The Iso-singlet Down Quark Model and CP Violation Experiments

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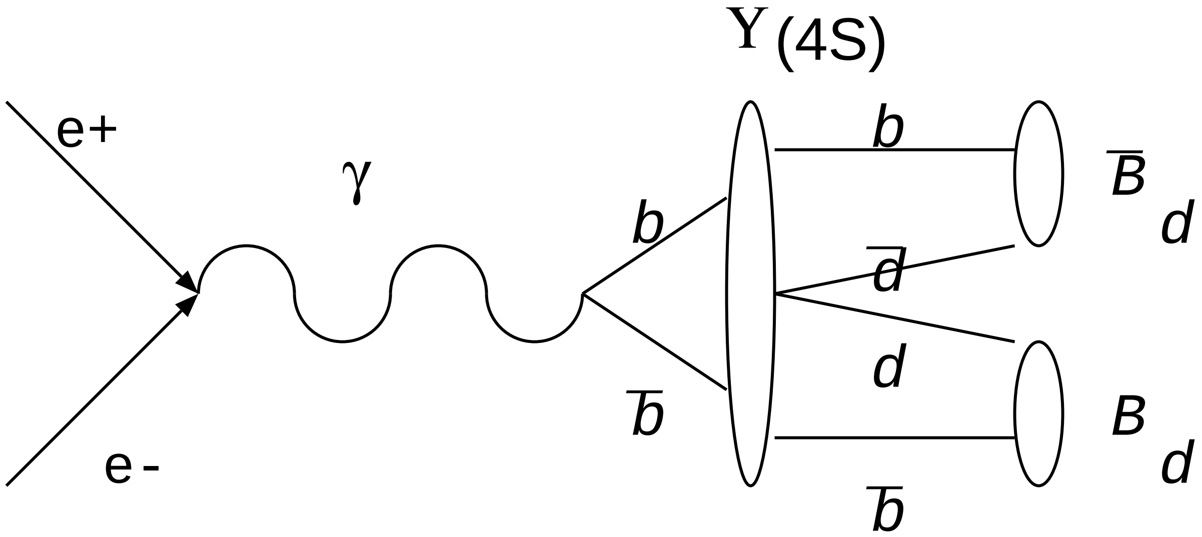
1 Introduction

- To decide whether the B Factory is significantly testing the standard CKM model of CP violation, and to determine the "reach" of the B factory in ruling out "new physics" models, we need several alternate but full physical models for comparison.
- The flavor changing neutral current (FCNC) model resulting from extra weak iso-singlet down quarks, as in E_6 with one for each generation, introduces new phases, and has not been ruled out by present experiments.
- In this talk, the predictions are constrained by new experiments with the full inclusion of SM amplitudes.
- The constraints are updated for $\sin(2\beta)$ measurements, new x_s bounds, new BNL results on $K^+ \to \pi^+ \nu\bar{\nu}$, and for ϵ'/ϵ.
- New analysis: Donovan Hawkins and Dennis Silverman, hep-ph/0205011, (2002). Latest published: D. Silverman, Phys. Rev. D **58**, 095006 (1998), hep-ph/9806489.
- Previous collaborators: Myron Bander, Michael Shin, Yossi Nir, Woon-Seng Choong, and Tony Yao.

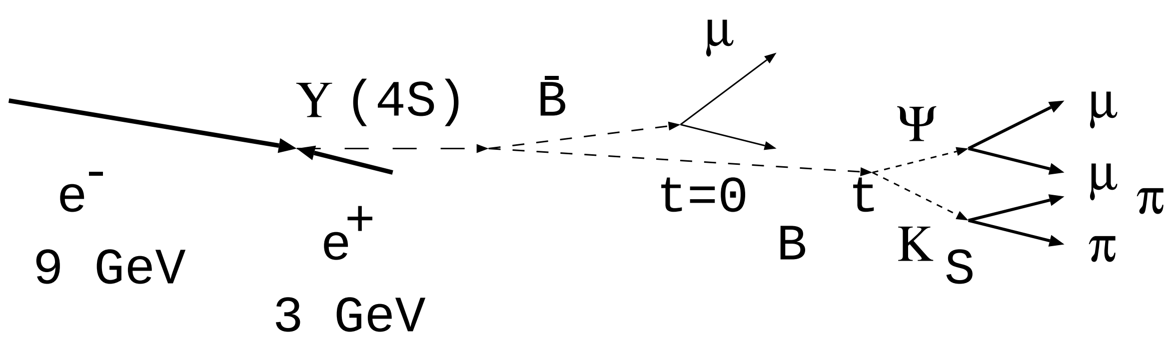
2 Production in a B Factory

$b-\bar{b}$ quarks are produced in pairs. To control the energy and state in which they are produced, they are best produced in an e^-e^+ collider where their mesons $B\bar{B}$ are the only particles produced. This can be enhanced by a factor of 5 by producing them from a resonance of $b-\bar{b}$ quarks into bottomonium mesons called Υs. The $\Upsilon(4S)$ at (10.580) GeV, is just above the $B-\bar{B}$ threshold at $2m_B = 10.56$ GeV.



Since the B $\bar{B}$ pair were made from a virtual photon, and B and $\bar{B}$ are spinless, they are in a P wave in their center of mass. If one, say $\bar{B}$, were to mix to a B by CP violation, the state would have two identical B bosons in an $L=1$, antisymmetric state. This is forbidden by Bose symmetry which requires identical bosons to be symmetric. So there is always one B and one $\bar{B}$ meson, until one decays.

3 Asymmetric B Factories and Tagging B and $\bar{B}$ Decays



- In the center of mass, the B and $\bar{B}$ move slowly, a distance of 30μm in one lifetime. The vertex detector resolution is larger however, about 50μm.
- The solution to observe B movement before decay is to boost the whole created system by making an Asymmetric B Factory, projecting the B and $\bar{B}$ forward with $\beta = v/c = 0.5$. The average separation between decays is now 180μm.
- The semileptonic $\bar{B}$ decay is tagged by the semileptonic decay to a μ^-, and the time at its decay is defined as $t = 0$.
- The B propagates until time t where it decays to CP eigenstate $J/\Psi + K_S$.
- The electron momentum of 9 GeV and the positron of 3.1 GeV create a virtual photon with center of mass energy that of the $\Upsilon(4S)$.
- Locations
  (BELLE) KEK, Tsukuba, Japan (8 GeV e^- + 3.5 GeV e^+)
  (BaBar) SLAC, Stanford, PEP II (9 GeV e^- + 3.1 GeV e^+)
- Luminosity
  3×10^{33} to 10^{34} /cm^2/sec

4 Diagonalize Mixing B and $\bar{B}$ States to Mass Eigenstates

- Flavor eigenstates: $|B^0\rangle$, $|\bar{B}^0\rangle$
- CP eigenstates:

$$C|B^0\rangle = |\bar{B}^0\rangle$$
$$CP|B^0\rangle = -|\bar{B}^0\rangle$$

$$CP+: \quad |B_+\rangle = \frac{1}{\sqrt{2}}(|B^0\rangle - |\bar{B}^0\rangle)$$

$$CP-: \quad |B_-\rangle = \frac{1}{\sqrt{2}}(|B^0\rangle + |\bar{B}^0\rangle)$$

- In $|B^0\rangle$, $|\bar{B}^0\rangle$ space, diagonalize H which has mixing element $\langle B^0|H|\bar{B}^0\rangle = M_{12}$.
- Since $\Gamma_{12} \approx M_{12}/100$ is very small and can be ignored, the deviation from CP eigenstates is determined by

$$\frac{q}{p} = \sqrt{\frac{M_{12}^*}{M_{12}}} = \frac{V_{tb}^* V_{td}}{(V_{tb}^* V_{td})^*} = e^{2i\beta}$$

  where q/p is of magnitude one.
- The presence of V_{td} in H with a non-zero phase β makes H CP violating.
- The mass eigenstates are then

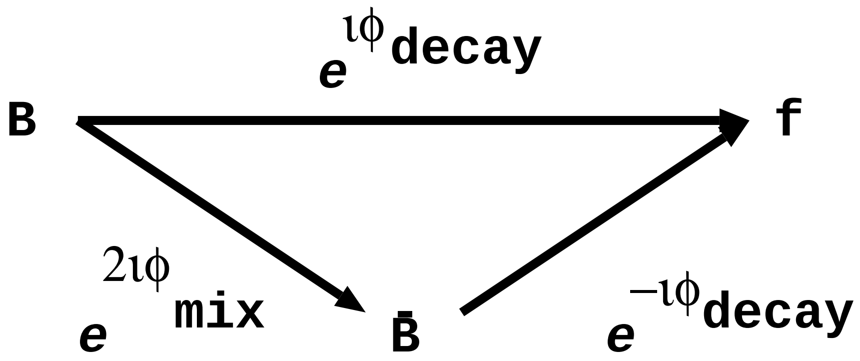
$$\begin{aligned} |\psi_+\rangle &= \frac{1}{\sqrt{|p|^2 + |q|^2}}[p|B^0\rangle - q|\bar{B}^0\rangle] \\ |\psi_-\rangle &= \frac{1}{\sqrt{|p|^2 + |q|^2}}[p|B^0\rangle + q|\bar{B}^0\rangle]. \end{aligned}$$

- The mixing M_{12} causes a mass difference between mass eigenstates

$$\Delta m = m_1 - m_2 = 2\mathrm{Re}(pq).$$

5 How to Detect a Phase? - Interference, but of course.

- In decays from only one process, the phase is irrelevant because $\Gamma = |A|^2$ destroys the phase of the A amplitude.
- Two interfering amplitudes are necessary to show effects of their relative phase difference.
- Since B and $\bar{B}$ are CP conjugates, the only way their interference could be detected is with final states which are CP self-conjugate, or CP eigenstates $|f\rangle$ where
$$CP|f\rangle = \pm|f\rangle$$
- Then we have two interfering paths to the final state, the direct B decay, and the mixing of the B to $\bar{B}$ followed by the $\bar{B}$ decay.
- For $B_d \to \bar{B}_d$, $\phi_{\rm mix} = -\beta$, while for $B_s \to \bar{B}_s$, $\phi_{\rm mix} = 0$.



6 $B - \bar{B}$ Mixing and CP Violating Decay Asymmetries

- The tagged $\bar{B}$ at time $t = 0$ leaves a pure B state $|B(0)\rangle = |B\rangle_0$.
- This develops with mixing as time t grows, and projects to final state f as

$$\langle f|B(t)\rangle = e^{-\Gamma t/2} e^{-i(m_1+\Delta m/2)t} \left[\cos\left(\frac{\Delta m t}{2}\right) \langle f|B\rangle_0 + i e^{2i\phi_{\text{mixing}}} \sin\left(\frac{\Delta m t}{2}\right) \langle f|\bar{B}\rangle_0 \right].$$

- The decays have phases $\langle f|\bar{B}\rangle / \langle f|B\rangle = e^{-2i\phi_{\text{decay}}}$.
- The decay rate from the initial B to the CP eigenstate f becomes

$$\Gamma(B(t) \to f) \propto e^{-t/\tau_B} [1 - \sin(2(\phi_{\text{mixing}} - \phi_{\text{decay}})) \sin(xt/\tau_B)]$$

where $x = \Delta m/\Gamma = \Delta m \tau_B$ compares the mixing and decay rates.

- For B_d^0, $x_d = 0.71$. For a complete cycle of oscillation, a rather long time is needed for B_d^0

$$t_{\text{cycle}} = 2\pi\tau_B/x_d = 8.8\tau_B$$

- If B^0 is tagged instead and $\bar{B}^0$ propagates, its decay rate to f, $\Gamma(\bar{B}(t) \to f)$, has the opposite sign in front of the sine term.
- This gives the asymmetry definition

$$A_{CP} \sin(xt/\tau_B) = \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to f)}{\Gamma(B \to f) + \Gamma(\bar{B} \to f)}$$

- For the standard model, and the principal decay $B \to \Psi K_S$, the asymmetry becomes

$$A_{CP} = -\sin(2(\phi_{\text{mixing}} - \phi_{\text{decay}})) = -\text{Im}\left[\frac{(V_{tb}^* V_{td})}{(V_{tb}^* V_{td})^*} \frac{(V_{cb}^* V_{cs})^*}{(V_{cb}^* V_{cs})} \right] = \sin(2\beta)$$

- We see the key result, that the coefficient of the oscillation depends purely on CKM matrix elements, and is independent of strong interaction effects, as long as there is only one diagram contributing.
- As we expect for CP violation, both an imaginary part or phase is necessary, as well as mixing between two states of opposite CP, namely B and $\bar{B}$, that shows up in making Δm or x non-zero.

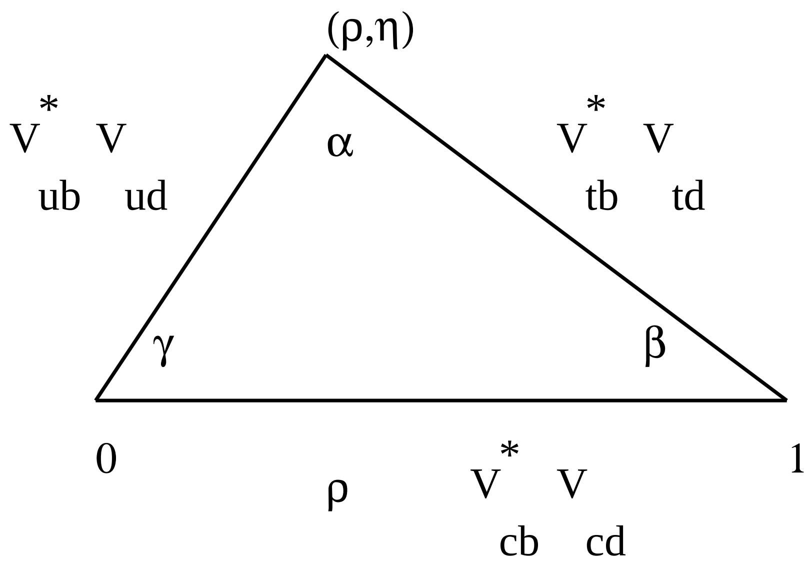
7 The SM Unitarity Triangle

- The matrix elements or angles in the CKM matrix are often displayed in the complex plane with complex number "vectors" given by the unitarity orthogonality relation between the b and d columns

$$V_{ub}^* V_{ud} + V_{tb}^* V_{td} + V_{cb}^* V_{cd} = 0$$

- The triangle is then scaled to a base length of 1, and $V_{ub} = s_{13} \exp(-i\delta_{13})$ and V_{td} and are often shown by ρ and η, where

$$\begin{aligned} \rho + i\eta &= V_{ub}^* V_{ud} / |V_{cb}^* V_{cd}| \simeq s_{13} \exp(i\delta)/(s_{12}s_{23}) \\ V_{tb}^* V_{td} / |V_{cb}^* V_{cd}| &= 1 - \rho - i\eta \end{aligned}$$



- The enclosed angles are $\delta_{13} = \gamma = \delta$, α, and β.

8 Iso-singlet Down Quark Mixing

- The initial quarks of definite weak isospin in E_6, for each generation are: the left handed iso-doublet (u^0_{iL}, d^0_{iL}), their right handed iso-singlets u^0_{iR} and d^0_{iR}, and the yet to be found iso-singlet pair D^0_{iL} and D^0_{iR}.
- We can take the initial up quark matrix to be the mass eigenstates, so $u^0_i = u_i$, giving $V^u = I_{3\times 3}$.
- The down quarks (d^0_i, D^0_i) corresponding to the same generations as u_i mix to form mass eigenstates (d_i, D_i) via the matrix $V^d(6\times 6)$.
- The weak interaction charged current matrix is then $U(3\times 6) = V^{u\dagger} \times V^d$, the 3×6 matrix that is the upper three rows of V^d.
- The upper three rows of $V^d(6\times 6)$ are the linear combinations that make up the weak isospin doublets d^0_i.
- The lower three rows of V^d are the three linear combinations of (d_i, D_i) that are the iso-singlet D^0_i which cannot couple to up quarks by the weak interactions.
- We truncate the V^d matrix to the 4×4 matrix using only the D quark that mixes most, giving the Four Down Quark Model (FDQM).
- The D mixture now has weak charged currents to u, c, and t quarks with amplitudes $s_{14}e^{-i\delta_{14}}$, $s_{24}e^{-i\delta_{24}}$, and s_{34}, respectively, which is the fourth column.
- The fourth row gives the linear combination that is the initial iso-singlet D^0_1.
- The leading terms in the 4×4 Down Quark Mixing Matrix With 6 Angles and 3 Phases are

$$V = \begin{array}{c} \\ u \\ c \\ t \\ 4 \end{array} \begin{array}{c} \begin{array}{cccc} \quad d \quad & \quad s \quad & \quad b \quad & \quad D \quad \end{array} \\ \begin{pmatrix} c_{12}c_{34} & s_{12}c_{34} & s_{13}e^{-i\delta_{13}} & s_{14}e^{-i\delta_{14}} \\ -s_{12} & 1 & s_{23} & s_{24}e^{-i\delta_{24}} \\ (s_{12}s_{23} - s_{13}e^{i\delta_{13}}) & -s_{23} & 1 & s_{34} \\ V_{4d} & V_{4s} & V_{4b} & V_{44} \end{pmatrix} \end{array},$$

$$\begin{aligned} V^*_{4d} &= -s_{14}e^{-i\delta_{14}} + s_{24}e^{-i\delta_{24}}s_{12} - s_{34}(s_{12}s_{23} - s_{13}e^{-i\delta_{13}}), \\ V^*_{4s} &= -s_{24}e^{-i\delta_{24}} - s_{14}e^{-i\delta_{14}}s_{12} + s_{34}(s_{23} + s_{12}s_{13}e^{-i\delta_{13}}), \\ V^*_{4b} &= -s_{34} - s_{24}e^{-i\delta_{24}}s_{23} - s_{14}e^{-i\delta_{14}}s_{13}e^{i\delta_{13}}. \end{aligned}$$

9 Charged Currents in the FDQM

For $k_u = 1, 2, 3$ and $j = 1, 2, 3, 4$

$$J^{\mu-} = \bar{u}^0_{k_u L}\gamma^\mu d^0_{k_u L} = V_{k_u j}\bar{u}_{k_u L}\gamma^\mu d_{jL}$$

$$\mathcal{L} = \frac{g}{\sqrt{2}}(W^-_\mu J^{\mu+} + W^+_\mu J^{\mu-}).$$

- Here the 3×4 submatrix $V_{k_u,j}$ of V couples the three up quarks to the four down quarks.
- The 3×3 submatrix of V for $k_u, j = 1, 2, 3$ takes the role of the CKM matrix, but it is not unitary by itself.

10 Derivation of Flavor Changing Neutral Currents

- The weak isospin matrix in the weak isospin down quark eigenstates is

$$t_3 = \begin{array}{c} \\ d^0_{1L} \\ d^0_{2L} \\ d^0_{3L} \\ D^0_{1L} \end{array} \begin{array}{c} \begin{array}{cccc} d^0_{1L} & d^0_{2L} & d^0_{3L} & D^0_{1L} \end{array} \\ \begin{pmatrix} -1/2 & 0 & 0 & 0 \\ 0 & -1/2 & 0 & 0 \\ 0 & 0 & -1/2 & 0 \\ 0 & 0 & 0 & 0 = -1/2 + 1/2 \end{pmatrix} \end{array}$$

- For $i, j, k, m = 1, 2, 3, 4$,

$$\begin{aligned} \mathcal{L}^Z &= \frac{e}{\sin\theta_W \cos\theta_W} \bar{d}^0_{kL} (t_3)_{km} \gamma^\mu d^0_{mL} \\ (t_3)_{km} &= -\frac{1}{2}\delta_{km} + \frac{1}{2}\delta_{k4}\delta_{4m} \\ d^0_{mL} &= V_{mj} d_{jL} \\ \bar{d}^0_{kL} &= \bar{d}_{iL} V^*_{ki} \end{aligned}$$

$$\mathcal{L}^Z = \frac{e}{\sin\theta_W \cos\theta_W} \bar{d}_{iL} V^*_{ki} \left(-\frac{1}{2}\delta_{km} + \frac{1}{2}\delta_{k4}\delta_{m4} \right) \gamma_\mu V_{mj} d_{jL} Z^\mu$$

- In the first term, the currents are diagonal from orthogonality

$$V^*_{ki} V_{kj} = \delta_{ij}.$$

- The second term isolates matrix elements with a 4 component giving flavor changing neutral currents and a correction to diagonal currents

$$\mathcal{L}^Z = \frac{e}{\sin\theta_W \cos\theta_W} \left(-\frac{1}{2} \bar{d}_{iL} \gamma_\mu d_{iL} + \frac{1}{2} \bar{d}_{iL} V^*_{4i} V_{4j} \gamma_\mu d_{jL} \right) Z^\mu$$

- The currents for $i \neq j$ are FCNC given by the mixings to the fourth down quark by

$$-U_{ij} \equiv V^*_{4i} V_{4j} \quad \text{for} \quad i \neq j.$$

- The FCNC couplings of the down quarks to the Z are then given by

$$\mathcal{L}^Z_{FCNC} = -\frac{e}{2\sin\theta_W \cos\theta_W} U_{ij} \bar{d}_{iL} \gamma^\mu d_{jL} Z_\mu.$$

- There will be constraints on three FCNC amplitudes:

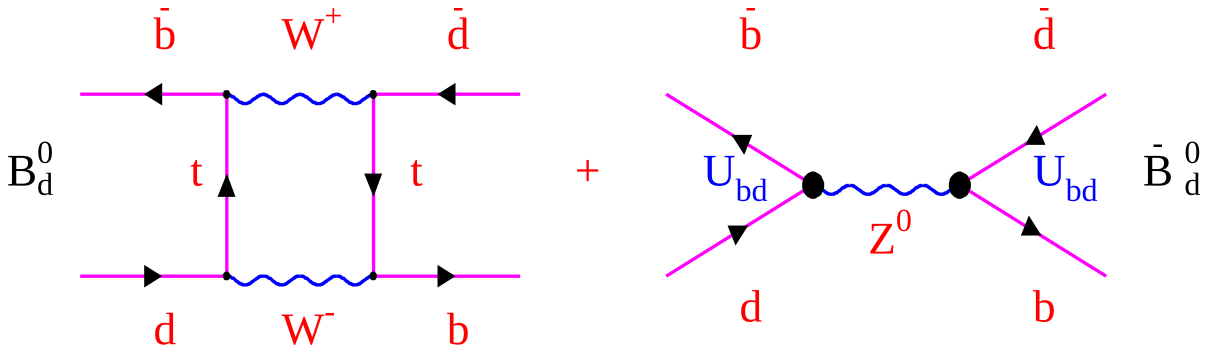
$$\begin{aligned} -U_{ds} &= V_{4d}^* V_{4s} \\ -U_{sb} &= V_{4s}^* V_{4b} \\ -U_{bd} &= V_{4b}^* V_{4d} \end{aligned}$$

- The diagonal neutral current couplings are reduced in strength by the amplitudes into the FCNC, becoming

$$\mathcal{L}_{NC}^{Z} = -\frac{e}{2\sin\theta_W \cos\theta_W} \sum_i (1 - |V_{4i}|^2) \bar{d}_{iL} \gamma^\mu d_{iL} Z_\mu.$$

11 $B_d - \bar{B}_d$ Mixing

- The FCNC give rise to a second order FCNC tree level meson mixing diagram using Z^0 exchange.



$$x_d = \frac{2G_F}{3\sqrt{2}} B_B f_B^2 m_B \eta_B \tau_B \left| U^2_{std-db} + (U_{db})^2 \right|$$

where $x_d = \Delta m_{B_d}/\Gamma_{B_d} = \tau_{B_d} \Delta m_{B_d} = \tau_{B_d} 2|M_{12}|$.

$$\begin{aligned} x_d &= 0.73 \pm 0.05, \\ \sqrt{B_B} f_B &= 0.230 \pm 0.035 \text{ GeV}. \end{aligned}$$

- We define the standard model amplitude for $B_d - \bar{B}_d$ mixing from x_d normalized so that it adds directly to U^2_{db}

$$U^2_{std-db} \equiv \frac{\alpha}{4\pi \sin^2 \theta_W} y_t f_2(y_t) (V^*_{td} V_{tb})^2.$$

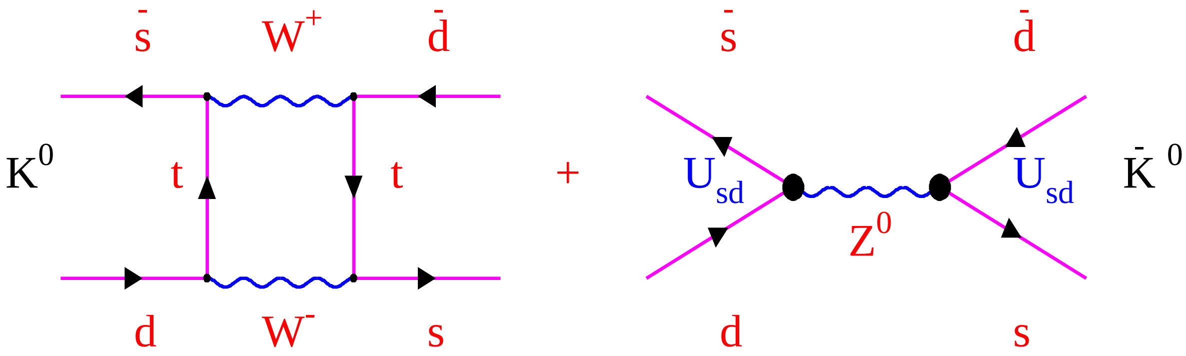
- To leading order in s_{34}, $s_{24} e^{-i\delta_{24}}$, and $s_{14} e^{-i\delta_{14}}$ we have:

$$U_{db} = s_{34} (s_{14} e^{-i\delta_{14}} + s_{34} V^*_{td} - s_{24} e^{-i\delta_{24}} s_{12}).$$

- The dominant term will turn out to be the s_{14} term with the δ_{14} phase, and the other terms are only a 5% correction.

12 Bounds on FCNC CP Violation in $|\epsilon|$

- There is a similar tree level second order FCNC meson mixing diagram in the K system.



$$M_{12} =< K^0|H|\bar{K}^0 >$$

$$1-2\epsilon = \sqrt{\frac{M_{12}^*}{M_{12}}} \approx 1 - i\mathrm{Im}(M_{12})$$

$$|\epsilon| = 2.27 \times 10^{-3}$$

$$|\epsilon| = \frac{G_F f_K^2 B_K m_K}{12\Delta m_K} \left|\mathrm{Im}(U^2_{std-ds}) + \mathrm{Im}(U^2_{ds})\right|.$$

where

$$U^2_{std-ds} \equiv \frac{\alpha}{4\pi \sin^2\theta_W}(\eta_2 y_t f_2(y_t)(V_{td}^* V_{ts})^2 + \ldots)$$

- Ignoring the SM terms to get a rough estimate of the size of the FCNC amplitudes gives the limits

$$\begin{aligned} |\mathrm{Im}[(U_{ds})^2]| &\leq 9.2 \times 10^{-10} \\ |\mathrm{Re}(U_{ds})\mathrm{Im}(U_{ds})| &\leq 4.6 \times 10^{-10}. \end{aligned}$$

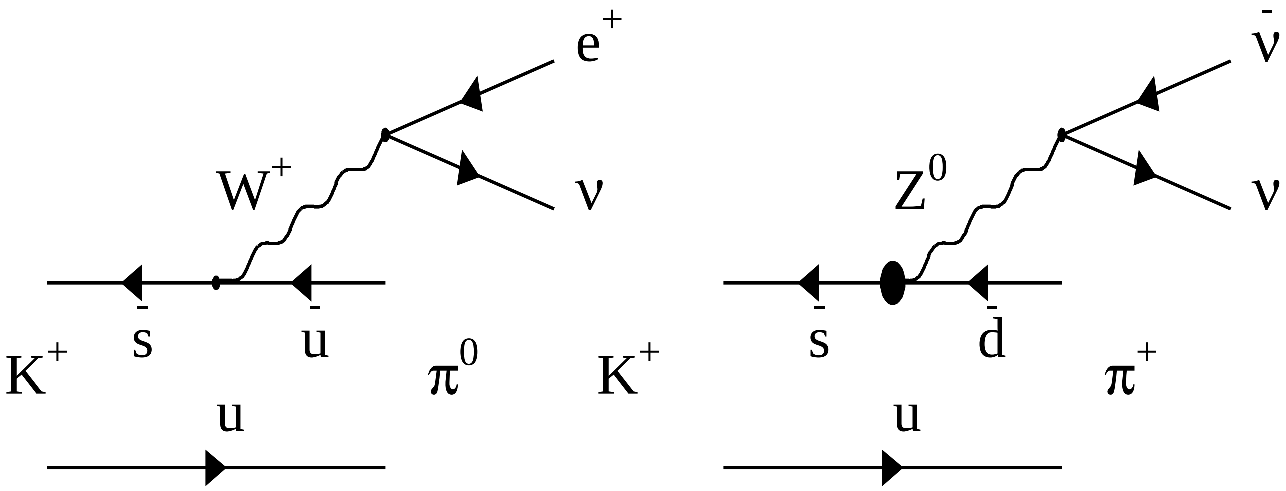
13 Bounds From $K^+ \to \pi^+\nu\bar{\nu}$

- BNL E-787, with two events, gives a branching ratio

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10},$$

  which is now in the standard model range of $(0.72 \pm 0.21) \times 10^{-10}$. Because of this, we have now added in the SM contribution to the extra down quark FCNC.

- The diagram on the right shows how the FCNC can contribute to this process. Similar Penguin diagrams for $\bar{s} \to \bar{d} + Z^0$ exist in the standard model contribution.



- To cancel out the hadronic interactions, $K^+ \to \pi^+\nu\bar{\nu}$ is scaled by the process on the left.

- To again just get an order of magnitude of the bound on $|U_{ds}|$, this becomes

$$\frac{\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})}{\mathrm{BR}(K^+ \to \pi^0 e^+\nu)} = \frac{1}{2}\frac{|U_{ds}|^2}{|V_{us}|^2}.$$

- Using the Poisson-χ^2 connection (D. Silverman, physics/9808004) gives a contribution to $\chi^2 = 2\langle n\rangle = 1.61 \times 10^9\ |U_{ds}|^2$ with $2 \times n_{\mathrm{observed}} = 4$ degrees of freedom.

- At 90% CL, where $\chi^2 = (1.64)^2$, this gives

$$|U_{ds}|^2 \leq 1.7 \times 10^{-9},$$

comparable to the limits from $|\epsilon|$.

14 Bound From $Z^0 \to b\bar{b}$

- The weak isovector part of $Z^0 \to b\bar{b}$ is reduced by $(1-|V_{4b}|^2)$ through

$$\begin{aligned} V^b &= -\frac{1}{2}(1-|V_{4b}|^2) + \frac{2}{3}\sin^2\theta_W + \frac{1}{3}\rho_t, \\ A^b &= -\frac{1}{2}(1-|V_{4b}|^2) + \frac{1}{3}\rho_t \\ C_{QCD} &= 3(1.0385) \\ \Gamma^{std}(Z^0 \to b\bar{b}) &= \frac{C_{QCD} G_F m_Z^3}{6\sqrt{2}\pi}\left[(V^b)^2 + (A^b)^2\right] \end{aligned}$$

  where $\rho_t = 0.0094$ for $m_t = 174$ GeV.

- Present data and theory give

$$\begin{aligned} R_b^{\exp} &= 0.21642 \pm 0.00073 \\ R_b^{\text{theory}} &= 0.2158 \pm 0.0003 \end{aligned}$$

- Note that the $|V_{4b}|$ effect is to decrease R_b, while the experiment is about 1σ above the theory.

- To lowest order in $|V_{4b}|$ the FDQM effect is

$$\frac{\Gamma_{b\bar{b}}^{std+FCNC}}{\Gamma_{b\bar{b}}^{std}} = (1 - 2.29|V_{4b}|^2).$$

- This gives a contribution to χ^2

$$\chi^2 = \left(\frac{0.2164 - 0.2158(1-2.29|V_{4b}|^2)}{0.00073}\right)^2,$$

$$\chi^2 = (0.82 + 0.68 \times 10^3 |V_{4b}|^2)^2.$$

- Taking the 90% CL limit at $\chi^2 = (1.64)^2$, gives the bound

$$|V_{4b}| \approx |s_{34}| \leq 0.035.$$

15 CKM, FCNC, and B Factory Experiments

- CKM Experiments (7) Commonly Used for Standard Model

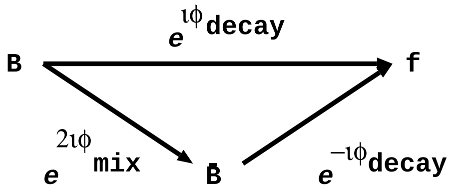
V_{us}	
$\|V_{cb}\| = 0.0404 \pm 0.0016$	
$\|V_{ub}/V_{cb}\| = 0.101 \pm 0.016$	
x_d	U_{db}
$\|\epsilon\|$	$\mathrm{Im}(U_{ds}^2)$
x_s bound	U_{sb}
$\sin(2\beta) = 0.78 \pm 0.08$	U_{db}^2

- Added Experiments (6 + 4 df) for the Four Down Quark Model

V_{ud}, V_{cd}	
$K_L \to \mu\mu$	$\mathrm{Re}(U_{ds})$
$B \to \mu\mu X_s$	$\|U_{sb}\|$
$Z^0 \to b\bar{b}$ (R_b)	$\|V_{4b}\|$
$K^+ \to \pi^+\nu\bar{\nu}$	$\|U_{ds}\|$
$\mathrm{Re}(\epsilon'/\epsilon) = 17.3 \pm 2.4$	$\mathrm{Im}(U_{ds})$

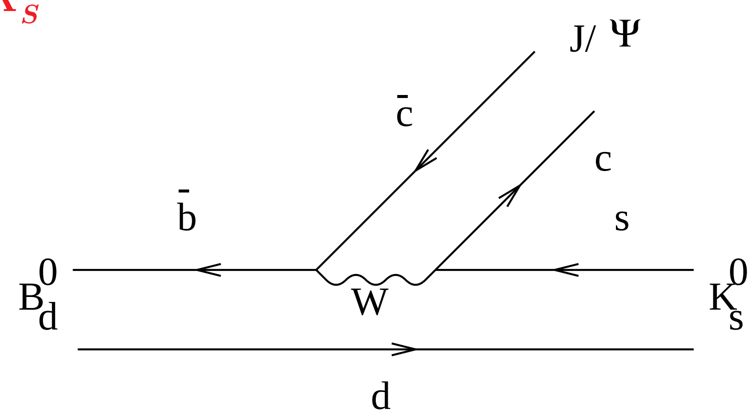
- B Factory Projected Experiment (1)

$\sin(2\alpha)$	U_{db}^2



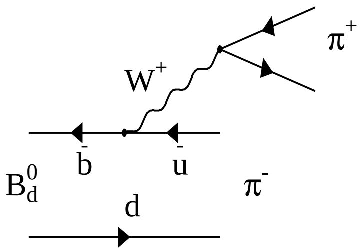
- $\sin(2\alpha)$ and $\sin(2\beta)$ are now defined as the measured B factory asymmetries, but they do not correspond to unitarity triangle or quadrangle angles in the four down quark model.

- $B_d^0 \to J/\Psi K_S^0$



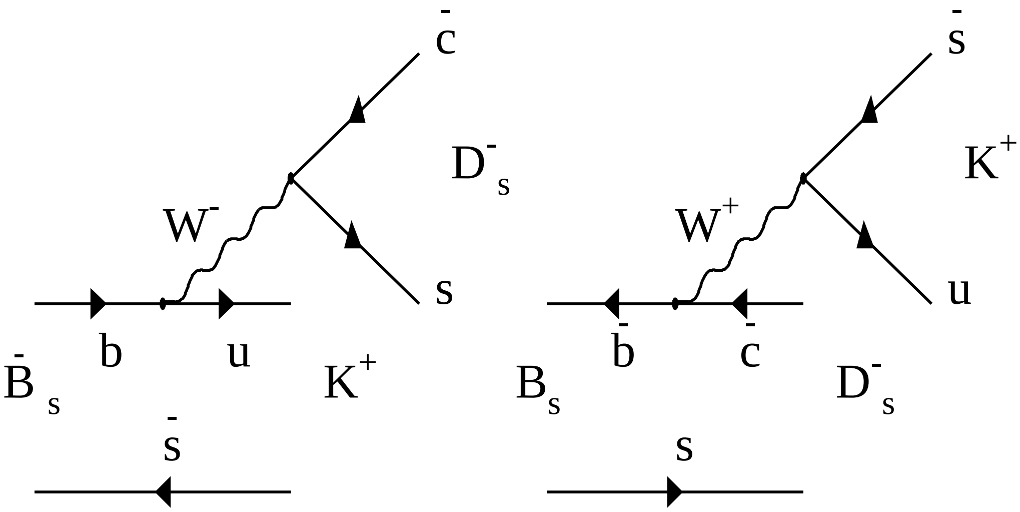
$$\sin(2\beta) \equiv A_{B_d^0 \to \Psi K_s^0} = \mathrm{Im}\left[\frac{(U_{std-db}^2 + U_{db}^2)}{|U_{std-db}^2 + U_{db}^2|}\frac{(V_{cb}^* V_{cs})}{(V_{cb}^* V_{cs})^*}\right]$$

- $B_d^0 \to \pi^+\pi^-$



$$\sin(2\alpha) \equiv -A_{B_d^0 \to \pi^+\pi^-} = -\mathrm{Im}\left[\frac{(U_{std-db}^2 + U_{db}^2)}{|U_{std-db}^2 + U_{db}^2|}\frac{(V_{ub}^* V_{ud})}{(V_{ub}^* V_{ud})^*}\right]$$

17 CP Violation and $\sin(\gamma)$ in $\bar{b} \to \bar{u} + c + \bar{s}$



- The B_s oscillation amplitude is almost real, allowing phases from decay amplitudes to be measured alone. The phase is

$$\phi_{qf} = -(2\phi(B_q \to \bar{B}_q) + \phi(\bar{B}_q \to f) - \phi(B_q \to f))$$

  Two of the four processes, out of those for B_s and $\bar{B}_s$ decays into final states f and $\bar{f}$, must be measured together. The largest branching ratios for $\sin(\gamma)$ processes are in

$$B_s,\ \bar{B}_s \to D_s^{\pm}\ K^{\mp}$$

  where the $BR \approx 2 \times 10^{-4}$.

- Here, the $\bar{B}_s$ decay to the final state involves V_{ub}^*, but the conjugate process for B_s does not involve $b \to u$ and is thus almost real. Since $V_{ub} = s_{13}e^{-i\gamma}$, and B_s mixing is almost real, the final asymmetry which is the imaginary part, only involves $\sin(\gamma)$, not $\sin(2\gamma)$.

- In the four down quark model

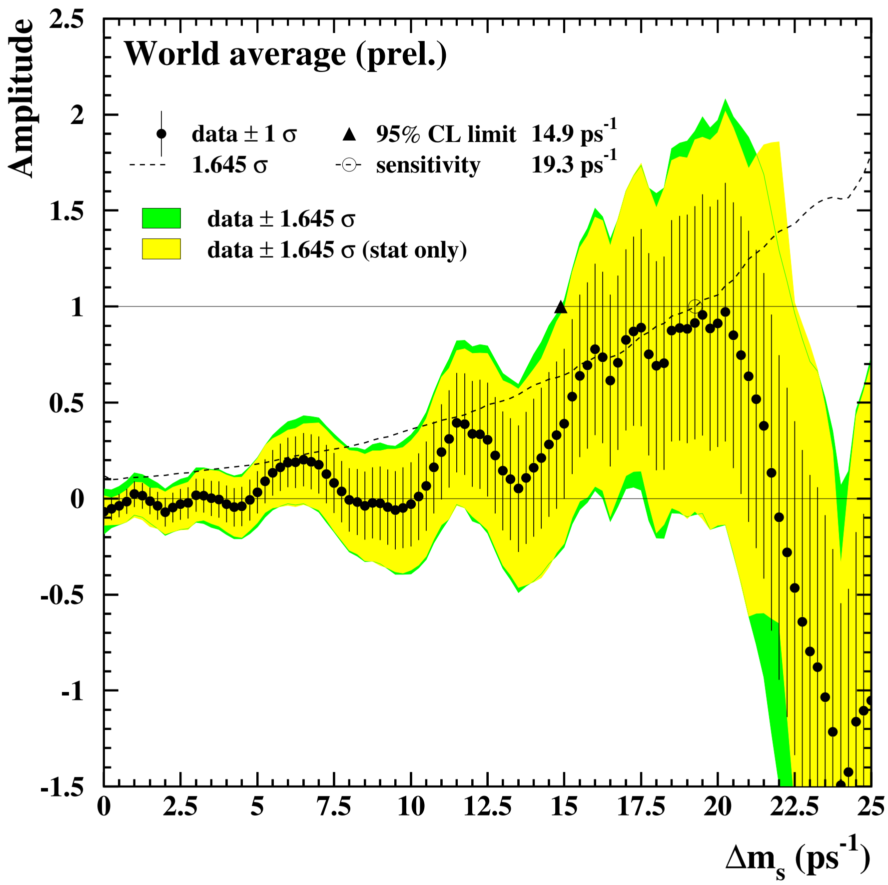
$$\sin(\gamma) = \mathrm{Im}\left(\frac{(U_{std-bs}^2 + U_{bs}^2)}{|U_{std-bs}^2 + U_{bs}^2|}\frac{(V_{ub}^* V_{cs})}{|V_{ub}^* V_{cs}|}\frac{(V_{cb}^* V_{us})}{|V_{cb}^* V_{us}|}\right).$$

18 The "Frequency" of B_s Oscillations, x_s

- Here we exclude the theoretical uncertainty on $B_{B_s} f_{B_s}^2$ by taking the ratio of x_s to x_d, which is better calculated, and in which we have also included the FCNC with Z^0 exchange

$$x_s = \frac{\Delta m_s}{\Gamma_{B_s}} = 1.35\ x_d \frac{|U_{std-bs}^2 + U_{bs}^2|}{|U_{std-db}^2 + U_{db}^2|}$$

- We now include the amplitude method analysis of LEP with SLD to assign a $\Delta\chi^2$ for each Δm_s calculated in the parameter grid. The world compiled data is shown in the figure below, where a value of 1 would be the detection of the correct Δm_s.



19 The B_s Decay Asymmetry, $\sin(2\phi_s)$

- In the standard model, B_s mixing involves $(V_{ts}^* V_{tb})^2$ which is almost exactly real. Thus almost no CP violating phase develops in the most likely B_s decays involving the real amplitude for $\bar{b} \to \bar{c} + c + \bar{s}$. This occurs in the decays $B_s \to J/\Psi\phi$, $B_s \to D_s^+ D_s^-$, and $B_s \to J/\Psi K_S$.
- The smallness of this asymmetry is a test of the SM.
- In the SM, the angle ϕ_s is the small angle in the $b - s$ unitarity triangle, whose non-zero value indicates CP violation.
- In the four down quark model, the CP violating B_s decay asymmetry is

$$\sin(2\phi_s) = \mathrm{Im}\left(\frac{(U_{std-bs}^2 + U_{bs}^2)}{|U_{std-bs}^2 + U_{bs}^2|}\frac{(V_{cb}^* V_{cs})}{(V_{cb} V_{cs}^*)}\right),$$

  which includes the double FCNC Z^0 exchange proportional to U_{bs}^2.
- Because of the additional flavor changing term in the FDQM, the angle given by the above asymmetry will not be an angle in a unitarity triangle.

20 Comprehensive Maximum Likelihood Analysis: Experiments and Degrees of Freedom

Standard Model Alone

4 parameters (3 angles, 1 phase)

- 7 common experiments - 4 parameters $\rightarrow$ 3 df

Standard Model With Comparison Experiments

4 parameters (3 angles, 1 phase)

- 7 common experiments + 6 FCNC df - 4 parameters $\rightarrow$ 9 df

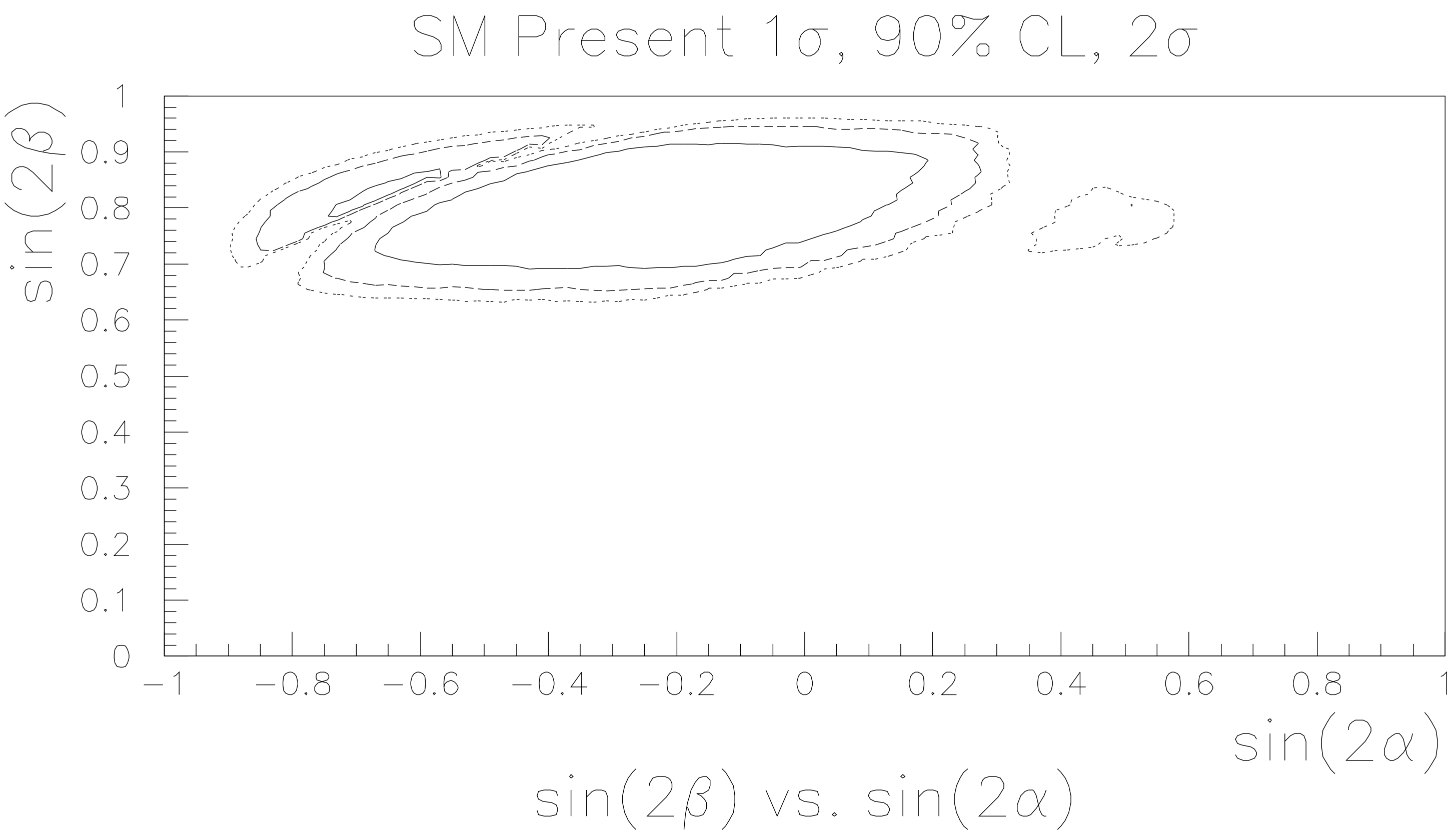
Four Down Quark Model

9 parameters (6 angles, 3 phases)

- 17 experimental df - 9 parameters $\rightarrow$ 8 df
- $\sin 2\alpha$ at B factory, add 1 expt. $\rightarrow$ 9 df

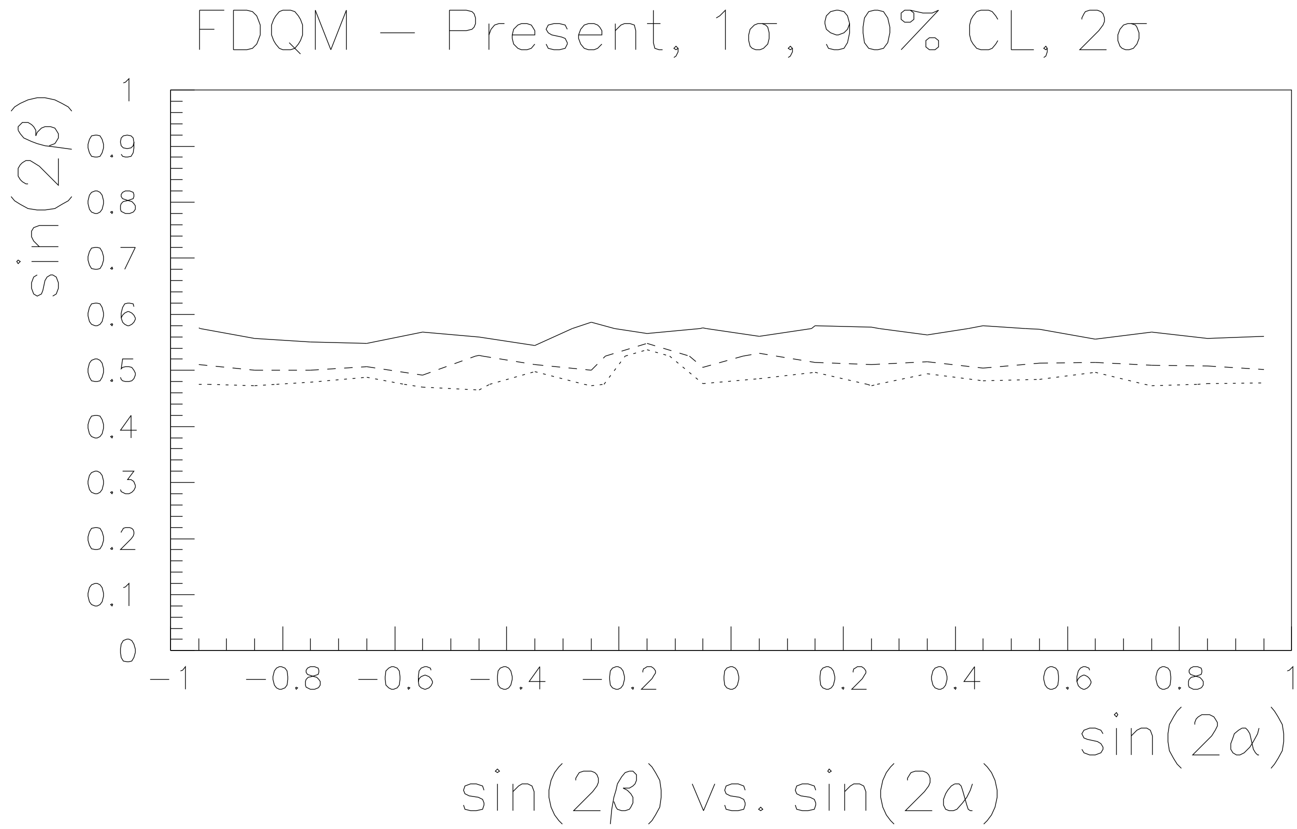
21 Standard Model Alone $(\sin(2\alpha), \sin(2\beta))$ Plot - Present Constraints

- In the figures we show the χ^2 contours with confidence levels (CL) at values equivalent to 1σ, 90% CL (1.64σ), and 2σ.
- In the SM plots, there are seven constraining experiments and four parameters, giving three degrees of freedom.
- The present BaBar and Belle average is $\sin(2\beta) = 0.78 \pm 0.08$.
- This gives $\beta = 25.6^{\circ}{}^{+4.0^{\circ}}_{-7.4^{\circ}}$.
- For the SM the $\sin(2\beta)$ range is from 0.63 to 0.96 at 2σ, centered around the experimental average of 0.78.
- The SM $\sin(2\alpha)$ range at 2σ is from -0.90 to +0.57.



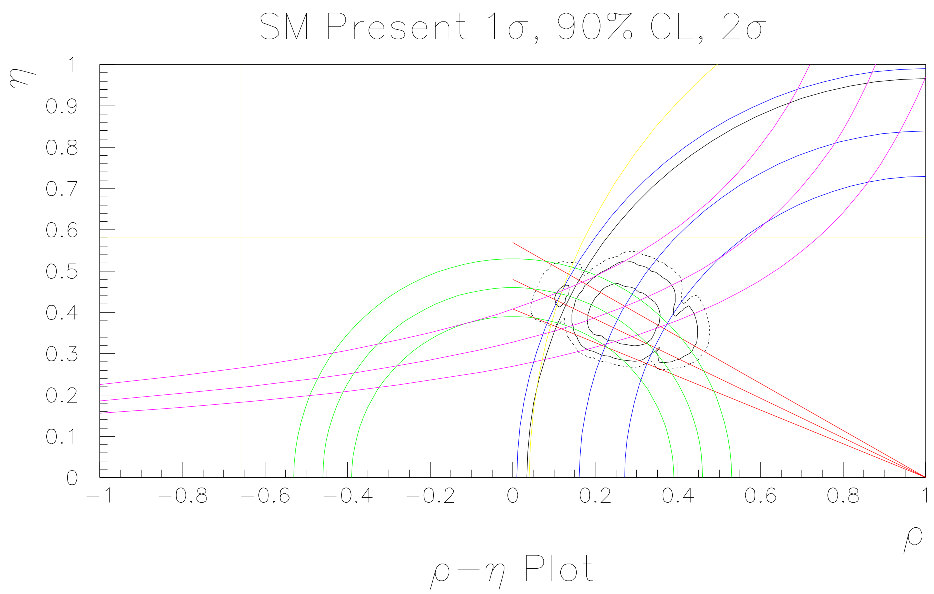
22 Four Down Quark Model $(\sin(2\alpha), \sin(2\beta))$ Plots - Present Limits

- In the FDQM analysis including FCNC experiments, there are 17 experimental df minus 9 parameters, giving 8 df.
- In the FDQM, all values of $\sin(2\alpha)$ are allowed.



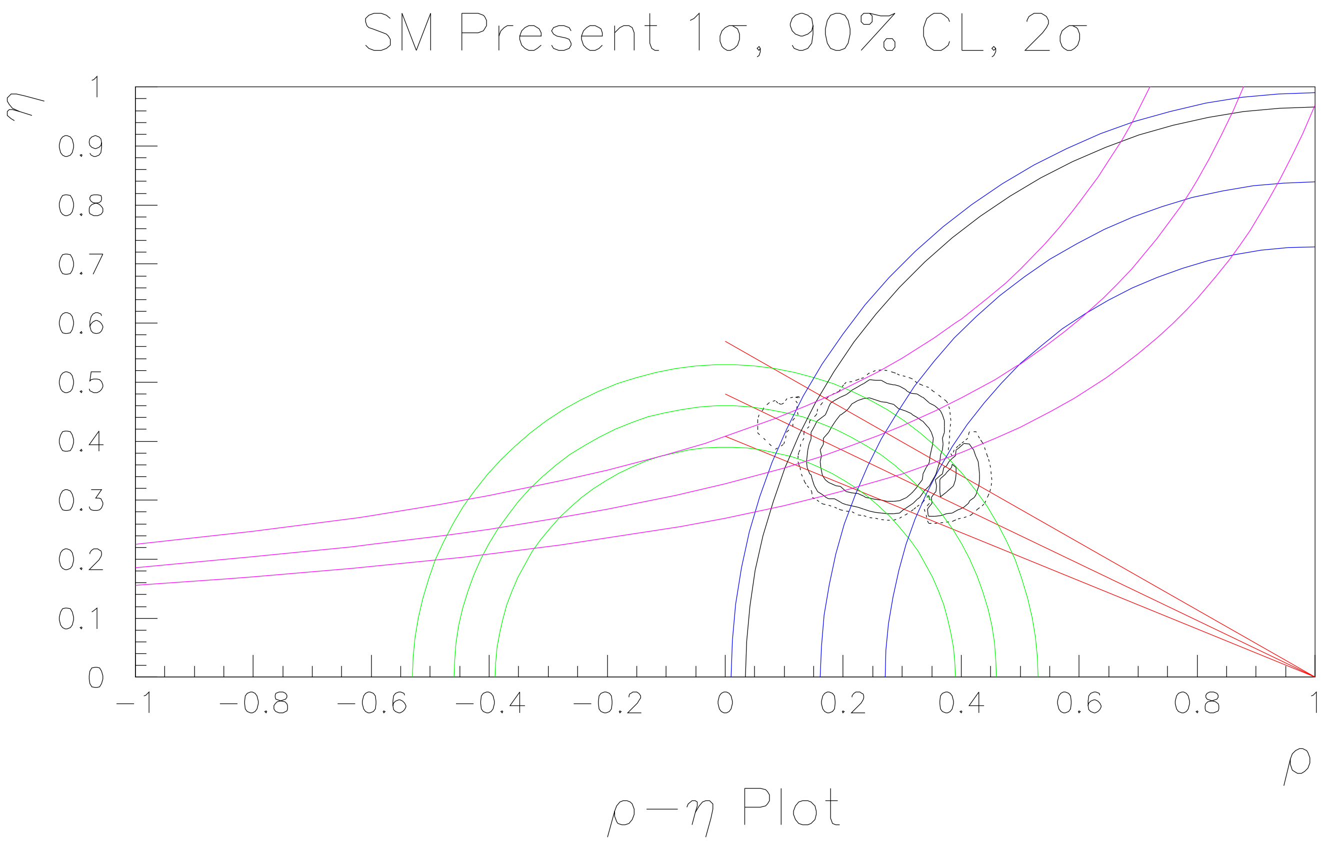
23 Standard Model with Comparison Experiments (ρ, η) Plot

- Here we depart from the analysis of the SM experiments alone to show the effects of the additional three K meson experiments. While they are not needed in the SM analyis, they are included in the FDQM analysis.
- In this case, there are $7 + 6 = 13$ experimental df minus 4 parameters giving 9 df.
- The loose K meson experimental contours for the SM are in yellow.
- For ϵ'/ϵ, the lower 1σ contour is horizontal, where the central contour would be a horizontal line at $\eta = 1.1$.
- For $K_L \to \mu\mu$ the vertical contour is the lower 1σ contour with the central contour being a vertical line at $\rho = 1.2$. This includes, conservatively, a large and uncertain long distance effect.
- For $K^+ \to \pi^+\nu\bar{\nu}$, the contour giving an additional $\chi^2 = 1$ is the arc of the circle centered about $(\rho, \eta) = (1.3, 0)$. It is not quite as restrictive in the SM as the 90% CL from the x_s or Δm_s limit, which is shown as the black circle.
- For the rest of the SM analysis we drop these three new K meson experiments.



24 Standard Model Alone (ρ, η) Plot

- Joint χ^2 enclosed contours are at 1σ, 90% CL, and 2σ.
- The Δm_s 90% circular arc is in black, although the analysis weights each Δm_s or each V_{td} in χ^2.
- The green half-circles about $(\rho, \eta) = (0, 0)$ are the center and 1σ contours for $|V_{ub}|$.
- The purple hyperbolas are the center and 1σ contours for ϵ.
- The blue quarter circles about $(\rho, \eta) = (1, 0)$ are for $|V_{td}|$ or from x_d in $B_d - \bar{B}_d$ mixing.
- The red lines emanating from $(\rho, \eta) = (1, 0)$ are the central and 1σ limits for $\sin(2\beta)$.



25 Four Down Quark Model: (ρ, η) Plots

- As in the SM, the plotted ρ and η are taken as the coordinates of V_{ub}^*, scaling the base of the $b-d$ unitarity triangle to unity.

$$\rho + i\eta = V_{ub}^* V_{ud} / |V_{cb}^* V_{cd}|$$

- There is now a unitarity quadrangle

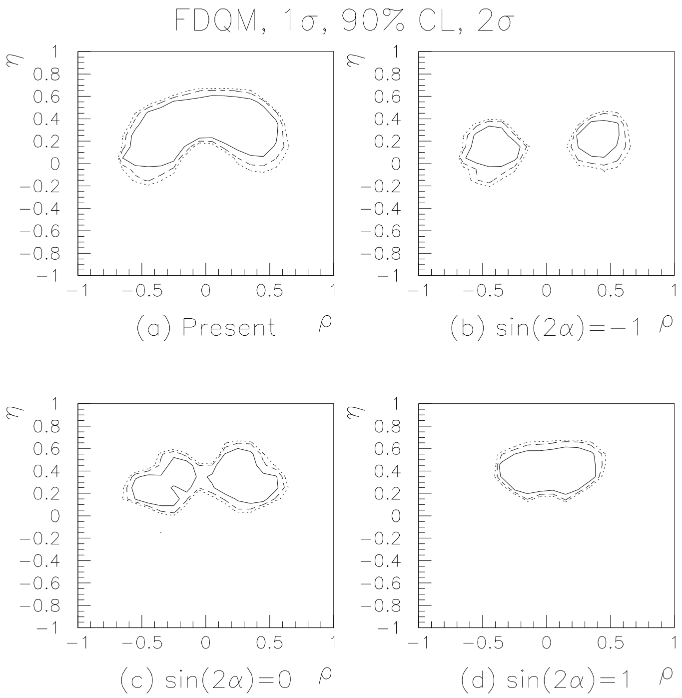
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} + V_{4b}^* V_{4d} = 0$$

  where the last term has limits $|U_{bd}/V_{cb}^* V_{cd}| \leq 0.15$, as will be shown later.

- The near half circles in $\gamma = \delta = \delta_{13}$ ($V_{ub}^* = s_{13} e^{i\delta_{13}}$) at present are due to δ_{14} or δ_{24} (which are related) becoming some of the source of the observed CP violation in ϵ, so that δ_{13} is less constrained. Then, δ_{13} can be closer to zero or 180° so that η can also be small.

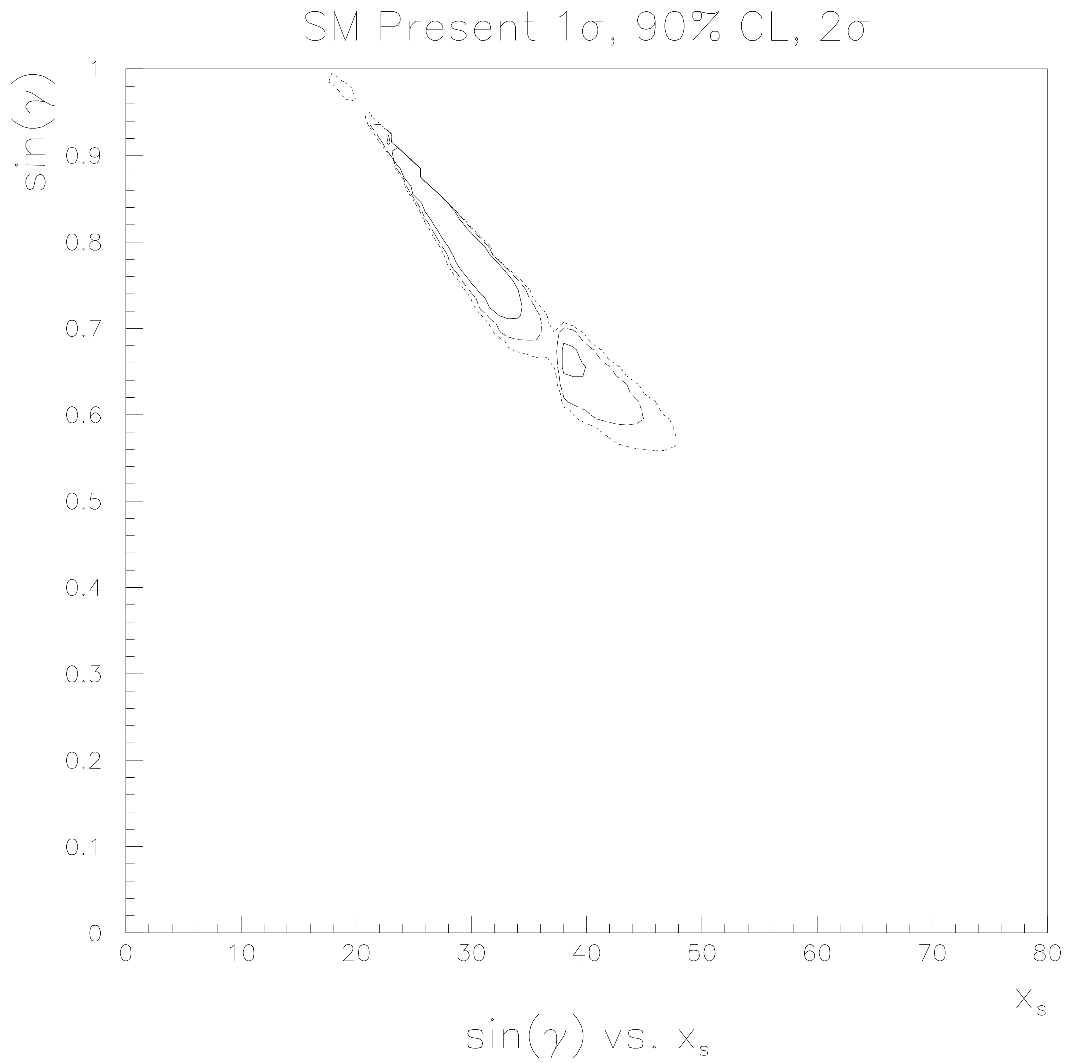
- The regions no longer go into the negative η half-plane due to the $K^+ \to \pi^+ \nu \bar{\nu}$ results.

- For projected $\sin(2\alpha) = +1$, 0, or -1, we see regions extended beyond the SM regions, which also allow δ_{13} or η to be small.



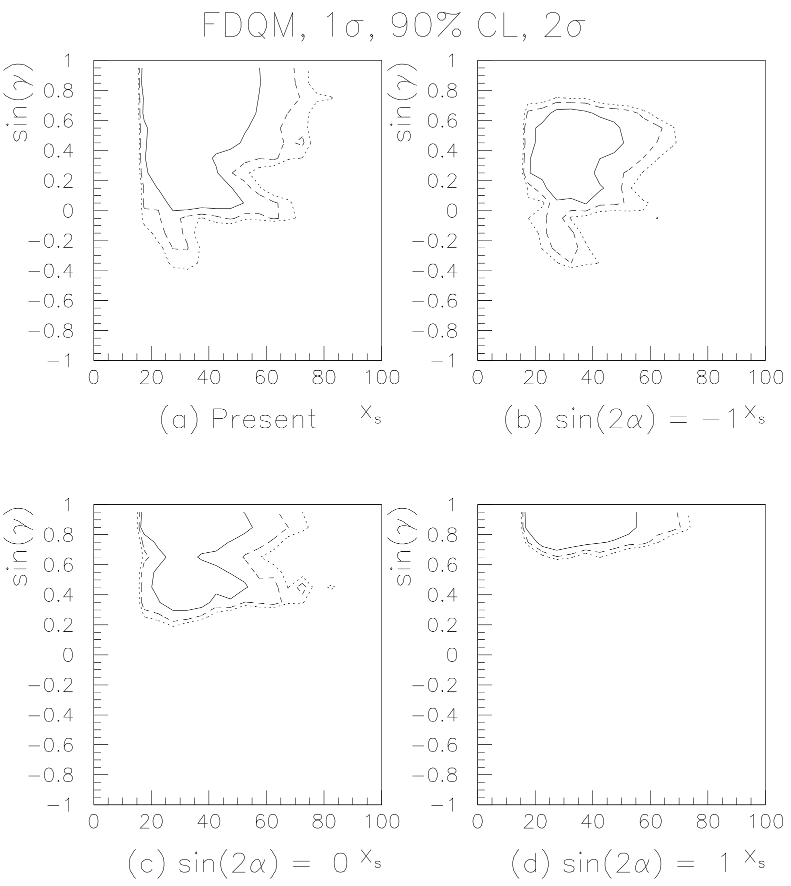
26 Standard Model Alone $(x_s, \sin(\gamma))$ Plots

- From present data at 2σ the limits are $0.56 \leq \sin(\gamma) \leq 0.99$, and $16 \leq x_s \leq 48$.
- Because of the approximately linear relation between x_s and $\sin(\gamma)$, an exact x_s measurement ($\propto 1/|V_{td}|^2$) can strongly constrain $\sin(\gamma)$ to ± 0.07 in the SM.



27 Four Down Quark Model $(x_s, \sin(\gamma))$ Plots

- In the FDQM, the extended $\sin(\gamma)$ range including negative $\sin(\gamma)$ is no longer needed as η is now positive or near zero due to the $\sin(2\beta)$ measurements.
- A larger $\sin(\gamma)$ range, from 0 to 1 at 1σ, is allowed in the FDQM than in the SM.
- The x_s allowed region in the FDQM is 16 to 80 at 2σ, larger than in the standard model.
- In the FDQM, there is no approximately linear relation between $\sin(\gamma)$ and x_s as there is in the SM. Thus an accurate measurement of x_s still leaves a very large region of $\sin(\gamma)$ available. A subsequent $\sin(\gamma)$ measurement will be needed to distinguish between the two models.



28 B_s Decay Asymmetry from B_s Mixing, $\sin(2\phi_s)$

- ϕ_s is the small angle in the $b-s$ unitarity triangle given by

$$V_{cb}^* V_{cs} + V_{tb}^* V_{ts} + V_{ub}^* V_{us} = 0.$$

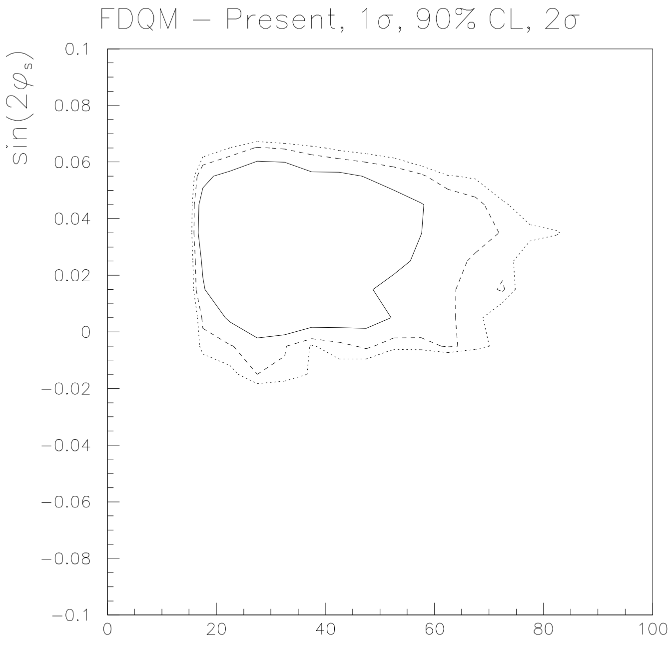
- In Wolfenstein terms this is

$$(A\lambda^2) \times 1 + 1 \times (-A\lambda^2) + (A\lambda^3(\rho + i\eta)) \times \lambda = 0.$$

- Then, $\sin(\phi_s) = A\lambda^4\eta / A\lambda^2 = \lambda^2\eta$.
- This is almost zero in the Standard Model where $\sin(2\phi_s) = 2\lambda^2\eta = 0.10\eta$, or at 2σ

$$0.030 \leq \sin(2\phi_s) \leq 0.060.$$

- In the FDQM, $-0.2 \leq \sin(2\phi_s) \leq 0.065$ at 2σ.
- Here the range continues down to zero since η can go down to zero.
- Hence, a value of $\sin(2\phi_s) \leq 0.03$ would signify a deviation from the SM.



B_s Asymmetry $\sin(2\varphi_s)$ vs x_s

29 Fourth Side of the Unitary Quadrangle U_{bd}

➤ Unitarity of the $b - d$ columns has four terms, which may be written as

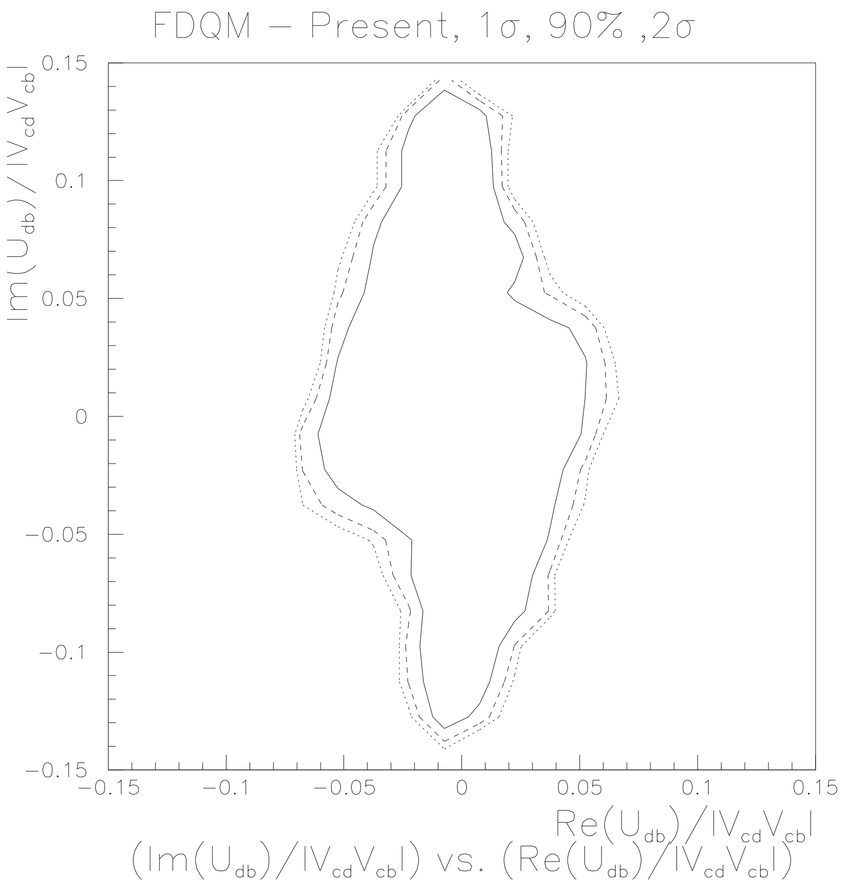
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} - U_{bd} = 0, \tag{1}$$

since $-U_{bd} = V_{4b}^* V_{4d}$. (We use $U_{db} = U_{bd}^*$).

➤ As the unitarity triangle is scaled by $|V_{cb}^* V_{cd}|$ to make a unit base, the complex plot of U_{bd} is also so scaled.

➤ The length of the $U_{bd}/|V_{cb}^* V_{cd}|$ side is thus of the order of 0.1, compared to the unit base in the (ρ, η) plot, prefering possibly a more vertical direction.

➤ The accuracy of angles and sides of the unitarity triangle must and should reach this accuracy for a good test of the SM.

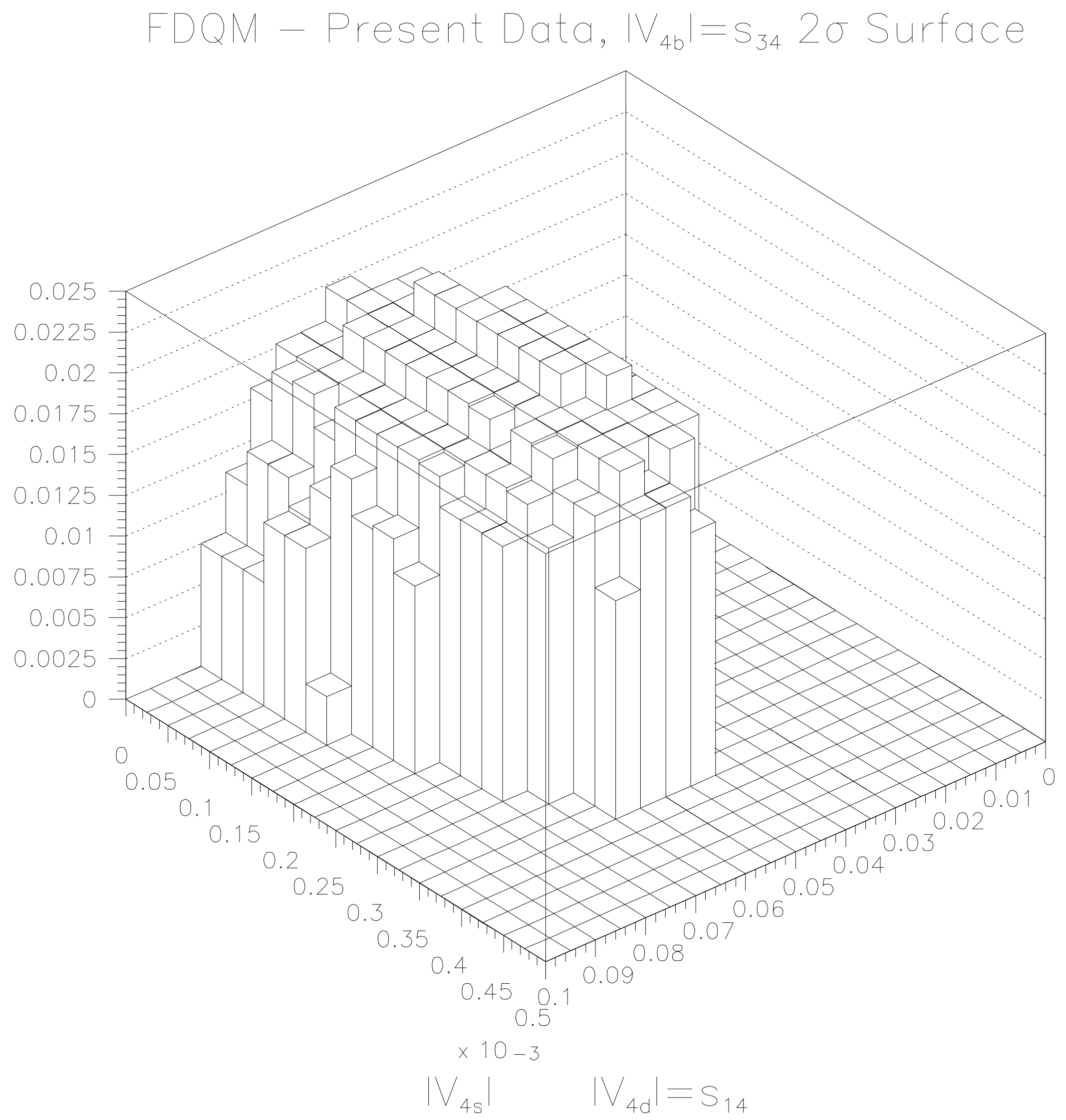


30 Size of the Mixing Matrix Elements and Mixing Angles

- To 5% accuracy, $V_{4d} = -s_{14}e^{i\delta_{14}}$, and its magnitude ranges from 0.04 to 0.08 at 2σ (see next slide).
- To 10% accuracy, $V_{4b} = -s_{34}$, and its magnitude ranges up to 0.023 at 2σ.
- V_{4s} is bounded by 0.0004, and requires a fine cancellation in $-s_{24}e^{i\delta_{24}} - s_{12}s_{14}e^{i\delta_{14}}$, such that $s_{24} \approx s_{12}s_{14}$ and $\delta_{24} = \delta_{14} + \pi$ to get the cancelling minus sign.
- This means that there is effectively only one new phase, which we may consider as δ_{14}.
- From the cancellation, s_{24} ranges from 0.009 to 0.017 at 2σ.
- The cancellation is to about 1/20 of the value of s_{24}.
- The third term in V_{4s}, $s_{34}(s_{23} + s_{12}s_{13}e^{i\delta_{13}})$ then contributes the same order, ≤ 0.0009.
- The cancellation does not mean fine tuning since one could have parametrized V_{4s} by s_{24} instead. However, the incredibly small size of $|V_{4s}| \leq \lambda^5$ could be considered a fine tuning itself.
- In Wolfenstein terms, $|V_{4d}| = s_{14} \approx \lambda^2$, $s_{24} \approx s_{12}s_{14} \approx \lambda^3$, $|V_{4b}| = s_{34} < \lambda^2/2$, but $|V_{4s}| \leq \lambda^5$. The sequence violates the heirarchical expectation from the 3×3 CKM matrix.
- In the double FCNC Z^0 exchange amplitude in $B_d - \bar{B}_d$ mixing, via

$$U_{db} = -V_{4d}^* V_{4b} = s_{14}e^{-i\delta_{14}}s_{34},$$

it is only the δ_{14} phase in $(U_{db})^2 \approx e^{-2i\delta_{14}}$ that can add to the SM box diagram term with its phase $e^{2i\beta}$.


FDQM − Present Data, $|V_{4b}|=s_{34}$ 2σ Surface
0.025
0.0225
0.02
0.0175
0.015
0.0125
0.01
0.0075
0.005
0.0025
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
x 10 −3
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
$|V_{4s}|$
$|V_{4d}|=s_{14}$

31 Conclusions for Iso-singlet Down Quark Models

- FCNC can contribute significantly to $B_d - \bar{B}_d$ mixing and to $B_s - \bar{B}_s$ mixing, and give new phases.
- All $\sin(2\alpha)$ are allowed.
- There are larger allowed regions in the (ρ, η) and in the $(x_s, \sin(\gamma))$ plots from new physics with new phases after the B factory results.
- This will require the additional experiments of x_s and $\sin(\gamma)$, first to isolate a region, and then to rule in or out a new physics model.
- In new physics models, the SM phase δ can be smaller or arbitrary, with the other phases causing the presently observed CP violation.
- The present range for x_s is from 16 to 48 at 2-σ in this SM analysis, and from 16 to 80 at 2-σ in the four down quark model.
- The $\sin(\gamma)$ range is from 0.56 to 0.99 at 2-σ in the SM analysis, and from 0 to 1 in the four down quark model.
- The unitarity triangle has to be measured to an accuracy of 0.1 to test the SM.
- Each E_6 generation also contains an iso-singlet neutrino, which may provide a connection between the quark and lepton searches for new physics.
- The mass of the lightest singlet down quark in E_6 could be roughly related to the mixing angle by

  $$\theta_{34}^2 \simeq m_b/m_D, \quad |V_{4b}| \simeq \theta_{34} \leq 0.02$$

  (from combined fits), giving

  $$m_D \geq 2500 \times m_b = 11 \text{ TeV}.$$

  Using the single R_b 90% CL limit of $|\theta_{34}| \leq 0.035$, which is not as good, gives $m_D \geq 4$ TeV. The previous analysis (1998) gave a limit of 1.2 TeV.
- This talk is on the web at http://www.physics.uci.edu/~silverma/newtalk.ps.