DOUBLE FEATURE:

A TALE OF TWO CP'S

AND

THE MYSTERY OF CHARMLESS HIGGS

PECULIARITIES OF SM.

- HIERARCHICAL FERMION MASSES

$t \sim 175000$	$b \sim 4200$	$\tau \sim 1777$
$c \sim 1250$	$s \sim 100$	$\mu \sim 106$
$u \sim 2$	$d \sim 5$	$e \sim 0.5$

- MIXING BETW U AND D FERMIONS

$$V_{CKM} = \begin{pmatrix} \langle u|d\rangle & \langle u|s\rangle & \langle u|b\rangle \\ \langle c|d\rangle & \langle c|s\rangle & \langle c|b\rangle \\ \langle t|d\rangle & \langle t|s\rangle & \langle t|b\rangle \end{pmatrix} \sim \begin{pmatrix} .975 & .222 & .004 \\ .222 & .974 & .046 \\ .009 & .039 & .999 \end{pmatrix}$$

? WHY?

- TANTALISING CLOSE TO SITUATION WITH MASS MATRICES

$$\underset{\sim}{m}_U \sim \underset{\sim}{m}_D = \underset{\sim}{m}^0_{U,D} \; \underline{\alpha} \times \underline{\alpha}^+ \qquad \text{(RANK 1)}$$

WHERE $\underline{\alpha}$ IND. OF FLAVOUR

→ ONLY ONE MASSIVE STATE : (t, b, τ)
$\underset{\sim}{V}_{CKM} = \underset{\sim}{I}$

SUGGESTED ~30 YRS AGO AS ZEROTH ORDER APPROX. (FRITSCH, HARARI etc)

? HOW GO FURTHER ?

- OUR ANSWER (1998):

  α AND m ROTATE WITH SCALE μ

- μ-DEP. CONSEQUENCE OF RENORM.$^{\underline{N}}$

  FAMILIAR EX.: RUNNING α_s, m_b.

- THAT m ROTATES IS NOT NEW.

  [OCCURS EVEN IN STANDARD SM]

  THERE: MIXING $\longrightarrow$ ROTATION

- WHAT IS NEW IN OUR PROPOSAL IS:

  ROTATION $\longrightarrow$ MIXING

  (+ MASS HIERARCHY)

? WHY DOES ROTATION MATTER?

[EX.: WHEN m_b DEPENDS ON μ: $m(\mu)$ WHAT IS THE PHYSICAL MASS OF b?

? WHAT IS THE PHYSICAL MASS OF b?

ANS: $m_b^{(PHYS)} = m_b(\mu = m_b)$.]

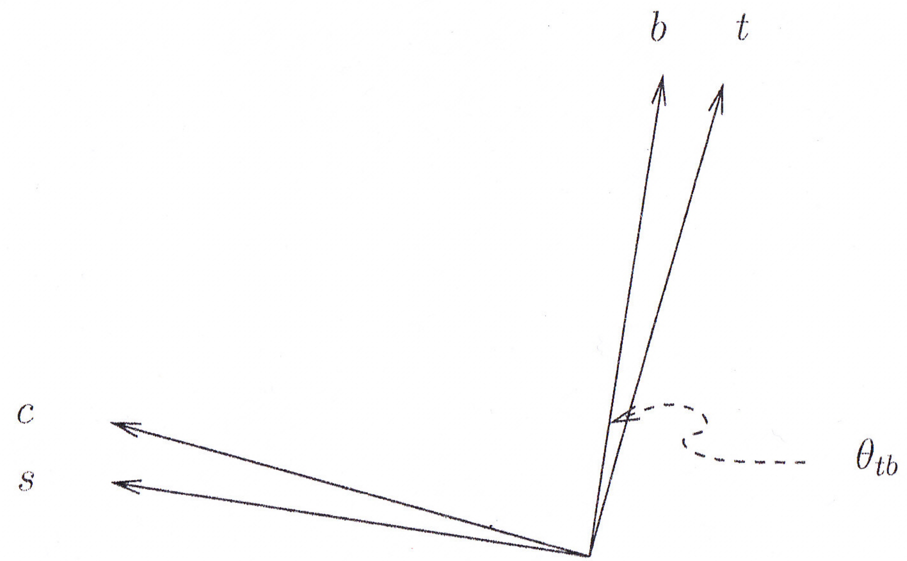
- WHEN $\underset{\sim}{m}$ ROTATES, EVEN STATE VECTORS DEPENDS ON μ, e.g. $\underline{V}_b(\mu)$
  HENCE PHYSICAL STATE VECTOR:

$$\underline{V}_b^{(PHYS)} = \underline{V}_b(\mu = m_b)$$

→ { U-D MIXING,
MASS HIERARCHY.

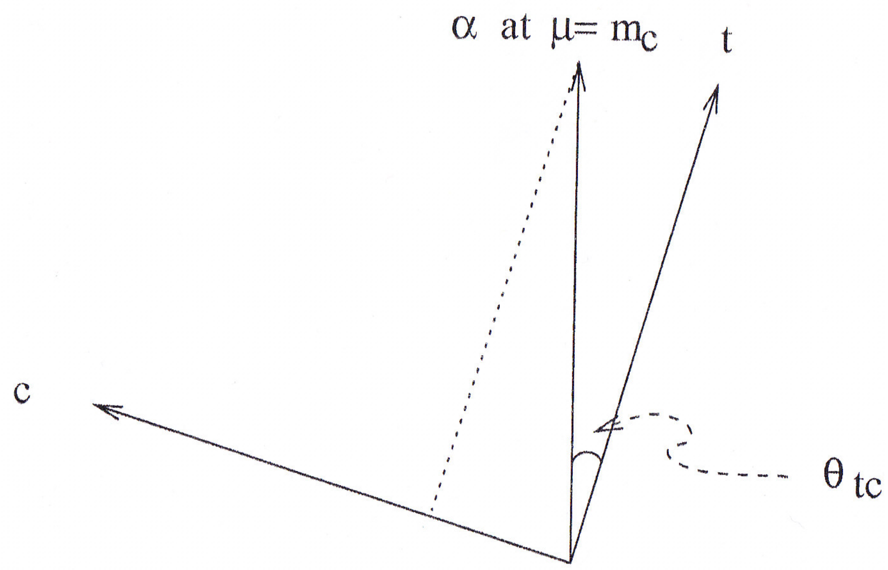
[EASILY SEEN WHEN ONLY 2 GENERATIONS]

- THAT ROTATION GIVES U-D MIXING: (ILLUSTRATED FOR CASE WITH 2 GENERATIONS)



$$\begin{pmatrix} V_{cs} & V_{cb} \\ V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} \langle \mathbf{v}_c | \mathbf{v}_s \rangle & \langle \mathbf{v}_c | \mathbf{v}_b \rangle \\ \langle \mathbf{v}_t | \mathbf{v}_s \rangle & \langle \mathbf{v}_t | \mathbf{v}_b \rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{tb} & \sin\theta_{tb} \\ -\sin\theta_{tb} & \cos\theta_{tb} \end{pmatrix}$$

THAT ROTATION GIVES HIERARCHICAL MASSES:



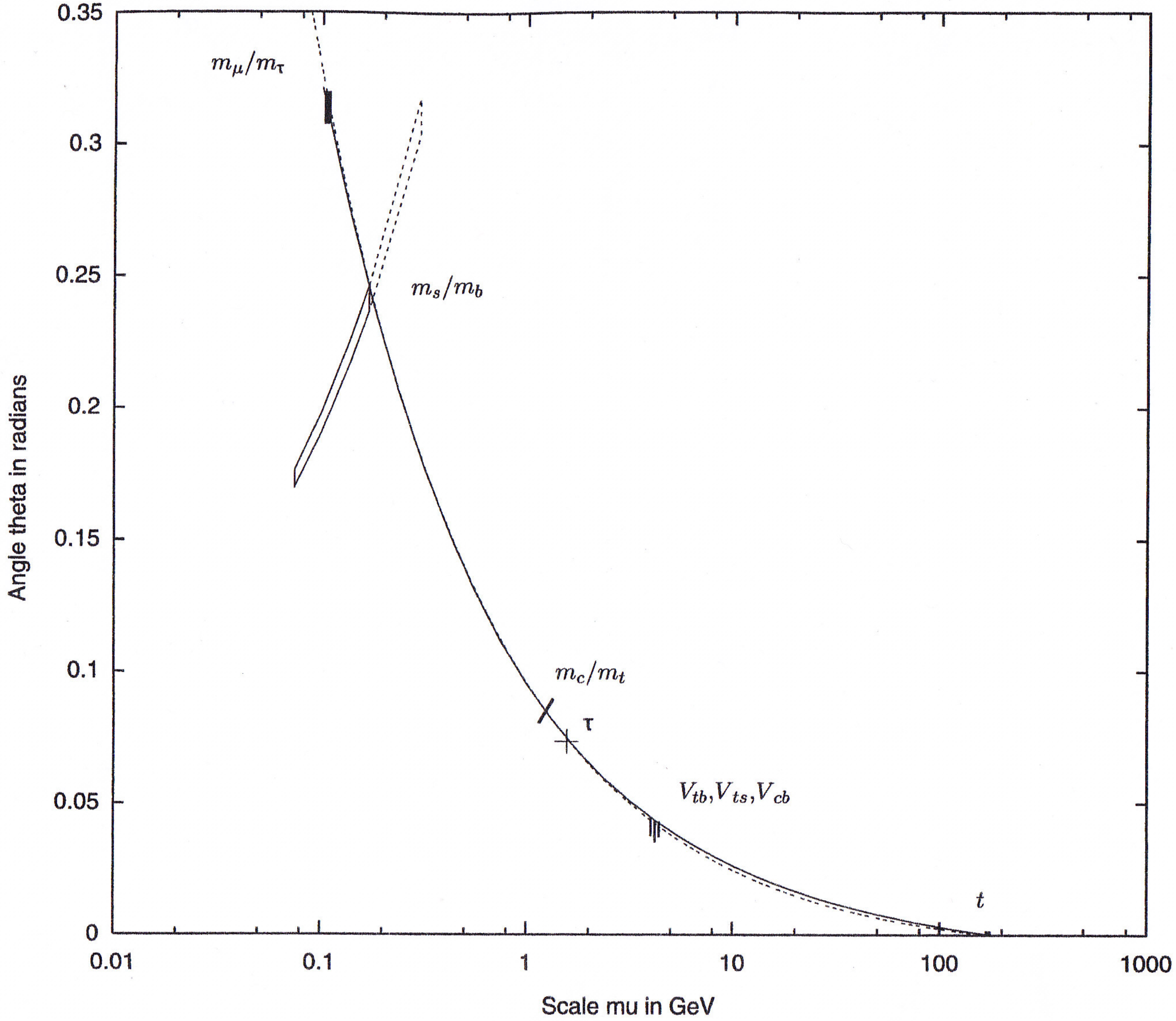
"LEAKAGE"

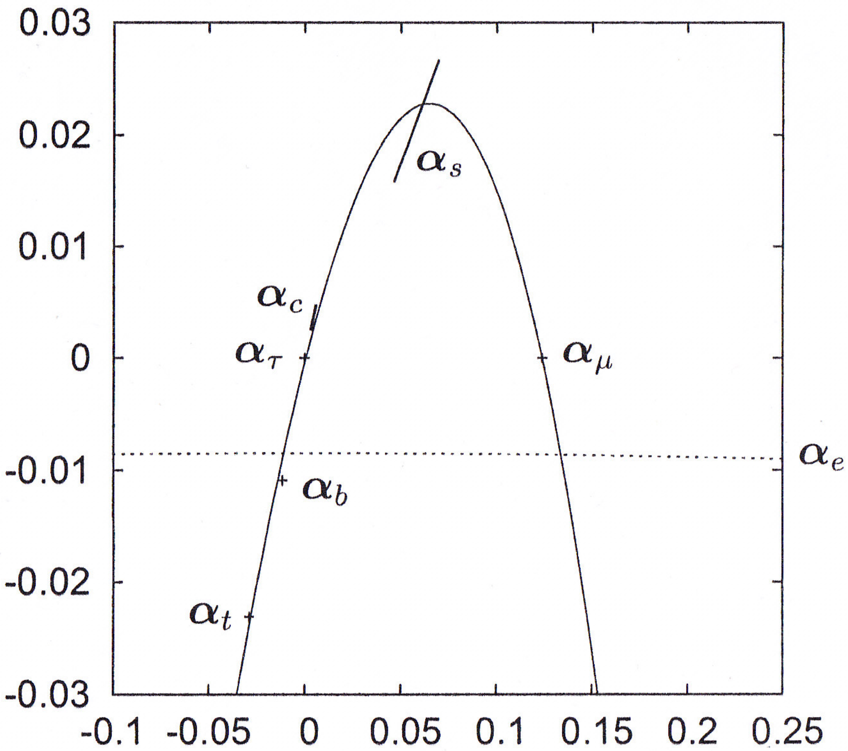
$$\mu = \langle \mathbf{v}_c | m(\mu) | \mathbf{v}_c \rangle = m_U^{\circ} | \langle \mathbf{v}_c | \boldsymbol{\alpha}(\mu) \rangle |^2 .$$

$$m_c = m_U^{\circ} \sin^2 \theta_{tc}$$

- DOES IT WORK? SEEMS TO:

[• EVEN FOR 3-G. (SLIDE) 7']





- BAKER, TSOU (NEW)

FITTED $|V_{CKM}|$:

$$\begin{pmatrix} 0.97372 & 0.2277 & 0.00393 \\ 0.2276 & 0.97282 & 0.04237 \\ 0.00813 & 0.04176 & 0.999094 \end{pmatrix}$$

cf. EXPT:

$$\begin{pmatrix} 0.97383^{+0.00024}_{-0.00023} & 0.2272^{+0.0010}_{-0.0010} & (3.96^{+0.09}_{-0.09}) \times 10^{-3} \\ 0.2271^{+0.0010}_{-0.0010} & 0.97296^{+0.00024}_{-0.00024} & (42.21^{+0.10}_{-0.80}) \times 10^{-3} \\ (8.14^{+0.32}_{-0.64}) \times 10^{-3} & (41.61^{+0.12}_{-0.78}) \times 10^{-3} & 0.999100^{+0.000034}_{-0.000004} \end{pmatrix}$$

- NOTE (See later): $J = 3.05 \times 10^{-5} \Rightarrow \theta = 1.36$ rad.

(NEEDED FOR GOOD FIT)

WE GOT TO THAT POINT ~ 10 YRS AGO

? WHAT NEXT?

A CONSTRUCT THEORY FOR ROTATION,

B SOLVE OTHER PROBLEM?
GIVE NEW PREDICTION?
REAL TEST OF IDEA.

A MUCH WORK AND RESULT.
(SEMINAR ~ 2 YRS AGO + MORE SINCE)

B NEW RESULTS ONLY THIS LAST YR

I SOLUTION OF CP PROBLEMS

II PREDICTIONS FOR HIGGS DECAY.

I SOLVE CP PROBLEMS.

• STRONG CP PROBLEM.

(REMINDER) IN QCD, GAUGE SYMMETRY ADMITS TERM IN ACTION OF FORM:

$$-\frac{\theta}{16\pi^2}\, \mathrm{Tr}\, F_{\mu\nu} F_{\rho\sigma}\, \varepsilon^{\mu\nu\rho\sigma} \qquad [\text{ANY } \theta]$$

[θ-ANGLE TERM, OF TOPOLOGICAL ORIGIN]

VIOLATES CP → NEUTRON EDM.

EXPT. (K. GREEN et al.)

→ $\theta \lesssim 10^{-10}$? WHY?

POPULAR EXPLANATION: AXION TH.
(PECCEI - QUINN, WEINBERG, WILCZEK)

BUT NO SIGN AFTER 40 YRS. OF SEARCH.

- 'WEAK CP PROBLEM' R

(REMINDER) GAUGE SYM.. IN WEAK CURRENT
ALLOW V_{CKM} TO HAVE ~~CP~~ PHASE:
(KOBAYASHI – MASKAWA)
FOUND IN EXPT. BUT JARLSKOG INV.

$$J \sim 3 \times 10^{-5}.$$

? WHY SO SMALL?
[K–M GAVE NO REASON FOR PHASE
NOR ESTIMATE, ONLY EXISTENCE]
AGAIN UNSOLVED FOR $\gtrsim$ 30 YRS.

- SOLUTION FOUND NOW FOR BOTH WITH ROTATION

? HOW? EXPLOIT CHINK IN ARMOUR OF STRONG CP PROBLEM!

REMINDER: (KNOWN RESULT)

PHYSICS IN QFT GIVEN BY FEYNMAN INTEGRALS: $\int \delta\psi_q \cdots e^{i\mathcal{A}[\psi_q, \dots]}$

IF CHANGE INT. VARIABLE:

$$\delta\psi_q \to \delta\psi_q', \qquad \psi_q' = e^{i\alpha_q \gamma_5}\psi_q$$

[CHIRAL TRANSFORMATION]

JACOBIAN OF TRANS$^{\text{N}}$ GIVES FACTOR

$$e^{i\frac{\alpha_q}{2} F_{\mu\nu} F_{\rho\sigma} \varepsilon^{\mu\nu\rho\sigma}}$$

EXACTLY SAME FORM AS THETA-ANGLE TERM.

⋮

- HENCE IF WE CHOOSE $\alpha_q = -\theta/2$ [WITH NO CHANGE IN PHYSICS] CAN CANCEL θ-ANGLE TERM. (?)

BUT MASS TERM:

$$m_q \bar{\psi}_q \psi_q = \frac{1}{2} m_q \left[\bar{\psi}_q (1+\gamma_5) \psi_q + \bar{\psi}_q (1-\gamma_5) \psi_q \right]$$

$$\xrightarrow[\text{CH. TRANS}]{} \frac{1}{2} \left[m_q e^{2i\alpha_q} \bar{\psi}_q (1+\gamma_5) \psi_q + m_q e^{-2i\alpha_q} \bar{\psi}_q (1-\gamma_5) \psi_q \right]$$

MASS PARAMETER BECOMES COMPLEX. STILL VIOLATES CP, HENCE NO GOOD.

UNLESS $m_q = 0$. X

BUT EXPT. SHOW NO QUARK WITH $m_q = 0$

- WHAT'S NEW IN ROTATION SCENARIO?

MASS MATRIX $\underline{m} = m^0 \underline{\alpha}\, \underline{\alpha}^\dagger$

ALWAYS 2 STATES $\perp$ $\underline{\alpha}$ WITH ZERO EIGENVALUES.

$\therefore$ CAN ALWAYS REMOVE Θ-ANGLE TERM BY CHIRAL TRANFORM$^{\underline{N}}$ IN THOSE ZERO MODES.

(NO EDM (large)) FOR NEUTRONS)

YET: QUARK-MASSES NOT ZERO

$\because$ 'LEAKAGE'.

arXiv 0707.3358.

HAVE CAKE AND EAT IT?

[LONG KOWN TO US (JAKOV)]

- FOLLOW UP THIS YEAR: !!! arXiv 1002.3545

α ROTATES, i.e. CHANGES WITH μ.

HENCE CHIRAL TRANSF$^{\underline{N}}$ TO CANCEL Θ-ANGLE TERM ALSO CHANGE.

? HENCE AFFECTS CKM MATRIX WHICH IS A CONSEQUENCE OF ROTATION. HOW ?

- ANS. GIVES V_{CKM} A CP-VIOLATING PHASE DEP. ON Θ AND ROTA$^{\underline{N}}$.

- EST. OF ROTA$^{\underline{N}}$ FROM MASS 'LEAKAGE'

e.g. $m_c/m_t \longrightarrow J \sim \sin \Theta/2 \times 10^{-4}$

cf. EXPT: $J \sim 3 \times 10^{-5}$.

- NOTE FIT OF 7'

- IF CORRECT, THIS MEANS:
  - 1 SOLUTION OF STRONG CP PROB.
  - 2 LINKS STRONG & WEAK CP'S. (1ST TIME, KNOWN TO ME)
  - 3 GIVES ORIGIN OF KM PHASE.
  - 4 SOLVE 'WEAK CP PROB', i.e J SMALL.
  - 5 GIVES ESTIMATE OF J FROM ROTA^N: RIGHT ORDER OF MAGNITUDE.
  - 6 GIVES FOR 1ST TIME KM PHASE IN ROTATION SCHEME.

- 2 → STRONG & "WEAK" CP'S: SAME THING.

HENCE: 'A TALE OF TWO CP'S'

II NEW PREDICTIONS FOR HIGGS DECAY.

- $H \to f\bar{f}$, e.g. $b\bar{b}$, $c\bar{c}$ ETC.

STANDARD PREDICTIONS:

$$\text{e.g.} \quad \frac{\Gamma(c\bar{c})}{\Gamma(b\bar{b})} \sim \frac{m_c^2}{m_b^2} \sim 10\,\% \qquad (*)$$

REMINDER:

EXPAND $\Phi_H = \Phi_0 + \delta\Phi$

$$y_f \bar{\psi}_f \Phi \psi_f = y_f \bar{\psi}_f \Phi_0 \psi_f + y_f \bar{\psi}_f \delta\Phi \psi_f$$

"YUKAWA COUPLING TERM." $= y_f \Phi_0 (\bar{\psi}_f \psi_f) + y_f \bar{\psi}_f H \psi_f$

$m_f = y_f \Phi_0$; HIGGS COUPLING $= y_f$

⋮

⋮

HENCE $y_f \propto m_f$, $\Gamma_f \propto m_f^2$

HENCE (*) ABOVE.

? WHAT HAPPENS IN ROTATION SCENARIO?

MASS (MATRIX) TERM:

● (1) $m_T^0 \, \underline{\alpha} \, \underline{\alpha^+}$ $\qquad T = U, D.$

N1 ● (2) → ● (1)

● (1) → ● (2)

?

YUKAWA COUPLING?

● (2) $y_T (\underline{\bar{\Psi}} \cdot \underline{\alpha}) \phi (\underline{\alpha^+} \cdot \underline{\Psi})$

$\Phi = \Phi_0 + H$ $\longrightarrow$ $y_T \Phi_0 (\underline{\bar{\Psi}} \cdot \underline{\alpha})(\underline{\alpha^+} \cdot \underline{\Psi}) + y_T (\underline{\bar{\Psi}} \cdot \underline{\alpha}) H (\underline{\alpha^+} \cdot \underline{\Psi})$

$m_T = y_T \Phi_0 \, \underline{\alpha} \, \underline{\alpha^+}$; $Y_T = y_T \, \underline{\alpha} \, \underline{\alpha^+}$

- $\underset{\sim}{m}_T \propto \underset{\sim}{Y}_T \propto \underline{\alpha}\ \underline{\alpha}^+$

MASS MATRIX $\propto$ COUPLING MATRIX

WHERE BOTH MATRICES ROTATE. WITH μ.

- RECALL: MASS OF c TAKEN AT $\mu = m_c$:

$$m_c = m_U^0 \langle \underline{V}_c | \underline{\alpha}(m_c) \rangle \langle \underline{\alpha}^+(m_c) | \underline{V}_c \rangle$$

? AT WHAT SCALE SHOULD THE COUPLING y_c (OF H TO $c\bar{c}$) BE TAKEN AT?

CONVENTIONAL WISDOM SAYS IT SHOULD BE TAKEN AT $\mu = m_H$ FOR HIGGS DECAY.

- IF SO; FOR $H \to c\bar{c}$:

N2

$$y_c = y_U \langle \underline{V}_c | \underline{\alpha}(m_H) \rangle \langle \underline{\alpha}^+(m_H) | \underline{V}_c \rangle$$

- RECALL "LEAKAGE" MECH., SLIDE 6

IF $m_H \gtrsim 150$ GeV $\sim m_t = 175$ GeV,

THEN $\alpha(m_H) \sim \alpha(m_t) \perp V_c$

HENCE y_c VERY SMALL.

- $H \to c\bar{c}$ MUCH SUPPRESSED.

($H \to b\bar{b}$ NOT MUCH AFFECTED).

ESTIMATES READ OFF FROM 6

$$\Rightarrow \frac{\Gamma(H \to c\bar{c})}{\Gamma(H \to b\bar{b})} \sim 10^{-7}$$

cf. CONVENTIONAL $\sim \frac{m_c^2}{m_b^2} \sim 10\%$

- 'MYSTERY OF THE CHARMLESS HIGGS'

- OTHER EXAMPLES AND m_H - DEP., [SLIDE 19]

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BAKER, TSOU NEW

$$\frac{\Gamma(H \to f\bar{f})}{\Gamma(H \to b\bar{b})}$$

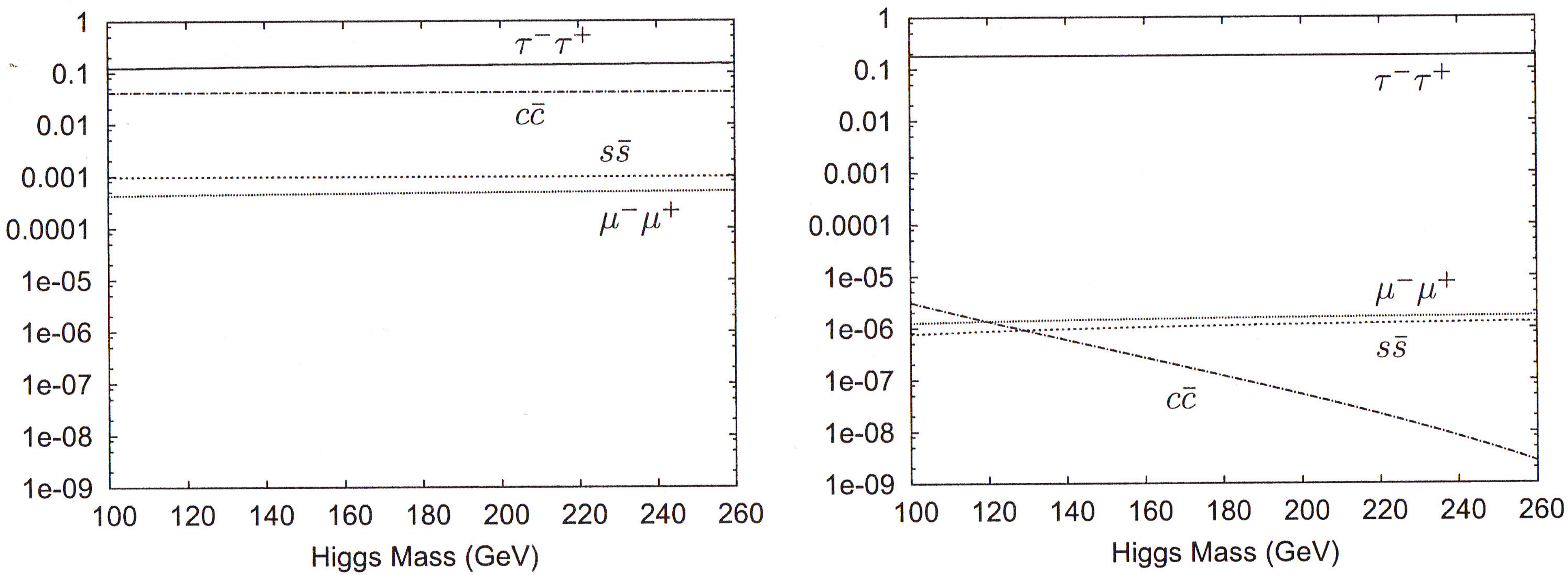

Figure 5: $\Gamma(H \to x\bar{x})/\Gamma(H \to b\bar{b})$ for various final state particles as predicted by the standard model (left) and the rotating mass matrix hypothesis (right).

- SIMILAR ANALYSIS GIVES FLAVOUR - VIOL^{NS}.

e.g. $\dfrac{\Gamma(H \to \tau\mu)}{\Gamma(H \to b\bar{b})} \sim 10^{-3}$.

II THESE RESULTS FOR H DECAY EXCITING BUT NOT AS SOLID TH. AS RESULT I ON ~~CP~~. N1 N2

- TWO TESTS: I AND II OF ROTATION + MIXING & HIERARCHY.

- IF BELIEVE MY EARLIER SEMINAR: GETTING TO THE ORIGIN OF BOTH GENERATION AND HIGGS !?