weinberg-Salam: Symmetry breaking via the Higgs mechanism

NEUTRAL CURRENTS AND CHARM

Leptonic Q_3 takes $e \leftrightarrow e$, $\mu \leftrightarrow \mu$, $\nu_e \leftrightarrow \nu_e$, $\nu_\mu \leftrightarrow \nu_\mu$. Arrange for quarks?

Bjorken-Glashow, others (1964): quark-lepton analogy allows banishment of hadronic $s \leftrightarrow d$ currents by introducing a second quark c ("charm") with charge $Q = 2/3$:

$$J_\alpha^{\rm hadron} = \bar{u}\gamma_\alpha(1-\gamma_5)(d\cos\theta + s\sin\theta) + \bar{c}\gamma_\alpha(1-\gamma_5)(-d\sin\theta + s\cos\theta)$$

Calculate Q_3 for hadrons and you will find it takes $u \leftrightarrow u$, $c \leftrightarrow c$, $d \leftrightarrow d$, and $s \leftrightarrow s$, i.e., it has *no flavor-changing neutral currents*

Leptons	Quarks	Quark mixing
$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$ $\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$	$\begin{pmatrix} u \\ d' \end{pmatrix}$ $\begin{pmatrix} c \\ s' \end{pmatrix}$	$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$

Two families of quarks and leptons; orthogonal mixing matrix for quarks

Glashow-Iliopoulos-Maiani (1970): charmed quark suppressed induced flavor-changing neutral currents in higher-order calculations (such as K^0–$\overline{K}^0$ mixing).

Gaillard-Lee (1973): Calculation in the new electroweak theory of cancellations due to charm in many rare kaon decays. Estimated that the charmed quark could have a mass of no more than 2 GeV/c^2. Hints at London (1974) Conference.

QUANTUM CHROMODYNAMICS AND CHARM

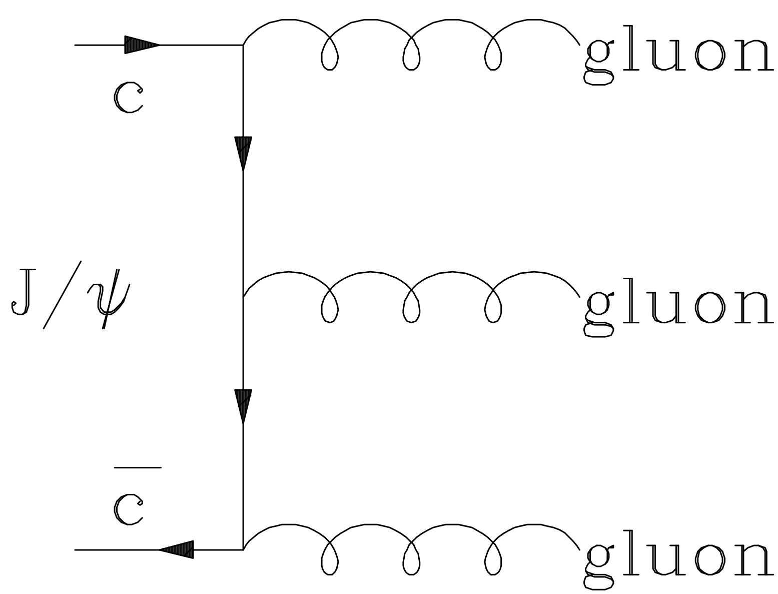
First hints of charm: short tracks in nuclear emulsion (Niu *et al.*, 1971)

Convincing discovery: Narrow $^3S_1$ $c\bar{c}$ ground state J/ψ (Ting/Richter, 1974)

Validated not only charm but also reality of quarks and applicability of QCD

QCD (quantum chromodynamics) developed as a strong-interaction theory which would preserve current algebra: vector-like theory; asymptotic freedom

Appelquist-Politzer: Lowest $c\bar{c}$ $^3S_1$ state was expected in QCD to have $\Gamma < 1$ MeV:

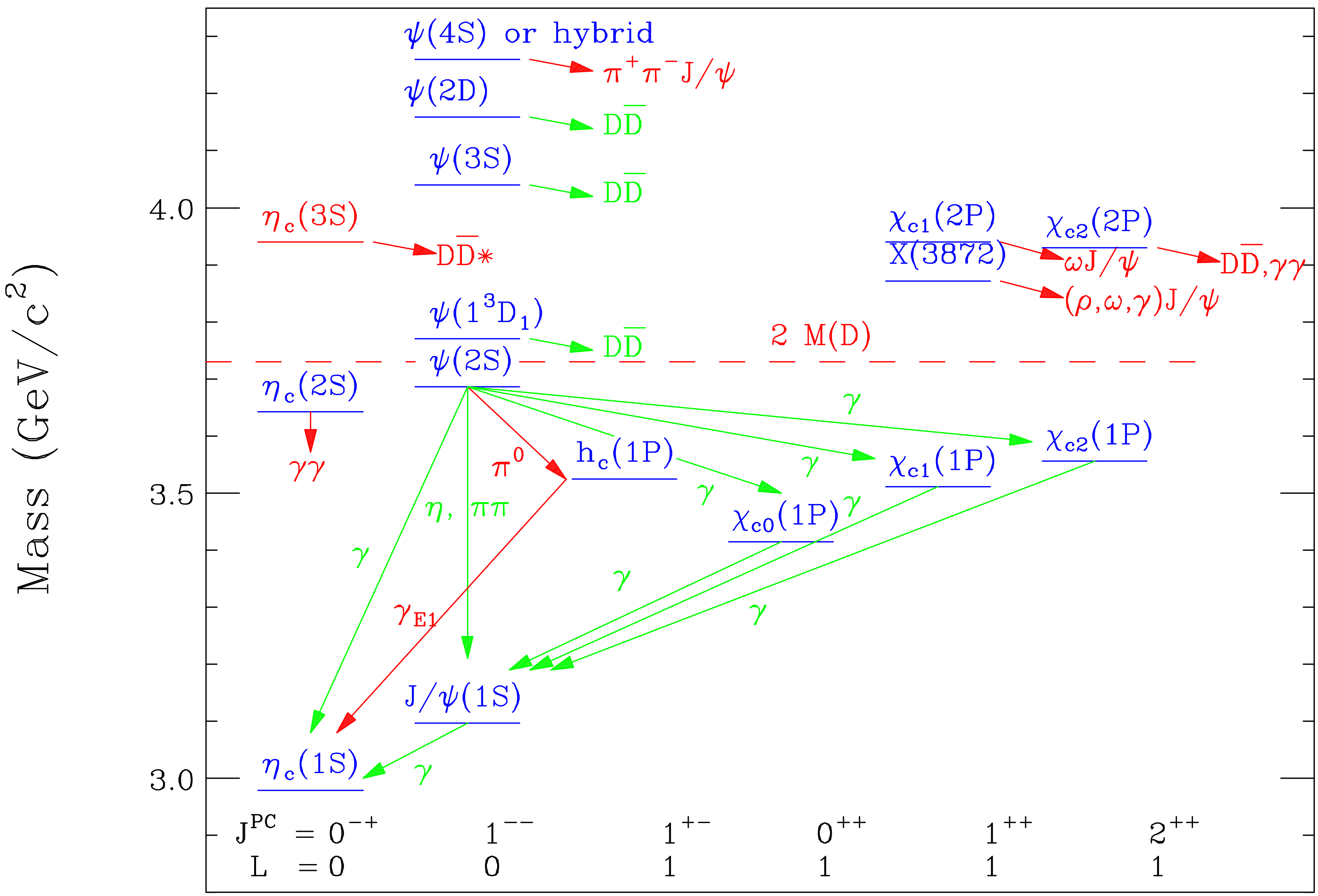


$\Gamma(J/\psi \to 3 \text{ gluons}) \sim \alpha_s^3$ $[\alpha_s(m_c) \simeq 0.3]$; small 3-body phase space ($\sim$ orthopositronium)

Observed 3-gluon width is even smaller than anticipated as a result of relativistic effects; $\Gamma_{\rm tot}(J/\psi) \simeq 0.1$ MeV

Charmonium has evolved into a fertile QCD laboratory: more known states than positronium

CHARMONIUM SPECTRUM



Red arrows: past year or two (BaBar, Belle, CLEO, CDF, . . .)

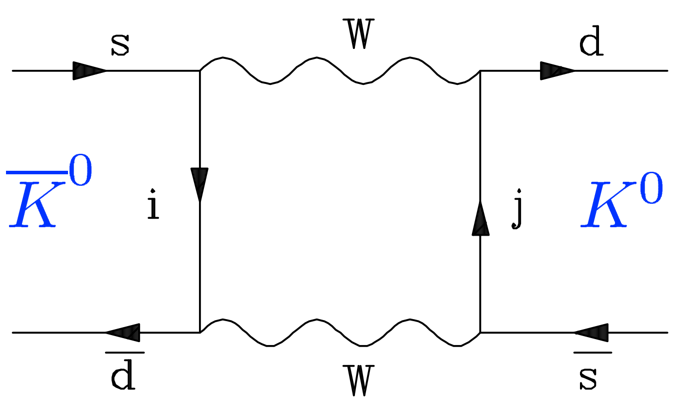
Test bed for lattice, leading candidate for dealing with long-distance QCD

KOBAYASHI-MASKAWA AND CP VIOLATION

Kobayashi and Maskawa (1973) took charm seriously; noted with only (u, d) and (c, s) could always choose charge-changing couplings to be real.

With additional pair of quarks (t for "top" and b for "bottom" or "beauty") this was no longer so; got physically meaningful complex phases in couplings describing charge-changing weak interactions, leading to CP violation

Effect in neutral kaon decays mainly is to induce CP-violating K^0–$\overline{K}^0$ mixing through box diagrams dominated by the heavy top quark contribution, e.g.:



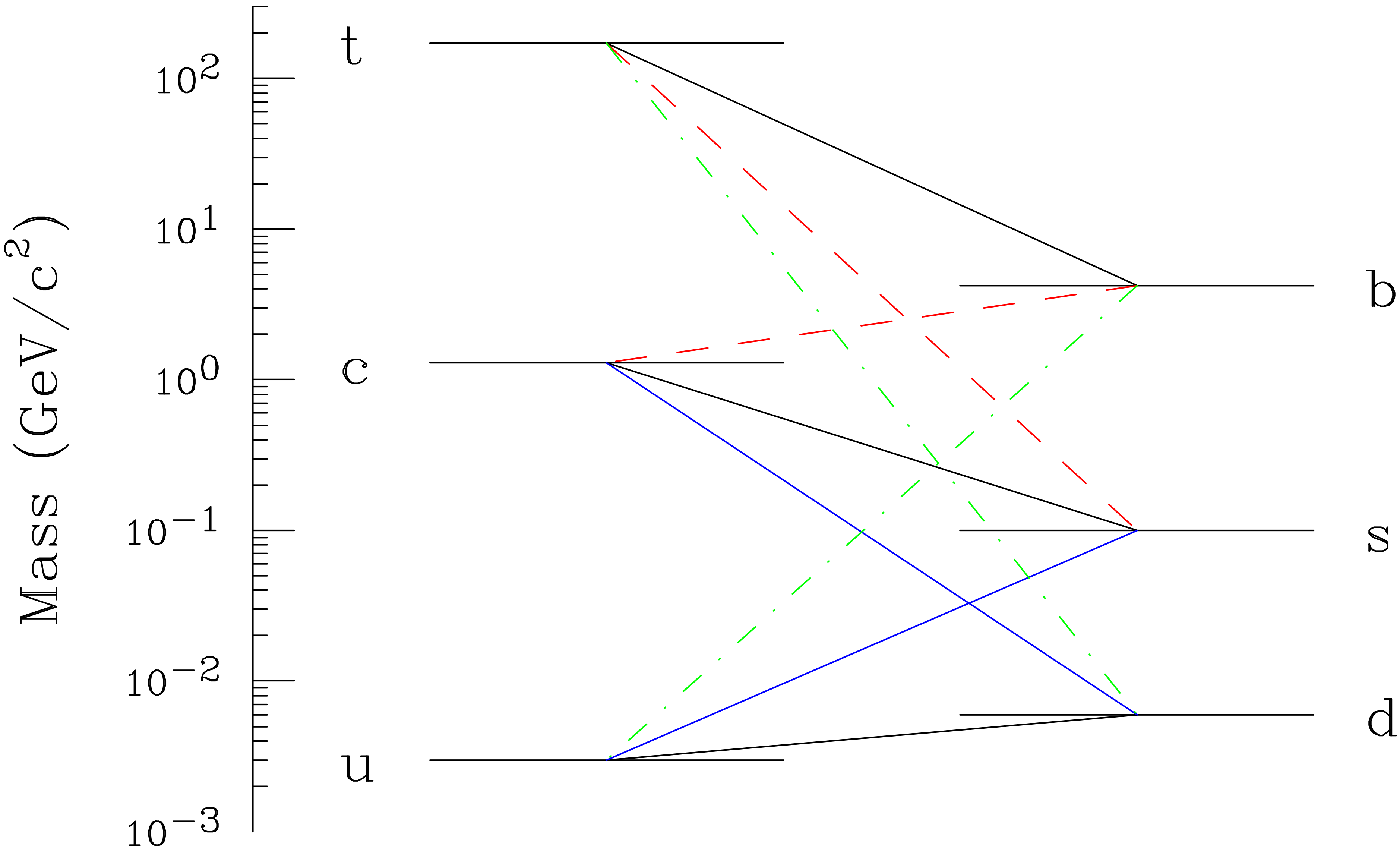
Here $i, j = (u, c, t)$. Standard parametrization: Non-removable phase in t-d-W coupling V_{td}

CP-violating mixing $\sim$ Im(V_{td}^2)

Key predictions: (1) Direct CP violation in $K \to \pi^+\pi^-$ vs. $\pi^0\pi^0$ (Winstein); (2) Large CP violation in B meson decays (Bigi–Carter–Sanda)

Study with asymmetric e^+e^- colliders (P. Oddone) at KEK and SLAC

PATTERN OF QUARK COUPLINGS



Couplings described by unitary matrix matrix V: $V_{ud} \simeq V_{cs} \simeq 0.974$, $V_{tb} \simeq 1$,
$V_{us} \simeq -V_{cd} \simeq 0.226$, $V_{cb} \simeq -V_{ts} \simeq 0.041$, $V_{td} \simeq 0.008e^{-i\ 21^\circ}$, $V_{ub} \simeq 0.004e^{-i\ 60^\circ}$

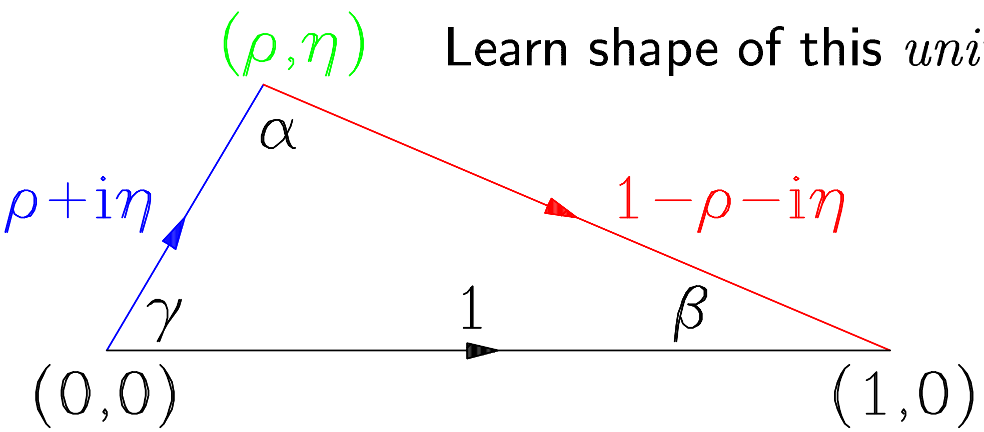
THE UNITARITY TRIANGLE

Parametrization invented by L. Wolfenstein; large phases in V_{td} and V_{ub}:

$$V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \simeq \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

and no redefinition of the quark phases can get rid of the phase in V

Unitarity of this *Cabibbo-Kobayashi-Maskawa* (CKM) matrix ($V^\dagger V = 1$) implies (e.g.) $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ or (rescaling) $(\rho + i\eta) + (1 - \rho - i\eta) = 1$



Learn shape of this *unitarity triangle* from various sources:

B–$\overline{B}$ mixing $\Rightarrow |1-\rho-i\eta|$

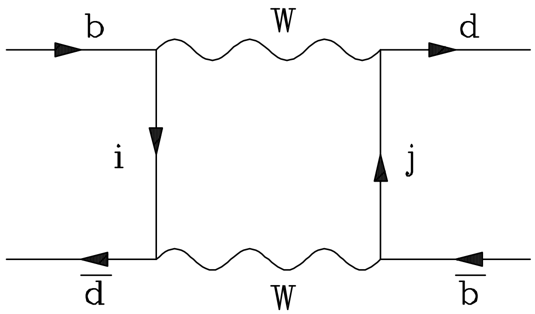
Charmless B decays $\Rightarrow |\rho + i\eta|$

Kaon CP violation $\Rightarrow \eta(1-\rho)$

Non-zero phases and large B–$\overline{B}$ mixing suggested in 1980s that CP violation in B meson decays would be *large* (vs. $\sim 10^{-3}$ in K^0 decays).

NEUTRAL B'S: MIXING AND CP VIOLATION

Loop diagram allows $b\bar{d} \leftrightarrow d\bar{b}$ transitions, quarks $i, j = u, c, t$ in loop



f_B^2 (B meson decay constant) governs matrix element of $b\bar{d} \leftrightarrow d\bar{b}$ operator

Parameter $B_B = 1$ if W exchange dominates

$f_B\sqrt{B_B}$ from lattice QCD, $\Delta m(B^0) \simeq 0.5$ ps^{-1} $\Rightarrow |V_{td}|$ to only $\sim 15\%$

Measurement of $|V_{ub}|$ through semileptonic B decays $\Rightarrow |\rho + i\eta| \simeq 0.4 \pm 0.1$

Strange B (B_s–$\overline{B}_s$) mixing: Same diagram with $d \to s$, $V_{ts} \simeq -V_{cb}$ well known

Mixing now observed (D0,CDF) CDF finds $\Delta m_s = 17.31^{+0.33}_{-0.18} \pm 0.07$ ps^{-1}

Constrains $|V_{td}/V_{ts}| = 0.208^{+0.008}_{-0.006}$ with $f_{B_s}\sqrt{B_{B_s}}/f_B\sqrt{B_B}$ from lattice

CP asymmetry in $B^0 \to J/\psi K_S$ (comparing rate with $\overline{B}^0 \to J/\psi K_S$) measures $\sin 2\beta = 0.674 \pm 0.026$ giving $\beta \simeq (21 \pm 1)^\circ$; B_s mixing $\Rightarrow \gamma \simeq (60^{+5}_{-4})^\circ$

Question addressable with a wealth of B decays: Is this picture sel f-consistent?

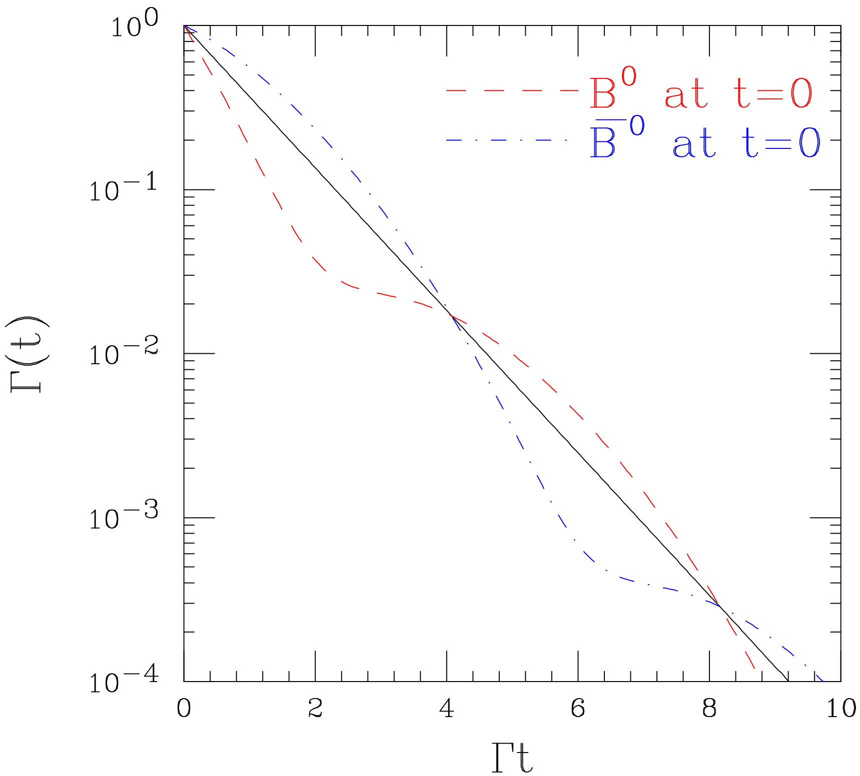
Answer: So far, so good, but there are a few things to watch.

CP ASYMMETRY IN $B^0 \to J/\psi K_S$

Produce $B^0\overline{B}^0$ in correlated state in e^+e^- collisons; "tag" flavor at $t=0$.

Asymmetric e^-, e^+ energies at SLAC, KEK (Japan) "B factories" give center of mass "boost," allowing for easier detection of decay vertices.

Decay rate $\Gamma(t)\left\{\begin{array}{c} B^0_{t=0} \\ \overline{B}^0_{t=0} \end{array}\right\} = e^{-\Gamma t}[1 \mp \sin(2\beta)\sin\Delta m t]$



$\Gamma \simeq 0.65 \times 10^{12}$ s^{-1} (decay rate)

$\Delta m \simeq 0.5 \times 10^{12}$ s^{-1} (mixing amp.)

First term: direct decay to $J/\psi K_S$

Second term: decay to $J/\psi K_S$ via mixing

B^0–$\overline{B}^0$ mixing amplitude has phase 2β

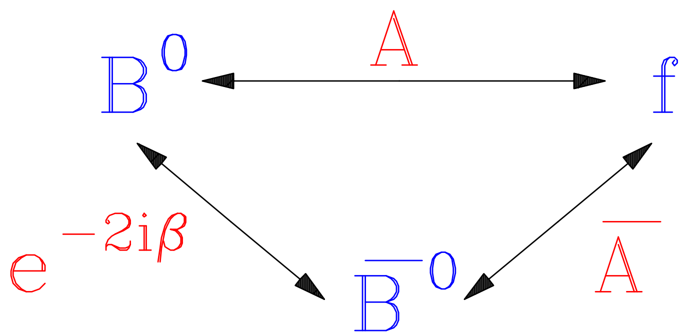
$$\frac{\Gamma(\overline{B}^0_{t=0}\to J/\psi K_S)-\Gamma(B^0_{t=0}\to J/\psi K_S)}{\Gamma(\overline{B}^0_{t=0}\to J/\psi K_S)+\Gamma(B^0_{t=0}\to J/\psi K_S)}$$

would be maximal $(=\frac{1}{2}\sin(2\beta)\simeq 0.34)$ if $\Delta m = \Gamma$; it is 97% of that.

TIME-DEPENDENT CP ASYMMETRIES

Decay to a CP eigenstate f characterized by parameters with $C^2 + D^2 + S^2 = 1$:

$$\Gamma[B^0(t) \to f] \sim e^{-\Gamma t}\,[\cosh(\Delta\Gamma t/2) - D\,\sinh(\Delta\Gamma t/2) + C\cos(\Delta m t) - S\sin(\Delta m t)]$$



$$\lambda \equiv e^{-2i\beta}\frac{\bar{A}}{A} \qquad S \equiv \frac{2\mathrm{Im}\lambda}{1+|\lambda|^2}$$

$$C \equiv \frac{1-|\lambda|^2}{1+|\lambda|^2} \qquad D \equiv \frac{2\mathrm{Re}\lambda}{1+|\lambda|^2}$$

Reminiscent of nonleptonic hyperon decay (s, p) or Stokes parameters $(E_{||}, E_{\perp})$:

$$D \Leftrightarrow \alpha \Leftrightarrow U/I \qquad S \Leftrightarrow \beta \Leftrightarrow V/I \qquad C \Leftrightarrow \gamma \Leftrightarrow Q/I$$

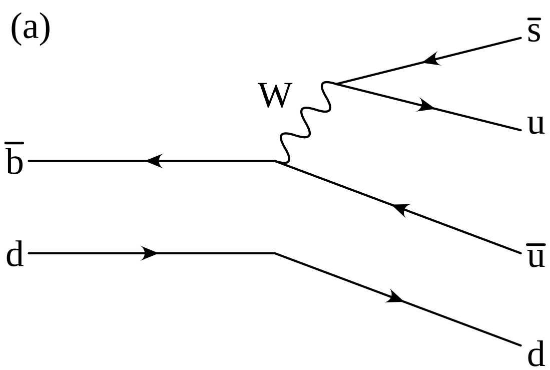
For B^0, $\Delta\Gamma$ is small; measure S, C with $S^2 + C^2 \leq 1$

When A is dominated by a single weak amplitude:

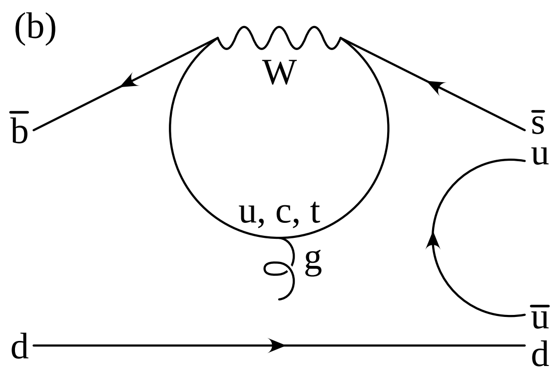
$$|\lambda| = 1 \qquad C = 0 \qquad S = \pm\sin[2\beta + \mathrm{Arg}(A/\bar{A})]$$

STRANGE PENGUINS?

Tree diagram:



Penguin diagram:



The loser of a darts game near CERN in 1977 agreed to use "penguin" in his next paper (J. Ellis +)

Several B decays involving K's in final state seem to be dominated by the $b \to s$ penguin. Expect coefficient of $\sin \Delta mt$ decay rate modulation to be $\sin 2\beta = 0.674 \pm 0.026$ as for $B^0 \to J/\psi K_S$. Observed values (Hazumi ICHEP06):

Final state	BaBar (SLAC)	Belle (KEK)	Average
$K_S\pi^0$	$0.33 \pm 0.26 \pm 0.04$	$0.33 \pm 0.35 \pm 0.08$	0.33 ± 0.21
$K_S\eta'$	$0.55 \pm 0.11 \pm 0.02$	$0.64 \pm 0.10 \pm 0.04$	0.59 ± 0.08
$K_S\phi$	$0.12 \pm 0.31 \pm 0.10$	$0.50 \pm 0.21 \pm 0.06$	0.39 ± 0.18

If deviations are due to new physics, should they be the same in each case?

UNFINISHED BUSINESS

B decays: processes involving $b \to s$ "penguin" diagrams

Expected CP asymmetries $\sim \sin 2\beta = 0.674 \pm 0.026$ in $B^0 \to K^0\pi^0$, $B^0 \to \eta' K^0$, $B^0 \to \phi K^0$; these processes give average $\sim 0.52 \pm 0.05$ (Hazumi ICHEP06), 2.6σ low. Standard Model deviations from nominal value bounded and small.

Electroweak theory requires a Higgs boson

Current thinking puts it just above the reach of recently terminated LEP experiments. The CERN Large Hadron Collider and possibly the Fermilab Tevatron will have a shot at it.

Pattern of quark masses and mixings

Originate from same physics (but no good ideas). A central question facing particle physics. Clues from emerging pattern of neutrino masses and mixings.

Our thanks to Jim Cronin

For uncovering the nature of the weak interaction through his studies of strange particle decays; helping prove the importance of quarks; exciting explorations of cosmic rays; and all-round wonderful physics!