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Stanford Linear Accelerator Center
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Using Charm to Probe New Physics

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- Physics Reports (in prep.)

Goals:

- Improve accuracy of Standard Model predictions
- Find models which have large effects in charm system
- Differentiate between possible models
 - Disentangle new physics effects by examining different channels

Motivation:

- test SM in up-quark sector
- SM FCNC rates small \Rightarrow possible window for new physics!
- high volume charm data
 - γ/c factory (?) ; LEP ; CLEO III ; SLAC/KEK B-factories ;
 - HERA ; Fermilab fixed target upgrades w/ main injector

Models

* 1) Standard Model

2) Extended Higgs Sector

* a) Two-Higgs-Doublet Models

b) Three-Higgs-Doublet Models

* c) Multi-Higgs Models with Flavor Changing Couplings

3) Additional $Q = -1/3$ Quarks

* a) Fourth Generation

* b) E_6

c) Mirror Fermions

4) Supersymmetry

* a) MSSM

* b) Non-degenerate \tilde{q} 's

c) R-Parity Violation

5) Left-Right Symmetric Models

* a) Classic LRM

* b) Alternate LRM (based on E_6)

c) Gronau-Wakaizumi (right-handed b decays)

6) Techni-color / Compositeness

a) Extended TC

* b) Leptoquarks

7) Family (Horizontal) Symmetries

Processes

* 1) $D^0 - \bar{D}^0$ Mixing

2) Rare Decays

$$D \rightarrow \mu^+ \mu^-$$

$$e^+ e^-$$

$$\mu^\pm e^\mp$$

$$\gamma\gamma$$

$$\gamma + X(\rho^0, \rho^\pm, \phi)$$

$$\bar{l}l + X(\pi^\pm, K^\pm, \bar{K})$$

$$\nu\bar{\nu} + X(\pi^0, \pi^\pm, K^\pm, \bar{K})$$

3) CP Violation

4) Asymmetries in

$$Z \rightarrow c\bar{c}$$

$D^0 - \bar{D}^0$ Mixing

$$\text{Exp't: } x_D = \frac{\Delta m_D}{\Gamma} \leq 0.083$$

$$r_D = \frac{\Gamma(D^0 \rightarrow l^- X)}{\Gamma(D^0 \rightarrow l^+ X)} < 8 \times 10^{-3} \quad (E791)$$

future sensitivity r_D at $10^{-5} - 10^{-4}$ level

$$\Delta m_D = \Delta m_{D_{\text{box}}} + \Delta m_{D_{\text{L.D.}}}$$

$\Delta m_{D_{\text{box}}}$: External momentum non-negligible! (Datta et al.)

$$H_{\text{eff}}^{\Delta c=2} = \frac{G_F \alpha}{\sqrt{2} 8\pi \lambda_W} \left[|V_{cs} V_{us}^*|^2 \left(I_1 \left(\frac{m_s^2}{m_c}, \frac{m_b^2}{m_c} \right) O - m_c^2 I_2 O' \right) \right. \\ \left. + |V_{cb} V_{ub}^*|^2 \left(I_3 \left(\frac{m_b^2}{m_c}, \frac{m_b^2}{m_c} \right) O - m_c^2 I_4 O' \right) \right]$$

$$O = \bar{u} \gamma_\mu (1 - \gamma_5) c \bar{u} \gamma_\mu (1 - \gamma_5) c$$

$$O' = \bar{u} (1 + \gamma_5) c \bar{u} (1 + \gamma_5) c$$

$$\boxed{\Delta m_{D_{\text{box}}} \sim 5 \times 10^{-15} \text{ GeV}}$$

$$\Delta m_{D_{\text{exp't}}} \sim 1.3 \times 10^{-13} \text{ GeV}$$

$\Delta m_{D_{\text{L.D.}}}$:

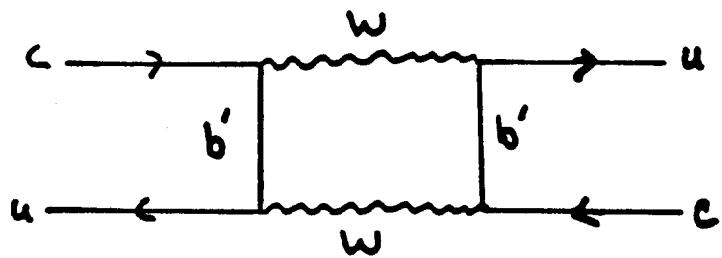
$$\Delta m_{D_{\text{L.D.}}} \sim \begin{cases} 10^{-4} \Gamma \simeq 10^{-16} \text{ GeV} & (\text{Donoghue et al}) \\ (1-2) \times 10^{-5} \Gamma \simeq 10^{-17} \text{ GeV} & \text{HQET (Georgi)} \end{cases}$$

Fourth Generation

CDF

$$m_{b'} > 85 \text{ GeV} \text{ if CC. decays}$$

$$> 65 \text{ GeV} \text{ if FCNC}$$



⇒ Neglect External momentum!

$$\Delta m_D = \frac{G_F^2 m_w^2 m_0}{6\pi^2} f_D^2 B_0 \eta \left| \frac{V_{cb'}}{V_{ub'}} V_{ub'}^* \right|^2 F\left(\frac{m_{b'}^2}{m_w^2}\right)$$

4 Generation CKM Unitarity:

$$+ \quad V_{cb} = 0.0362 \pm 0.0019 \pm 0.0020 \pm 0.0014 \quad (\text{CLEO})$$

$$+ \quad \left| \frac{V_{ub}}{V_{cb}} \right| = 0.08 \pm 0.02 \quad (\text{CLEO/ARBUS})$$

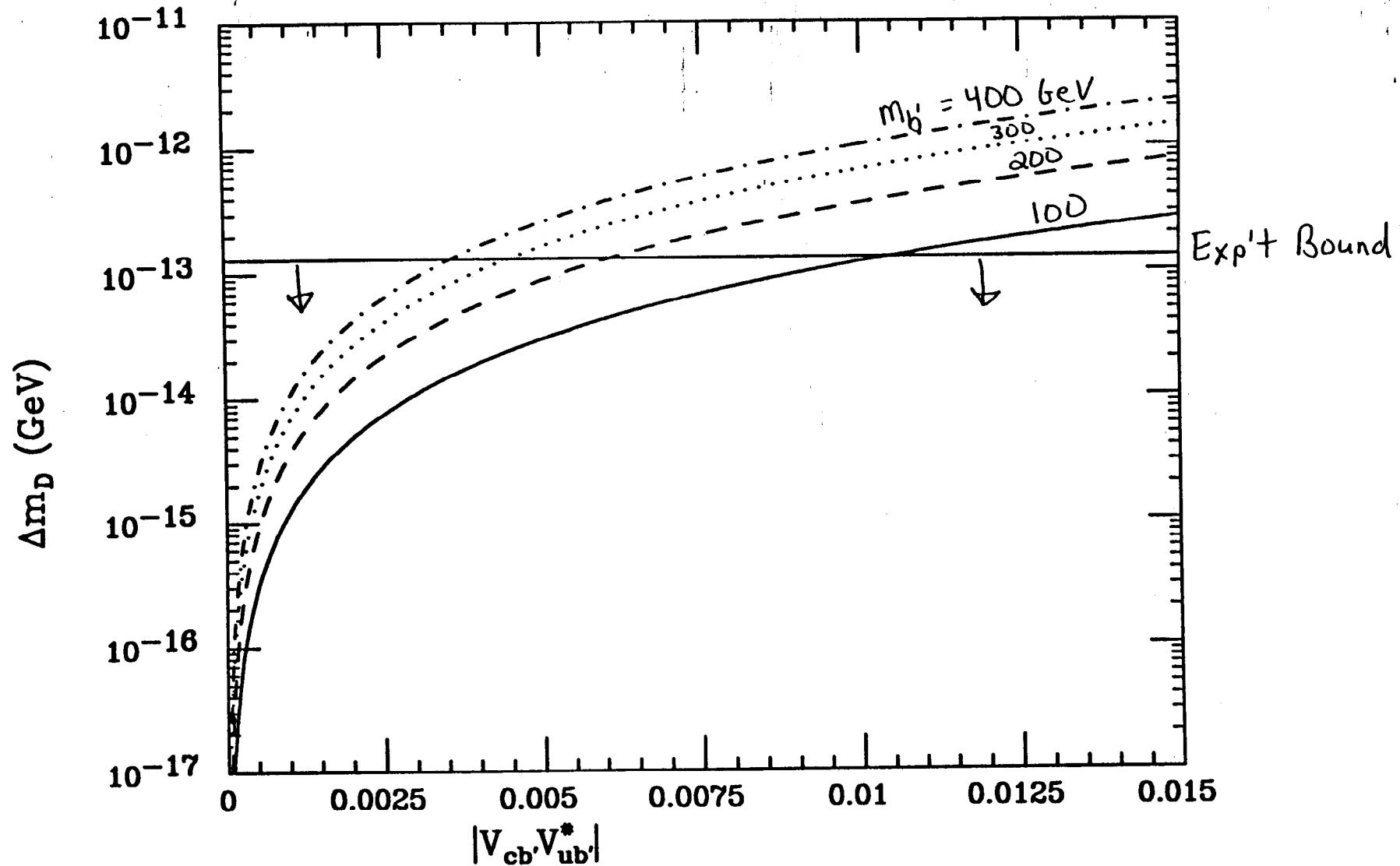
Naive estimate from 1994 PDG

$$|V_{ub'}|^2 = 1 - |V_{cd}|^2 - |V_{cs}|^2 - |V_{cb}|^2$$

$$\Rightarrow |V_{ub'}| < 0.078$$

$$|V_{cb'}| < 0.571$$

4th Generation Contributions to $D^0 - \bar{D}^0$



E₆

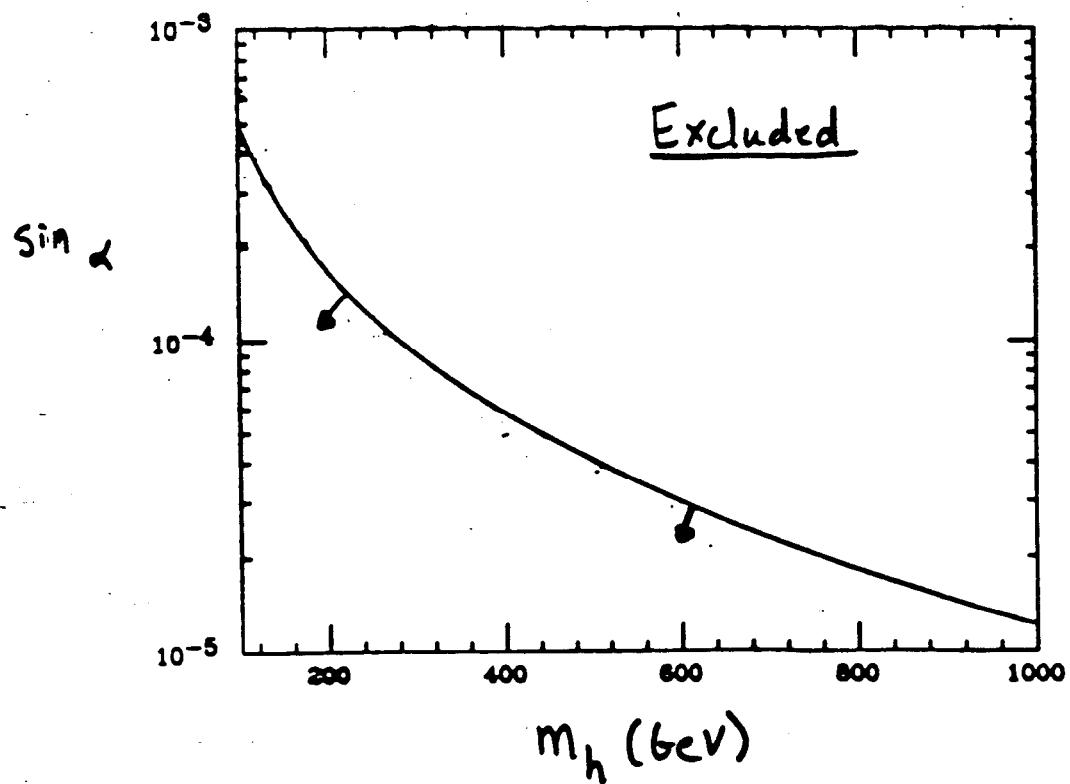
Exotic h-quark in 27

- vector-like, $Q = -\gamma_3$, iso-singlet

CKM matrix is not unitary

$$V_{CKM} = \begin{pmatrix} c_1 & s_1 c_3 & s_1 s_3 c_\delta & -s_1 s_3 s_\delta \\ -s_1 c_2 & c_1 c_2 c_3 + s_2 s_3 e^{i\delta} & (c_1 c_2 s_3 - s_2 c_3 e^{i\delta}) c_\delta & (-c_1 c_2 s_3 + s_2 c_3 e^{i\delta}) s_\delta \\ -s_1 s_2 & c_1 s_2 c_3 - c_2 s_3 e^{i\delta} & (c_1 s_2 s_3 + c_2 c_3 e^{i\delta}) c_\delta & -(c_1 s_2 s_3 - c_2 c_3 e^{i\delta}) s_\delta \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

for 1 generation
of h-quarks



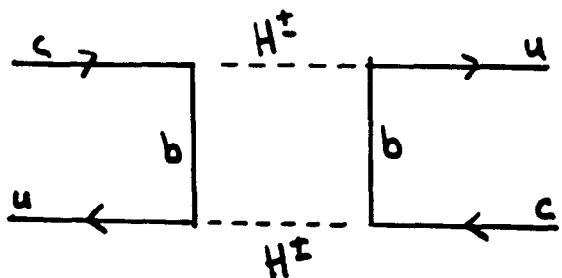
Multi-Higgs - Doublet - Models

• 2HDM

$$\begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \quad \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \xrightarrow{\text{S.S.B.}} h^0, H^0, A^0, H^\pm$$

$$v_1^2 + v_2^2 = v_{sm}^2$$

$$\Rightarrow \tan\beta \equiv v_2/v_1$$



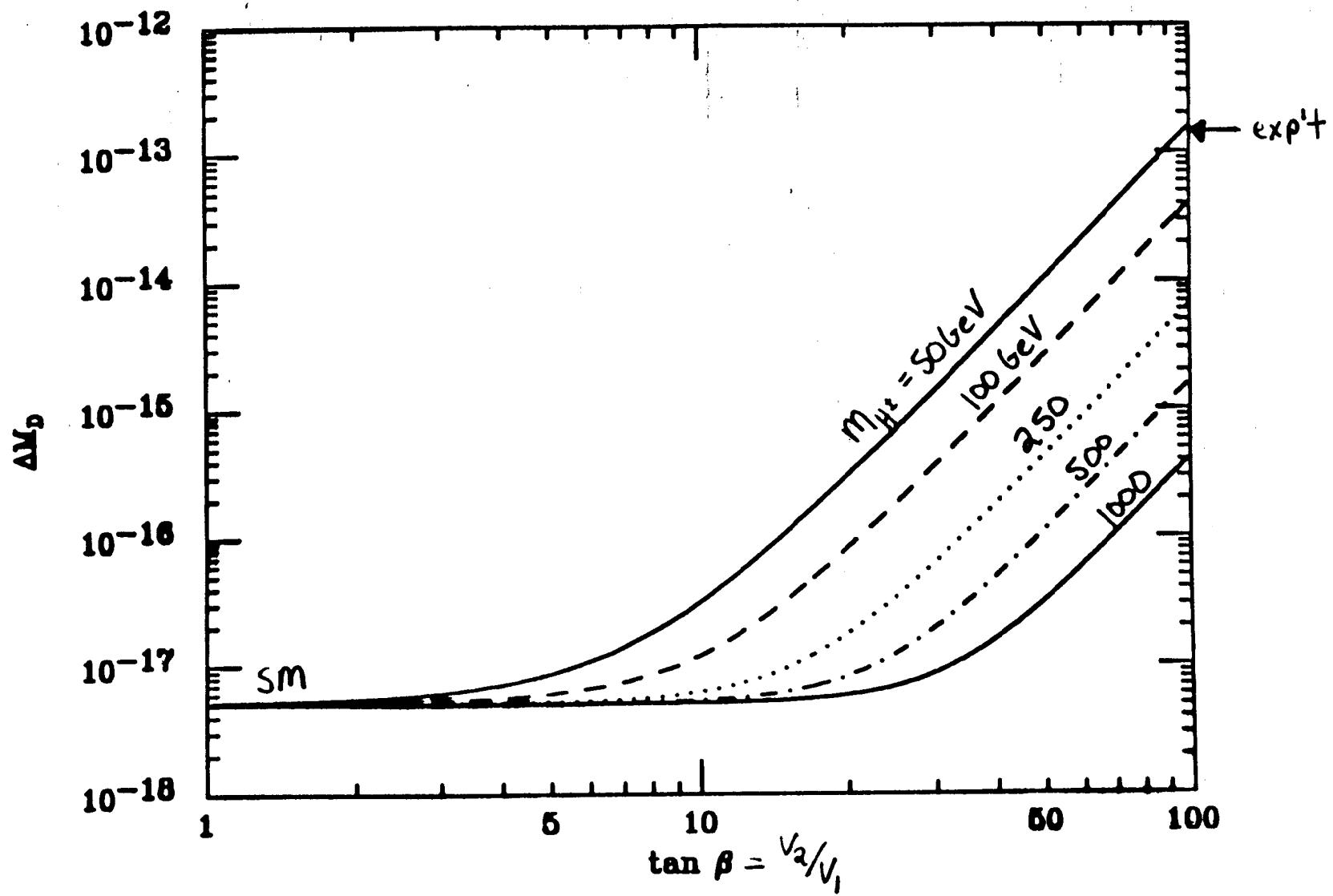
- No tree-level FCNC if each fermion type receives mass from only 1 doublet

$$\mathcal{L}_{cbH^+} = \frac{g}{2\sqrt{2}M_W} \left\{ \frac{m_c}{\tan\beta} V_{cb} \bar{c}(1-\gamma_5)b + m_b \tan\beta V_{cb} \bar{c}(1+\gamma_5)b \right\} H^+ + \text{h.c.}$$

$$\Delta m_D = \frac{G_F^2 M_W^2 m_D}{6\pi^2} f_D^2 \eta |V_{cb} V_{ub}^*|^2 \left[\frac{m_c^2}{m_W^2 \tan^2\beta} F_1 \left(\frac{m_c^2}{m_{H^\pm}^2} \right) + \frac{m_b^2 \tan^2\beta}{m_W^2} F_2 \left(\frac{m_b^2}{m_{H^\pm}^2} \right) \right]$$

Two-Higgs-Doublet-Model II

213



Flavor Changing Neutral Higgs

SM Higgs Coupling $\sim (\sqrt{2} G_F)^{1/2} m_f$

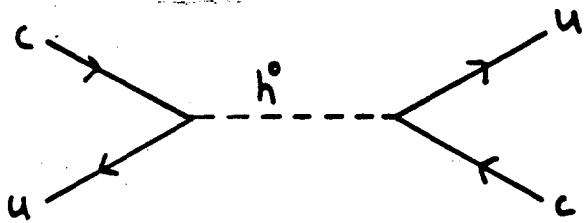
2HDM w/ FC Couplings

$$f_i \quad h^0 \quad f_j \quad \sim (\sqrt{2} G_F)^{1/2} \sqrt{m_i m_j} \Delta_{ij}$$

{ mixing factor
 Pakvasa + Sugawara
 Hall + Weinberg
 Cheng + Sher
 Hou ...

\Rightarrow small effect for light fermions

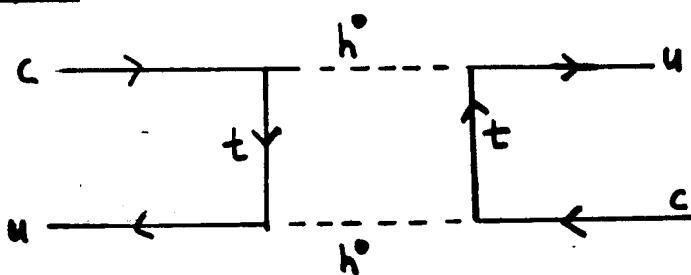
tree-level



$$\Delta m_D = \frac{4\sqrt{2} G_F m_u m_c \Delta^2 f_0^2 m_0}{3 m_h^2}$$

!

box

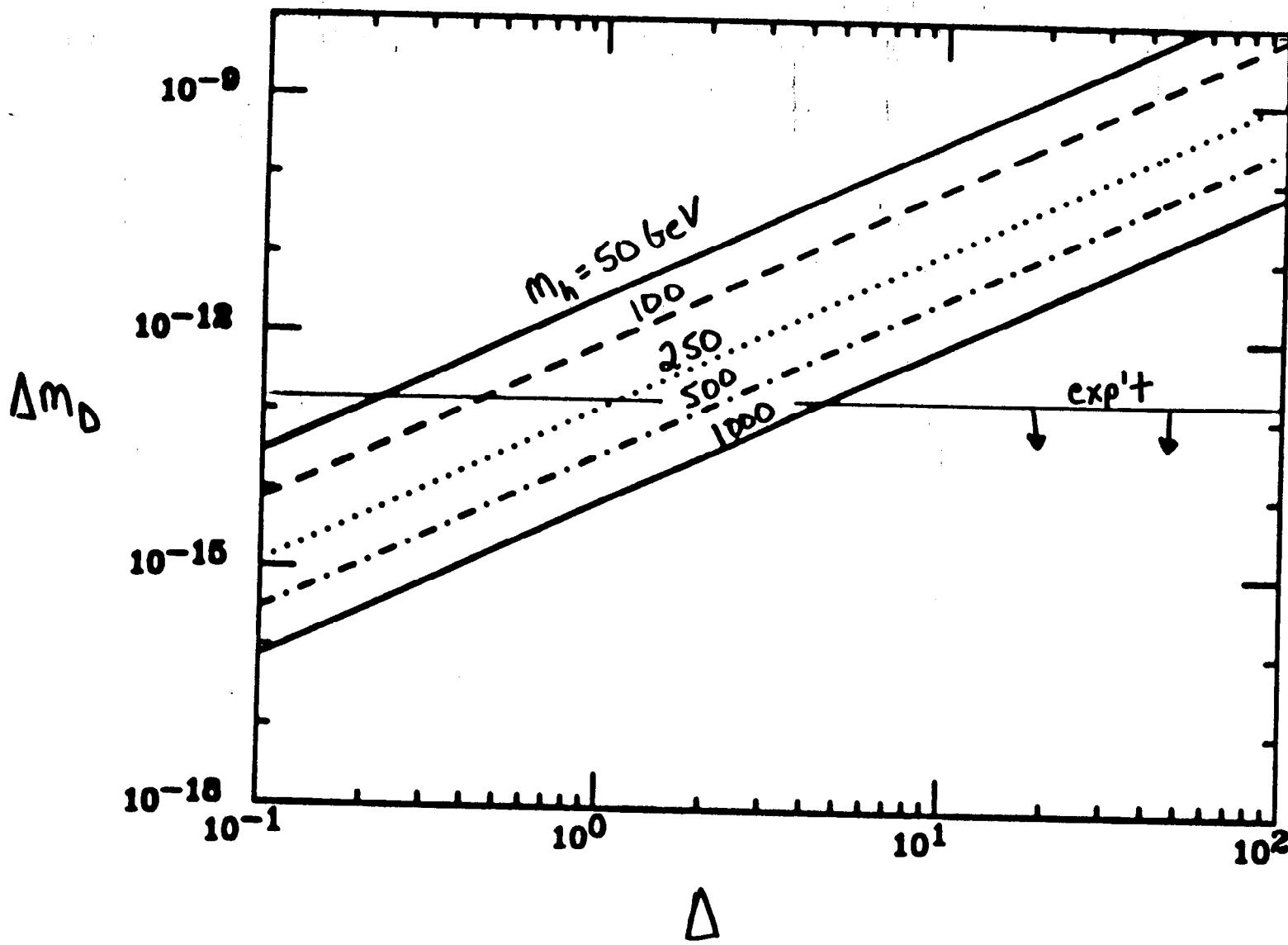


could be big!

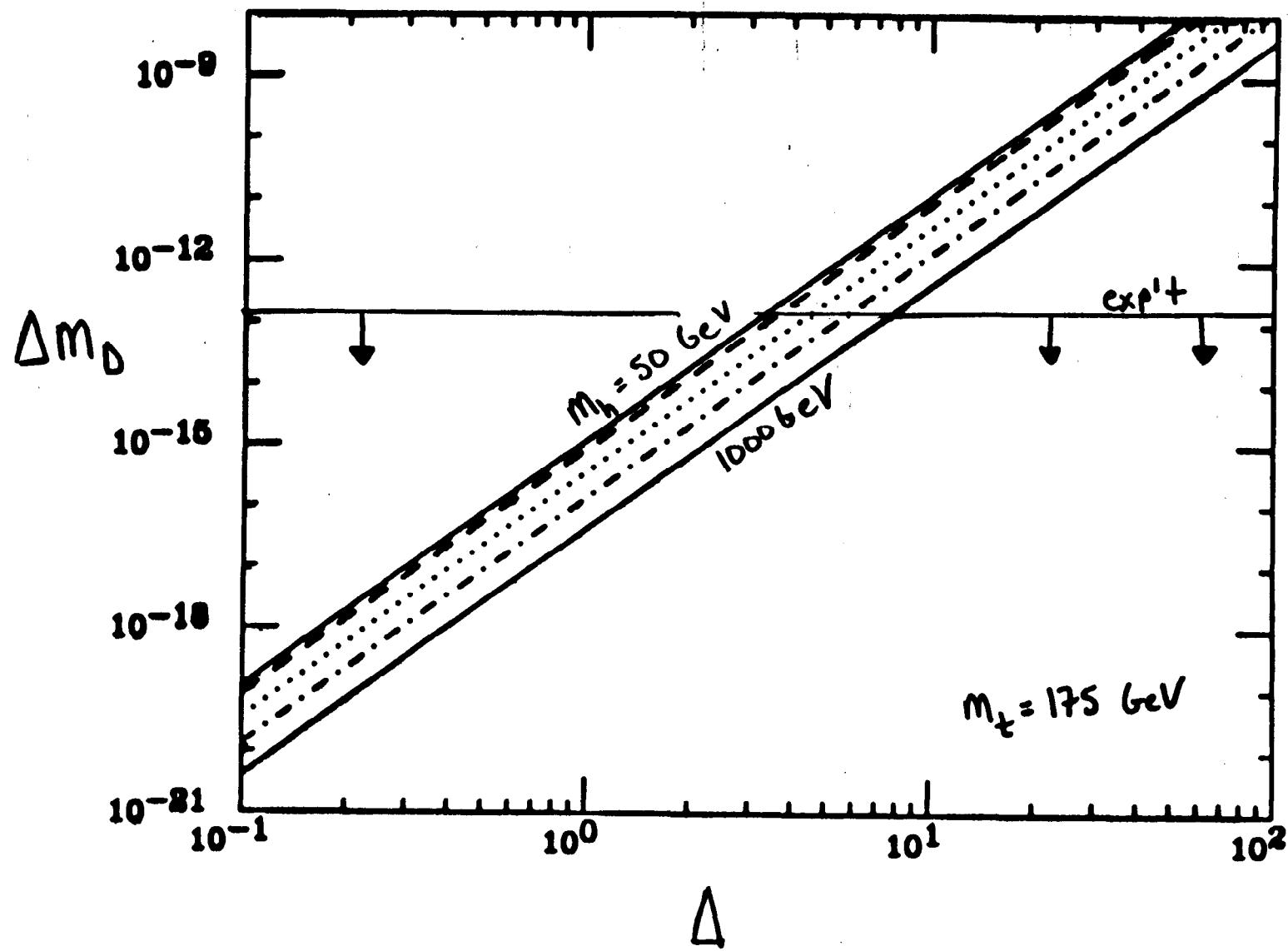
$$\Delta m_D = \frac{2 G_F^2 m_u m_c m_t^2 \Delta^4 f_0^2 m_0}{3 \pi^2 m_h^2} \left[\frac{1}{(x-1)} - \frac{\ln x}{(x-1)^2} - \frac{1}{2(x-1)^3} (x^2 - 4x + 3 + 2\ln x) \right]$$

$x = m_t^2 / m_h^2$

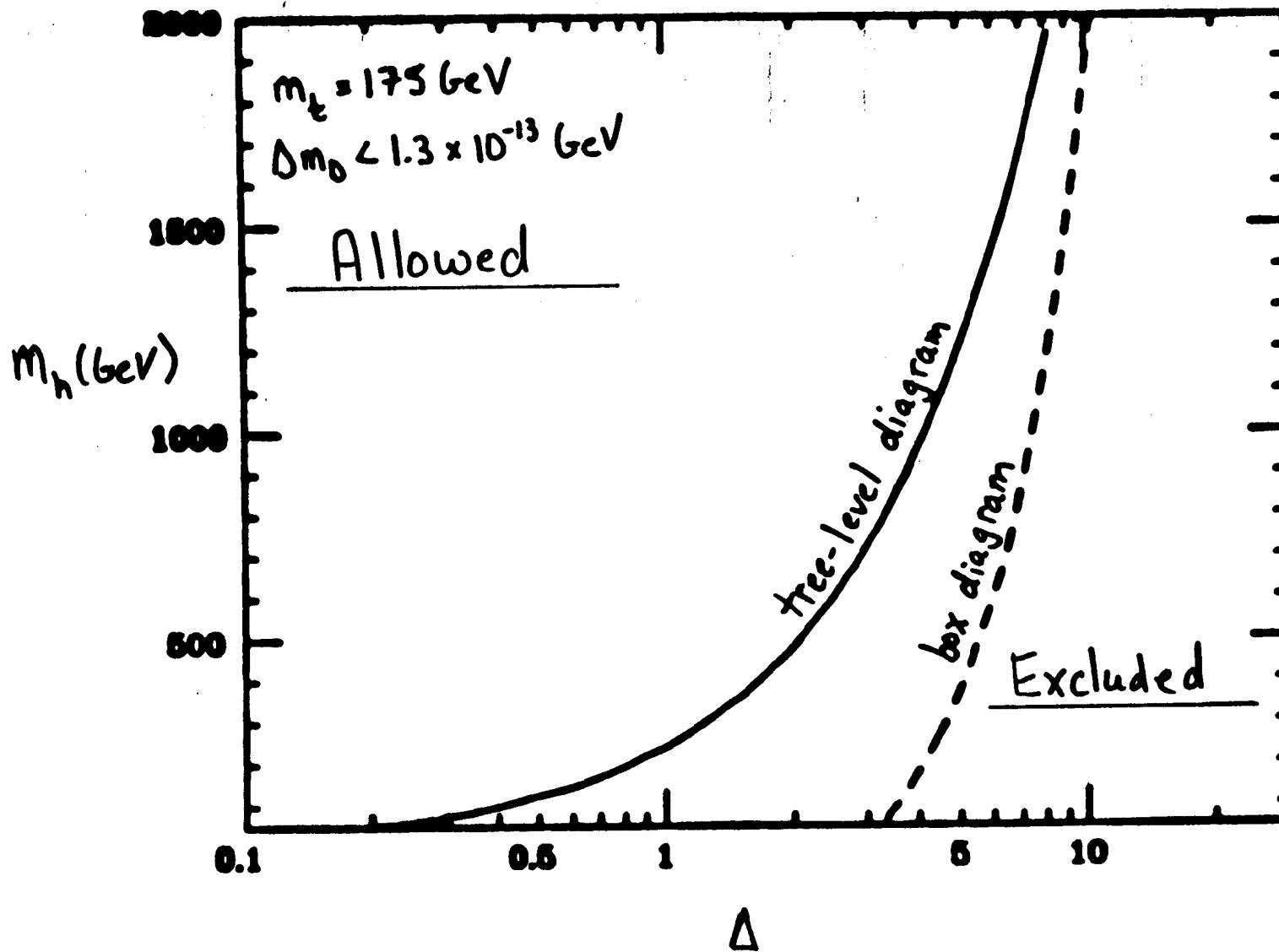
tree-level FC Higgs



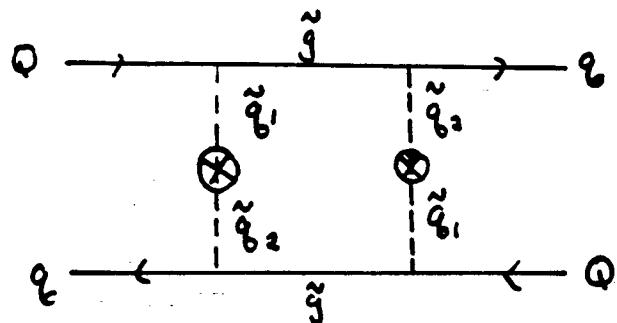
FC Higgs - Box Diagram



Flavor Changing Higgs



Supersymmetry



SUPER-KM basis
 $\Rightarrow \tilde{g} \tilde{q}_b q$ couplings
 flavor diagonal
 \Rightarrow FCNC generated by
 \tilde{q}_b mass mixing

$$\text{FC } \tilde{q}_b \text{ mass insertions: } (\Delta_{LL}^u)_{ij} = c (V^* (m_q^{diag})^2 V)_{ij}$$

$\Rightarrow \Delta m_K$ constrains squarks to be (approx.) degenerate

Alternative: Align $\tilde{q}_b + q$ mass matrices to suppress FCNC
 (Nir, Seiberg)

Can satisfy all FCNC constraints w/o degenerate \tilde{q}_b 's !

Prediction

$$(\Delta_{LL}^u)_{12} \sim 0.2$$

Expt limit from $D^0 - \bar{D}^0$ mixing gives

$$(\Delta_{LL}^u)_{12} < 0.1$$

\Rightarrow Predicts $D^0 - \bar{D}^0$ mixing just below expt bound !

Virtual Contributions

1) \tilde{W}^{\pm} + d,s,b

2) H^\pm + d,s,b

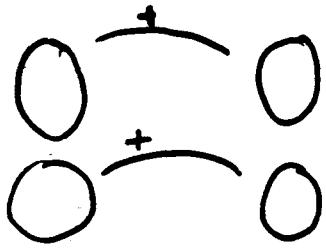
3) \tilde{g} + $\tilde{u}, \tilde{c}, \tilde{t}$

4) $\tilde{\chi}^0$ + $\tilde{u}, \tilde{c}, \tilde{t}$

5) $\tilde{\chi}^+$ + $\tilde{d}, \tilde{s}, \tilde{b}$

small!

small - except for large $\tan \beta$



light \tilde{t} - strong coupling ★★

light \tilde{t} ~ electroweak strength coupling

SUSY - GIM

$$m_{\tilde{t}}^2 = \begin{bmatrix} m_Q^2 + m_t^2 + m_{\tilde{t}}^2 c_{2\beta} (V_2 - x_w Q_t) & m_t (A_t - u/\tan \beta) \\ m_t (A_t - u/\tan \beta) & m_Q^2 + m_t^2 + m_{\tilde{t}}^2 c_{2\beta} x_w Q_t \end{bmatrix}$$

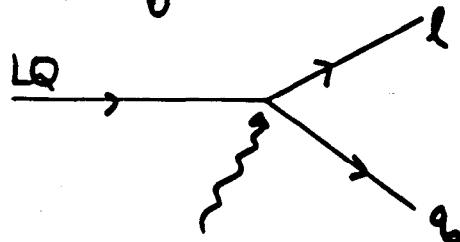
$$\tilde{t}_1 = \cos \theta_t \tilde{t}'_L - \sin \theta_t \tilde{t}'_R$$

$$\tilde{t}_2 = \sin \theta_t \tilde{t}'_L + \cos \theta_t \tilde{t}'_R$$

Mixing can be large!

light \tilde{t}_1 , 'favored' by $b \rightarrow s\gamma + Z \rightarrow b\bar{b}$

Leptoquarks



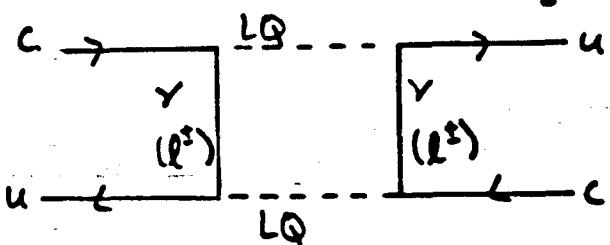
Naturally present in models which place q 's + l 's on equal footing

GUTS - SO(10), E₆
Compositeness
Technicolor

λ = 'unknown' coupling strength

$$\Rightarrow \frac{\lambda^2}{4\pi} = F \alpha$$

fudge factor

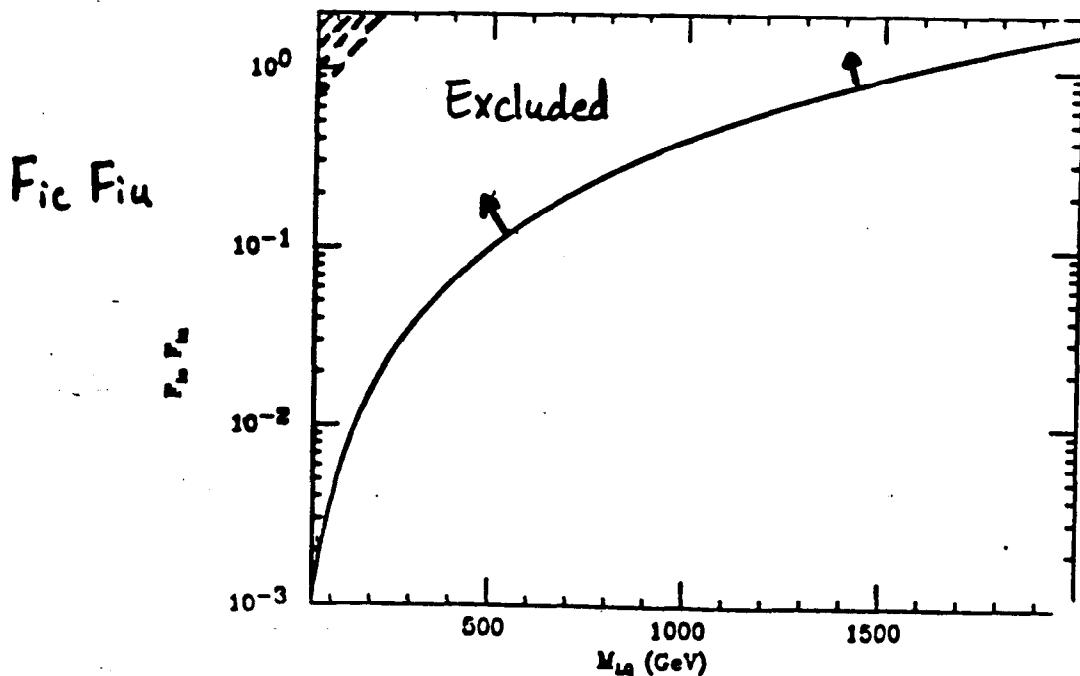


Scalar LQ contributions

$$\Delta m_D \sim |\lambda^{lc} \lambda^{lu}|^2 / (2\pi)^3 \frac{K^u K^l}{(K^u - m_{LQ}^2)^2 (K^l - m_{LQ}^2)^2} \times \langle D_1 \bar{O}_m \bar{l} D \rangle$$

Assume no LQ-GIM $\Rightarrow \frac{F_{lc} F_{lu}}{m_{LQ}^2} < \frac{196 \pi^2 \Delta m_D}{(4\pi^2)^2 f_D^2 m_D}$

HERA Excluded (Zeus)



Left-Right Symmetric Model

$$G_{EW} = \text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)_{B-L}$$

• Manifest LRS $\Rightarrow V_L = V_R$

$$\left. \begin{array}{l} m_{W_R} > 1 \text{ TeV} \\ m_H > 4 \text{ TeV} \end{array} \right\} \begin{array}{l} \text{from contributions} \\ \text{to } K_L - K_S \end{array} \quad (\text{Beall, Bender, Soni})$$

$$\Delta m_0 = \Delta m_0^H + \Delta m_0^{W_R} + \Delta m_0^{SM}$$

with $\Delta m_0^{W_R} \ll \Delta m_0^H < 10^{-16} \text{ GeV}$

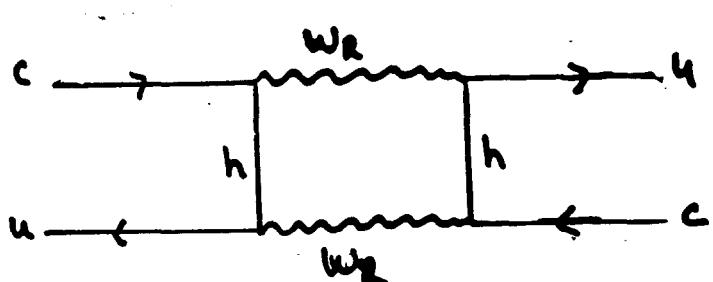
Alternate Left-Right Model

(E. Ma)

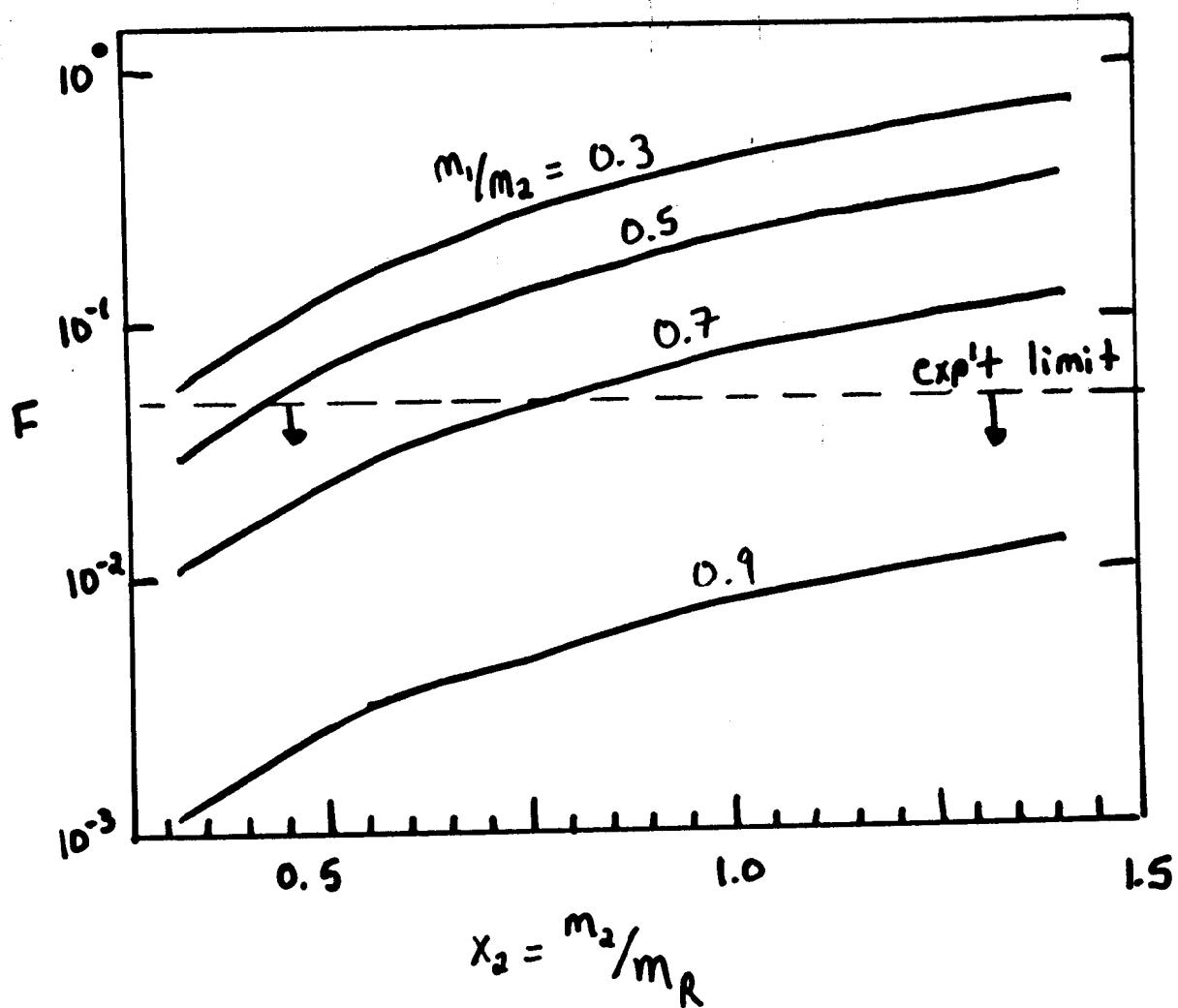
embedded in E₆ GUTS

W_R couples u_R to exotic h_R⁻ quarks

$$\frac{\Delta m_0}{3 \times 10^{-16} \text{ GeV}} = \left(\frac{m_W}{m_{W_R}} \right)^2 \frac{\sin^2 \theta_R}{0.05} \frac{\cos^2 \theta_R}{0.95} \left(\frac{f_D f_{B_D}}{150 \text{ MeV}} \right)^2 F(x_1, x_2)$$



$$x_i = \frac{m_{h_i}^2}{m_{W_R}^2}$$

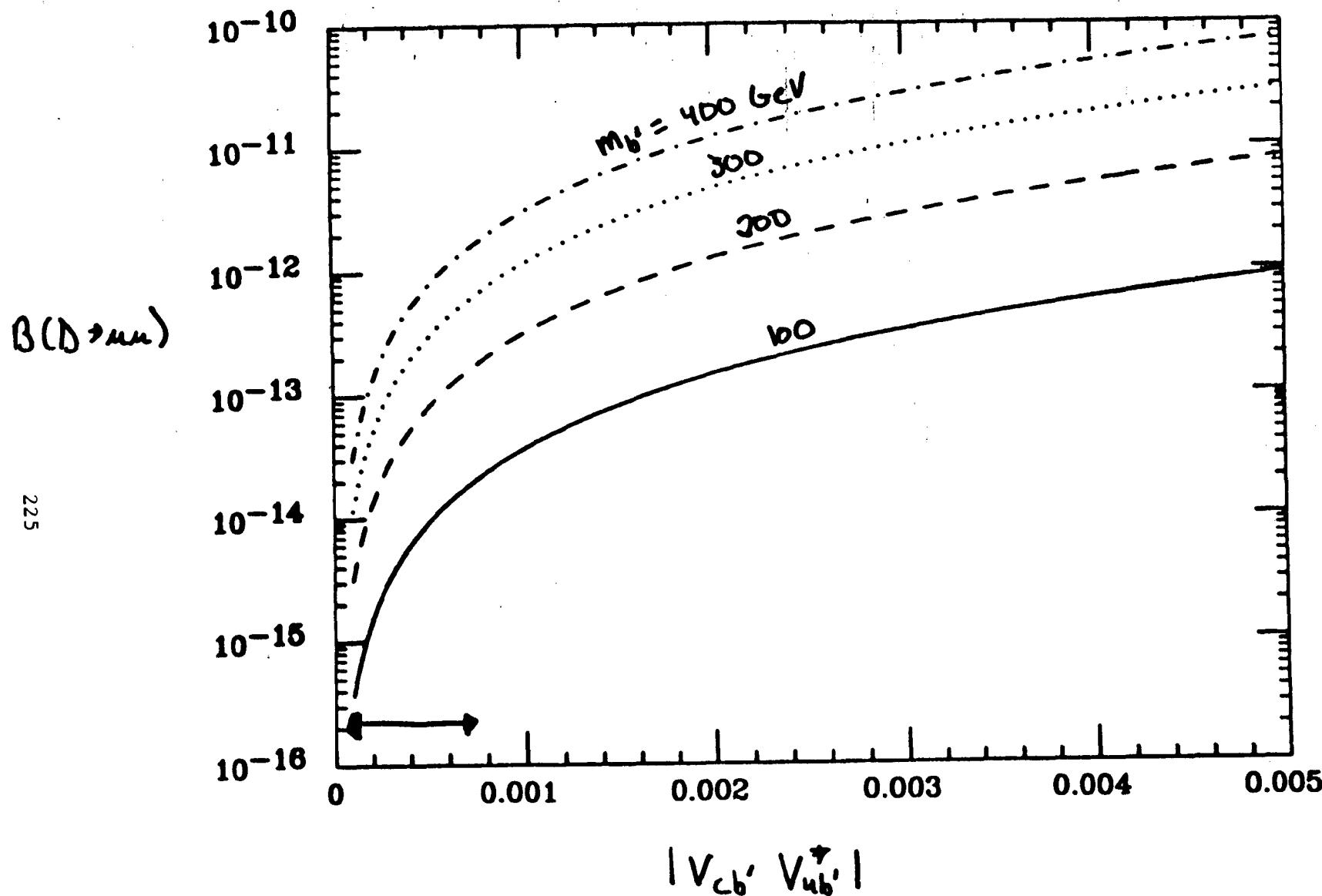


FCNC Branching Fractions in Standard Model

Process	Expt Limit (PDG94)	$B_{s.o.}$	$B_{L.D.}$
$D^0 \rightarrow \mu^+ \mu^-$	$< 1.1 \times 10^{-5}$	$(1-20) \times 10^{-19}$	$< 3 \times 10^{-15} *$
$D^0 \rightarrow e^+ e^-$	$< 1.3 \times 10^{-4}$	even smaller!	
$D^0 \rightarrow \mu^\pm e^\mp$	$< 1.0 \times 10^{-4}$	[$\begin{matrix} D \\ \text{heavy neutrino w/ } m_\nu > 50 \text{ GeV} \\ \leq 5 \times 10^{-22} \end{matrix}$] Unknown m_{ν_e} bounded by 10^{-16}	
$D^0 \rightarrow \gamma \gamma$	—		$< 3 \times 10^{-9}$
$D \rightarrow Y + X$		$\sim 10^{-6}$ (w/ QCD)	
$D^0 \rightarrow \rho^0 \gamma$	$< 1.4 \times 10^{-4}$ CLEO prelim		$< 2 \times 10^{-5}$
$D^0 \rightarrow \phi^0 \gamma$	$< 2.0 \times 10^{-4}$ "		$< 2 \times 10^{-4}$
$D^0 \rightarrow \rho^0 e^+ e^-$	$< 5 \times 10^{-4}$		
$D^+ \rightarrow \rho^+ \gamma$			$< 2 \times 10^{-4}$
$D \rightarrow l^+ l^- + X$		4×10^{-9}	
$D \rightarrow \pi^+ ee/\mu\mu$	$< 2.5/2.9 \times 10^{-3}$	$\text{few} \times 10^{-10}$	$< 10^{-8} *$
$D^+ \rightarrow K^+ ee/\mu\mu$	$< 4.8/9.2 \times 10^{-3}$	—	$< 10^{-15}$
$D^0 \rightarrow \bar{K}^0 ee/\mu\mu$	$< 1.7 \times 10^{-3}$	—	$< 2 \times 10^{-6}$
$D^0 \rightarrow \gamma \bar{\nu} + X$		2.0×10^{-15}	
$D^0 \rightarrow \pi^0 \gamma \bar{\nu}$		4.9×10^{-16}	$< 6 \times 10^{-16} *$
$D^0 \rightarrow \bar{K}^0 \gamma \bar{\nu}$		—	$< 10^{-12}$
$D^+ \rightarrow \gamma \bar{\nu} + X$		4.5×10^{-15}	
$D^+ \rightarrow \pi^+ \gamma \bar{\nu}$		3.9×10^{-16}	$< 8 \times 10^{-16} *$
$D^+ \rightarrow K^+ \gamma \bar{\nu}$		—	$< 10^{-14}$

new limits from E653/E697/E791 \Rightarrow 1-2 orders of magnitude improvement

Four Generation Standard Model



Short Distance QCD Corrections to $C \rightarrow u\gamma$ (LL) - RGE approach

(Gellman+Wilson)

$$H_{\text{eff}} = -\frac{4GF}{f_2^2} \bar{\gamma}_s \sum_{j=1}^8 C_j(\mu) O_j(\mu) \quad \bar{\gamma}_i = V_{ci} V_{ui}^*$$

$$O_1 = -(\bar{u}_\alpha \gamma_\mu P_L s_\beta)(\bar{s}_\beta \gamma^\mu P_L c_\alpha) - \frac{\gamma_4}{\gamma_s} (\bar{u}_\alpha \gamma_\mu P_L d_\beta)(\bar{d}_\beta \gamma^\mu P_L c_\alpha)$$

$$O_2 = -(\bar{u}_\alpha \gamma_\mu P_L s_\alpha)(\bar{s}_\beta \gamma^\mu P_L c_\beta) - \frac{\gamma_4}{\gamma_s} (\bar{u}_\alpha \gamma_\mu P_L d_\alpha)(\bar{d}_\beta \gamma^\mu P_L c_\beta)$$

$$O_3 = (\bar{u}_\alpha \gamma_\mu P_L c_\alpha) \sum_i (\bar{q}_{\beta i} \gamma^\mu P_L q_\beta) \quad O_4 = (\bar{u}_\alpha \gamma_\mu P_L \bar{c}_\beta) \sum_i (\bar{q}_{\beta i} \gamma^\mu P_L q_\alpha)$$

$$O_5 = (\bar{u}_\alpha \gamma_\mu P_L c_\alpha) \sum_i (\bar{q}_{\beta i} \gamma^\mu P_R q_\beta) \quad O_6 = (\bar{u}_\alpha \gamma_\mu P_R \bar{c}_\beta) \sum_i (\bar{q}_{\beta i} \gamma^\mu P_R q_\alpha)$$

$$O_7 = \frac{e}{16\pi^2 m_c} (\bar{u}_\alpha \sigma_{\mu\nu} P_R c_\alpha) F^{\mu\nu} \quad O_8 = \frac{1}{16\pi^2 m_c} (\bar{u}_\alpha \sigma_{\mu\nu} T_{\mu\rho}^a P_R c_\alpha) G^{a\mu\nu}$$

$$C_1(M_W) = 0, \quad C_2(M_W) = 1, \quad C_{3-6}(M_W) = 0$$

$$C_7(M_W) = F(x_s) + \frac{\gamma_b}{\gamma_s} F(x_b), \quad C_8(M_W) = G(x_s) + \frac{\gamma_b}{\gamma_s} G(x_b)$$

$$\text{Re } C_7(\mu) = U_{7L}^4(\mu, m_b) U_{4i}^5(m_b, m_W) \text{Re } C_i(M_W)$$

$$\text{Im } C_7(\mu) = U_{7L}^4(\mu, m_b) U_{4i}^5(m_b, m_W) \text{Im } C_i(M_W)$$

$$|C_7(\mu)|^2 = |\text{Re } C_7(\mu)|^2 + |\text{Im } C_7(\mu)|^2$$

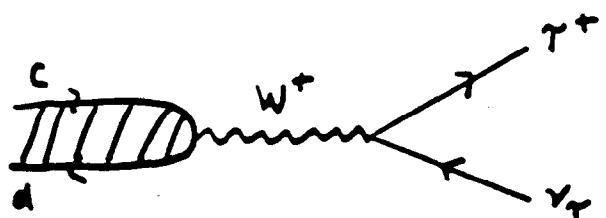
$\Rightarrow \mathcal{B}(C \rightarrow u\gamma) \sim 10^{-6} ! \Rightarrow$ entire rate is due to operator mixing!

Naive approach: GIM suppression softened to log suppression:

$$C_7 \rightarrow C_7(M_W) + \frac{4\alpha_S}{3\pi} \ln \frac{m_i^2}{m_c^2} \quad \begin{pmatrix} \text{Shifman, Vainshtein,} \\ + \text{Zakharov} \end{pmatrix}$$

gives $\mathcal{B}(C \rightarrow u\gamma) \sim 10^{-6} !$

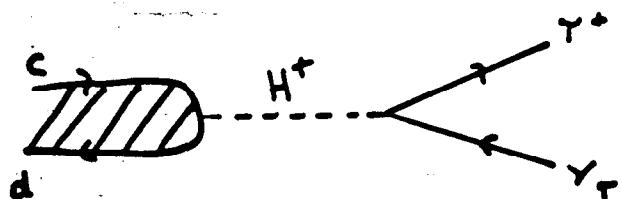
D → τγ



$$B(D^+ \rightarrow \tau^+ \gamma_\tau) = \frac{G_F m_0 m_\tau^2}{8\pi} \left[1 - \frac{m_\tau^2}{m_0^2} \right]^2 f_0^2 |V_{cd}|^2 \tau_0$$

$$\approx 9.6 \times 10^{-4}$$

H⁺ Contributions? (Important in B → τν)



$$\mathcal{L}_{cdH^+} = \frac{g}{2f_2 m_W} \left\{ \frac{m_c}{\tan\beta} V_{cd} \bar{c}(1-\gamma_5)d + m_d \tan\beta \bar{V}_{cd} \bar{c}(1+\gamma_5)d \right\} H^+ + h.c.$$

$$+ m_\tau \tan\beta \bar{\tau}(1+\gamma_5)\gamma_\mu$$

$$B(D^+ \rightarrow \tau^+ \gamma_\tau) = B_{sm} \left[1 + \underbrace{\frac{m_0^2}{m_{H^+}^2}}_{\text{small!}} \right]^2$$

Perhaps $D_s^+ \rightarrow \tau^+ \gamma$ is more interesting ??

$$B(D_s^+ \rightarrow \tau^+ \gamma) = B_{sm} \left[1 + \tan^2\beta \frac{m_{D_s}^2 m_s}{m_c m_{H^+}^2} \right] ; B_{sm} \sim 7.0 \times 10^{-2}$$

Summary

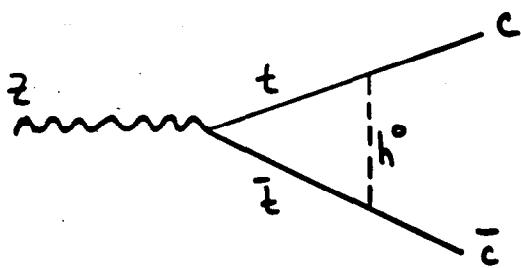
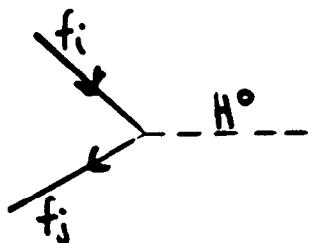
- Standard Model loop effects small in charm system
⇒ Generally dominated by long distance effects
- ⇒ Provides clean laboratory to probe new physics !!
- Unconventional non-standard models give largest contributions
generally not tested in K + B systems!
⇒ Imperative to continue search for rare charm
physics & highest possible precision !

Two-Higgs-Doublets with Flavor Changing Couplings

- Recent popularity

Hall, Weinberg
Antarcean et al
Hou
Sher

- SM Higgs coupling $\sim (\sqrt{2} G_F)^{1/2} m_f$
- 2HDM w/ FC $\sim (\sqrt{2} G_F)^{1/2} \sqrt{m_i m_j} X$
- ⇒ small effect for light fermions
largest effect in tch vertices!



$$\sim \frac{ig}{2c_w} \frac{G_F m_t m_c}{8\sqrt{2} \pi^2} X^2 \gamma_\mu (v \delta v - a \delta a) \gamma_5$$

loop integrals

How big can X be?

$$\frac{(g_{tch})^2}{4\pi} = \frac{\sqrt{2} G_F m_t m_c}{4\pi} X^2 \quad \text{becomes strong for } X \sim 30$$

$(w/ m_t = 170 \text{ GeV})$
 $m_c = 1.5 \text{ GeV}$

