What do We Know About Leptonic CP Violation?

- The CKM "model" provides, at present, an adequate parameterization of $\not{CP}$ in the quark sector

→ Is that all there is? Is CKM the sole source of $\not{CP}$? Probably <u>not</u>!

- Baryogenesis {• ϵ'/ϵ from KTeV?}
- Strong CP problem $\sim \frac{\theta}{32\pi^2}\tilde{F}F$

⇒ new Physics

* **But** at least we <u>believe</u> we know who all (?) of the important players <u>are</u> - <u>udscbt</u>

T. Rizzo
CC98

s. mele

hep-ph/9810333

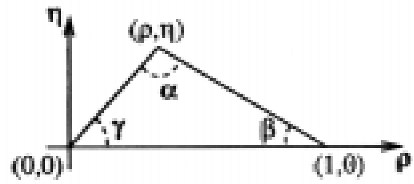


Figure 1: The unitarity triangle.

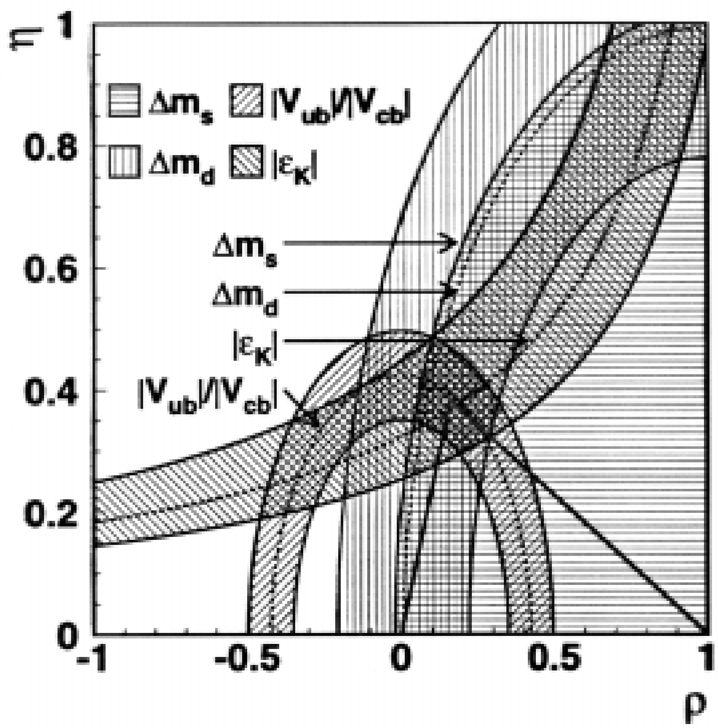


Figure 2: The current constraints and the favoured unitarity triangle. The constraint coming from B_s^0 oscillations is a limit at 95% of Confidence Level, while the others represent a $\pm1\sigma$ variation of the experimental and theoretical parameters entering the formulae in the text.

A. Stocchi

hep-ex/9902004

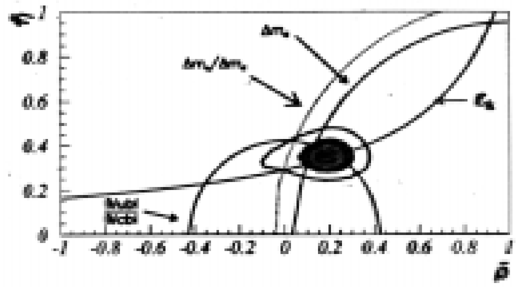


Figure 7: The $\bar{\rho}$ – $\bar{\eta}$ allowed region. The contours at 68% and 95% C.L. are shown. The continous lines correspond to the constraints obtained from the measurements of $\frac{|V_{ub}|}{|V_{cb}|}$, Δm_d, and ε_K. The dotted curve corresponds to the 95% C.L. limit obtained from the experimental limit on Δm_s.

$\sin 2\beta)_{fit} = 0.73 \pm 0.08$

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

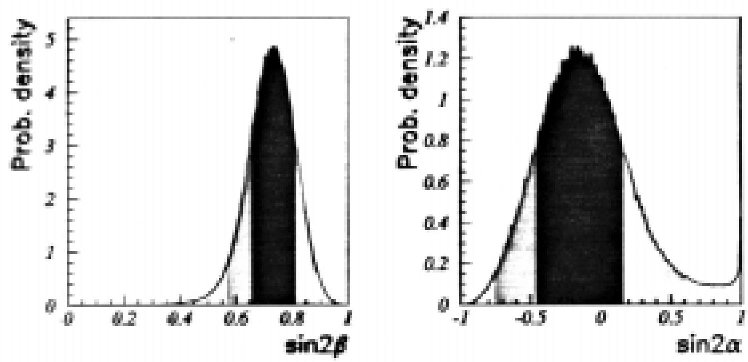


Figure 8: The $\sin 2\beta$ and $\sin 2\alpha$ probability density distributions. The dark-shaded and the clear shaded intervals correspond to 68% and 95% C.L. regions respectively.

F. Parodi et al
hep-ph/9802289

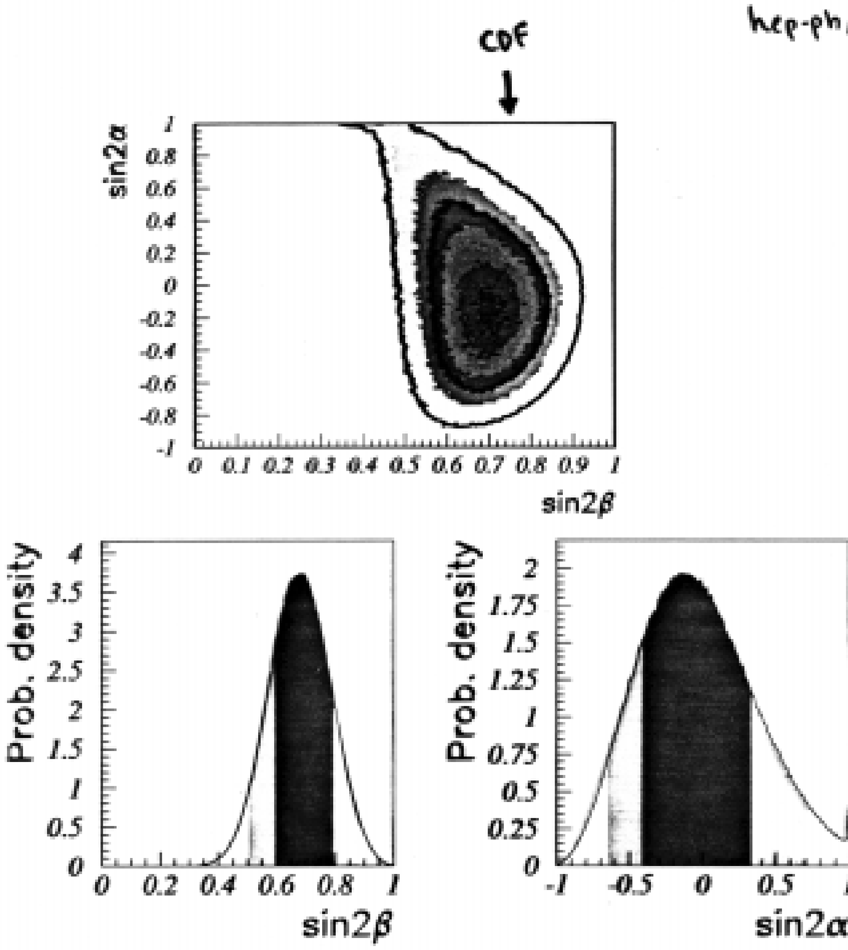


Figure 2: *The $\sin 2\alpha$ and $\sin 2\beta$ distributions have been obtained using the contraints corresponding to the values of the parameters listed in Table 1. The contours at 68% and 95 % are shown. The $\sin 2\alpha$ and $\sin 2\beta$ distributions are also shown. The dark-shaded and the clear-shaded intervals correspond, respectively, to 68% and 95 % confidence level regions.*

A Stocchi

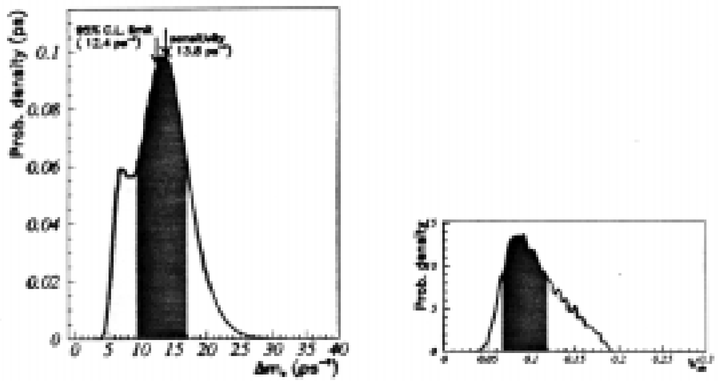


Figure 9: The left and the right plots show the probability density distributions for Δm_s and $|V_{ub}|/|V_{cb}|$ respectively. The dark-shaded and the clear shaded intervals correspond to 68% and 95% C.L. regions respectively.

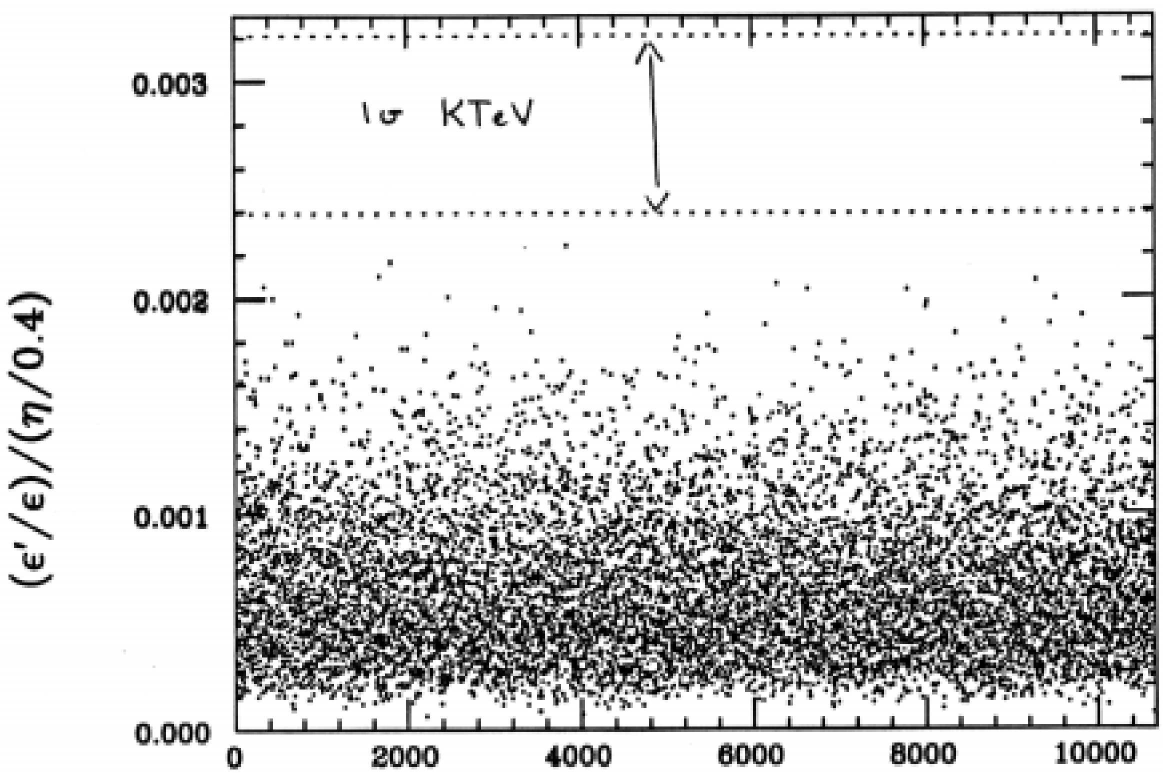
Table 3: The Δm_s and $|V_{ub}|/|V_{cb}|$ measured values are compared with those obtained using the fitting procedure after having removed them from the fit.

Quantity	Measured value	Fitted value
Δm_s	> 12.4 ps^{-1} at 95% C.L.	[9.5 - 17] ps^{-1} 68% C.L.
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	0.093 ± 0.014	$0.085^{+0.037}_{-0.023}$

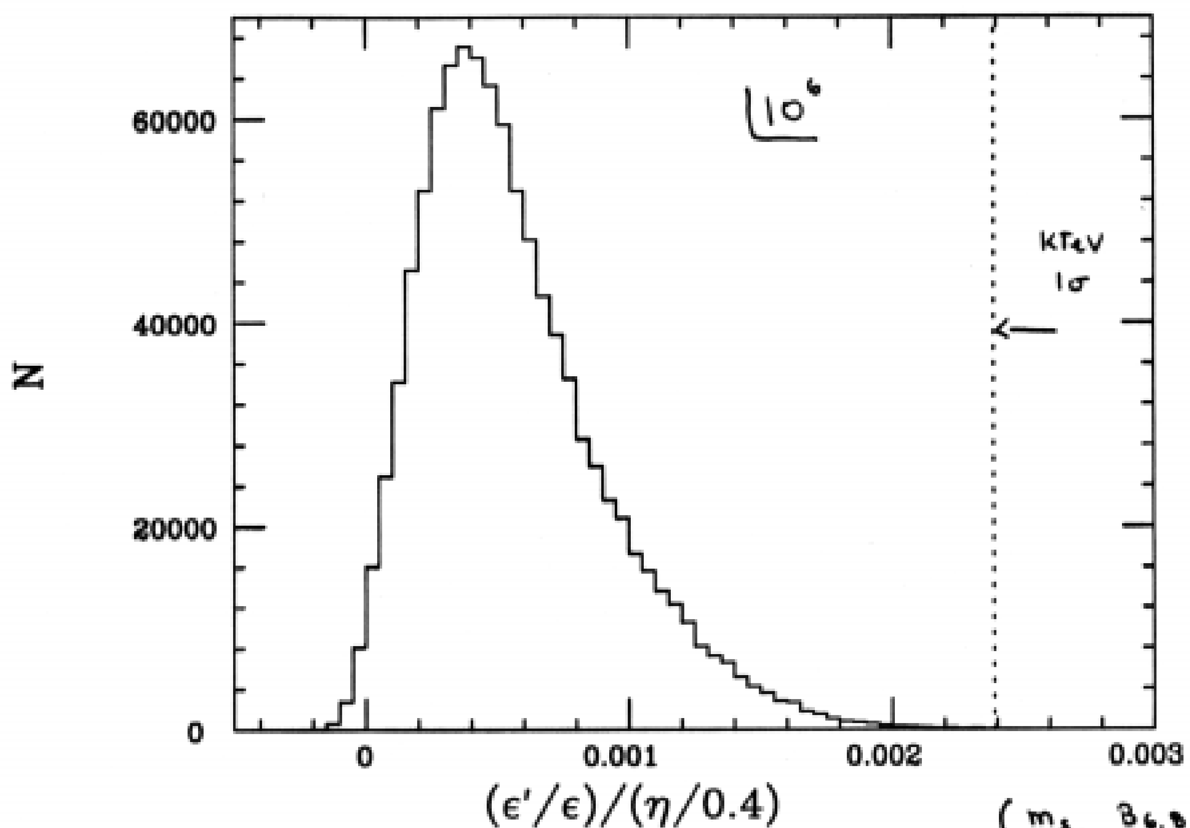
From these results the important impact of these two measurements in the determination of the allowed region for ρ and η is clear. Furthermore the expected probability distribution for Δm_s shows that present analyses are exploring the one sigma region.

Conclusions

Important improvements have been obtained in the last two years in the analyses of $B^0-\bar{B}^0$ oscillations. Combining LEP results with those from SLD and CDF, Δm_d frequency is presently known with a 3.4% relative error ($\Delta m_d = 0.477 \pm 0.017$ ps^{-1}). The sensitivity on Δm_s is at 13.8 ps^{-1} and, the actual LEP/SLD/CDF combined limit, of 12.4 ps^{-1} at 95% of C.L., is exploring the region where Δm_s is expected to be according to the analysis [4]. The measurement of Δm_s is still a challenge for LEP collaborations, $|V_{ub}|$ has been


(ε′/ε)/(η/0.4)
0.003
0.002
0.001
0.000
1σ KTeV
0
2000
4000
6000
8000
10000

Parameter Scan



$\epsilon'/\epsilon = (5.59 \pm 3.54)\cdot 10^{-4} \cdot (\eta/0.4)$

$\left\{ \begin{array}{l} m_s,\ B_{6,8},\ c_{6,8} \\ m_t,\ V_{cb},\ \Lambda^{(4)}_{QCD} \end{array} \right.$

- In the case of leptons, we don't yet know the players or how many there are: e.g, how many ν's are there?

→ Γ_Z → 3 light LH ν's only

→ Solar / Atmosp. / LSND → 3 diff. Δm_{ij}^2

$\therefore$ at least 4 masses

$\nu_{e,\mu,\tau} + \nu_s$, an isosinglet ν

→ Majorana or Dirac ?

→ See-saw ? Heavy neutral $\left\{ \begin{array}{l} \text{vector-like/} \\ \text{isosinglets} \end{array} \right.$?

$m_\nu \sim m_D^2 / m_N$

- With extra neutral fields $[\nu_s^i / N^i]$ there are many possible opportunities to generate $\cancel{CP}$ for leptons divorced from quarks

$\Longrightarrow$ How do we find $\cancel{CP}$ in the leptonic sector?

Usual Suspects $\left\{ \begin{array}{l} \text{edm's of charged leptons} \\ \cancel{CP} \text{ decays of } \tau \text{, e.g.,} \\ \quad \underline{\tau \to K\pi\nu} \end{array} \right.$

- **More** $\cancel{CP}$ in $\underline{\nu}$ <u>oscillation</u>

$$CPT: \quad P_{\nu_\alpha \to \nu_\beta} = P_{\bar{\nu}_\beta \to \bar{\nu}_\alpha}$$

$$\Longrightarrow \quad CP: \quad P_{\nu_\alpha \to \nu_\beta} = P_{\nu_\beta \to \nu_\alpha} = P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} \quad \Longleftarrow$$

$\Longrightarrow$ $\cancel{CP}$ arises here due to complex phase(s) in the leptonic CKM matrix - $\boxed{\text{"}\cancel{CP}\text{ in mixing"}}$

$$V^{\ell}_{CKM} \equiv U^{\dagger}_{\nu_L} U_{\ell_L}$$

$n_{ph} = \frac{1}{2}(n-1)(n-2)$

- 3 ℓ's ⊕ 3 Dirac ν's $\quad V^{\ell}_{CKM}$ has <u>3 angles</u> and <u>1 phase</u> $\{$ ν's massive + non-degenerate $\}$

<u>However</u> : You get <u>more</u> phases if :

$n_{ph} = \frac{1}{2}n(n-1)$

- 3 ℓ's $\oplus$ 3 Majorana ν's : 3 $\measuredangle$'s $\oplus$ 3 phases
- 3 ℓ's $\oplus$ 3 LH M. ν's $\oplus$ 1 isosinglet

$\rightarrow$ 6 phases <u>etc</u>

$\left\{ \begin{array}{l} V^{\ell} \text{ is first 3 columns of an } (3+n)\otimes(3+n) \\ \text{matrix - many } \measuredangle\text{'s + phases possible} \end{array} \right\}$

Simplest Case $\Big\}$ 3 ℓ's $\oplus$ 3 ν's

$d^2 \equiv m_2^2 - m_1^2 \sim 5 \cdot 10^{-6}\ eV^2$

$D^2 \equiv m_3^2 - m_1^2 \gg d^2 \sim 3 \cdot 10^{-3}\ eV^2$

$$A = \frac{P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}}{P_{\nu_\alpha \to \nu_\beta} + P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}} \quad \text{vs} \quad L$$

- Oscillations observed when

  $L \sim E/D^2$ but not $\cancel{CP}$

- To see $\cancel{CP}$ need $L \sim E/d^2$ or

$\nu_\mu - \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ $\Big\}$ Schubert hep-ph/9902215

<u>Extremely</u> long ~~base~~lines "?" $\boxed{L \gg E/D^2}$

$\nu_\mu \leftrightarrow \bar{\nu}_e$

* <u>Hard</u> to say the least.... <u>but</u> rewarding

$\longrightarrow$ Direct $\cancel{CP}$ test of mixing matrix

$\longrightarrow$ Scaling games with dipole moments

$$a_\ell \sim C\left({}^{m_\ell}/_{\Lambda}\right)^n \qquad\qquad d_\ell \sim C'\left({}^{m_\ell}/_{\Lambda}\right)^{n(-1)}$$

$n = ?$ $\left\{\begin{array}{l}\text{Common} \\ \text{feature of} \\ \text{many models}\end{array}\right.$

$n = 2$ in many cases : SM / $\overset{\text{MSSM}}{(\text{SUSY})}$ / $\underline{\text{low-scale Q.G.}}$! etc

- Imagine $\left\{\begin{array}{l}\text{(i)} \quad d^\tau_\gamma,\ a^\tau_\gamma \text{ not far below present bounds} \\ \text{(ii)} \quad C, C' \text{ generation independent}\end{array}\right.$

$\Rightarrow |d^\tau_\gamma| < 8.1 \cdot 10^{-16}$ e-cm $\qquad |a^\tau_\gamma| \lesssim 0.05$

<u>now</u>

- As we vary n, what does new physics <u>nearby</u> for <u>τ</u> tell us about $e + \mu$?

<u>Recall</u> $\quad |\Delta a^\gamma_e| \lesssim 4 \cdot 10^{-12}$

$|\Delta a^\gamma_\mu| \lesssim 8 \cdot 10^{-9}$

$|d^\gamma_e| \lesssim 8 \cdot 10^{-27}$ e-cm $\qquad |d^\gamma_\mu| \lesssim 4 \cdot 10^{-19}$ e-cm

	{e-cm} $\underline{d_\gamma^e}$	$\underline{d_\gamma^n}$	$\underline{a_\gamma^e}$	$\underline{a_\gamma^n}$	
$n = 1$	$\sim 8.9 \cdot 10^{-20}$	$\sim 2 \cdot 10^{-17}$	$\sim 1.4 \cdot 10^{-5}$	$\sim 3 \cdot 10^{-3}$	
2	$\sim 2.5 \cdot 10^{-23}$	$\sim 1 \cdot 10^{-18}$	$\sim 4 \cdot 10^{-9}$	$\sim 2 \cdot 10^{-4}$	
3	$\sim 7.4 \cdot 10^{-27}$ ✓	$\sim 6 \cdot 10^{-20}$ ✓	$\sim 1.1 \cdot 10^{-12}$ ✓	$\sim 1 \cdot 10^{-5}$	
4	—	—	—	$\sim 6 \cdot 10^{-7}$	
5(!)	—	—	—	$\sim 4 \cdot 10^{-8}$	still too big by ~4 !!

$$\begin{cases} n \geq 3 & \text{ok for } d^\gamma_{e,n} + a^e_\gamma \\ n \geq 5\text{-}6 & \text{for } a^n_\gamma \end{cases}$$

$\therefore$ models which satisfy present const's from e + μ bounds <u>will</u> <u>never</u> give large $a_\tau^\gamma / d_\tau^\gamma$ <u>if</u> simple scaling holds with <u>n = 1 or 2</u> – <u>lots</u> <u>of</u> <u>models</u>

OUTS?

- Operator Approach to edm's + mdm's
  {e.g, each gen. has a different new operator}

Escribano + Masso

$$\Delta \mathcal{L} = \frac{1}{\Lambda^2} \Big\{ \Big[C_{\tau B}\, \bar{L} \sigma^{\mu\nu} P_R \tau \phi + \tilde{C}_{\tau B}\, \bar{L} \sigma^{\mu\nu} i\gamma_5 P_R \tau \phi \Big] B_{\mu\nu}$$

$$+ \Big[C_{\tau W}\, \bar{L} \sigma^{\mu\nu} P_R \tau (\sigma^a \phi) + \tilde{C}_{\tau W}\, \bar{L} \sigma^{\mu\nu} i\gamma_5 P_R \tau (\sigma^a \phi) \Big]$$

$$\cdot\, W^a_{\mu\nu} \Big\}^{*} + \text{h.c.}$$

C's $= 1$ data implies

$\Lambda_e > 58 - 77$ PeV $\longleftarrow$ a long way to go

$\Lambda_\mu > 7 - 9$ TeV , $\Lambda_\tau > 0.4 - 0.5$ TeV

$*$ $\phi \to \frac{v}{\sqrt{2}}$, $B_{\mu\nu} = c_W A_{\mu\nu} - s_W Z_{\mu\nu}$, $W^3_{\mu\nu} = c_W Z_{\mu\nu} + s_W A_{\mu\nu}$

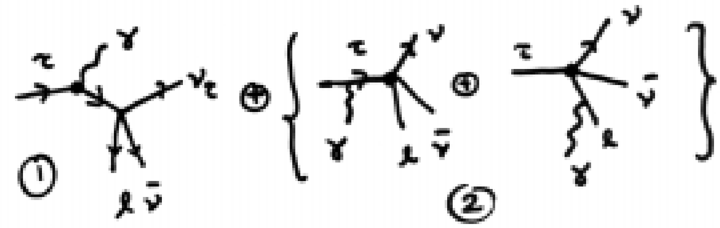
• $B_{\mu\nu}$ terms induce $a_\tau^{\gamma,Z}$ and $d_\tau^{\gamma,Z}$ only

• $W_{\mu\nu}$ terms induce $a_\tau^{\gamma,Z,W}$ and $d_\tau^{\gamma,Z\,W}$ and

$\Rightarrow$ new 4-point interactions due to gauge invariance

Test (?) in τ radiative Decays ?

SM ⊕



Anomalous γ Production

⊕

How big are these contributions ??

$B_{\mu\nu} \to$ 1 only , $W_{\mu\nu} \to$ 1 – 3

* Rate ? , E_γ, $\cos\theta_\gamma$, $M_{\ell\gamma}$? No Time !

OPAL: $B(\tau \to \mu\nu\nu\gamma) =$

$(3.0 \pm 0.4 \pm 0.5)\cdot 10^{-3}$ $E_\gamma > 20$ MeV

$(2.7 \pm 0.6)\cdot 10^{-3}$ > 37 MeV

Mark II: $(2.3 \pm 1.1)\cdot 10^{-3}$ $E_\gamma > 37$ MeV

$\left\{ \begin{array}{l} \text{SMMC } (E_\gamma > 20\text{ MeV}) \text{ is } \underline{2.82\cdot 10^{-3}} \\ \text{Distributions agree with SM expectations} \end{array} \right.$ SO FAR

$\because$ <u>More Ways</u> to <u>Circumvent</u> m_ℓ^n <u>scaling</u>

→ factor of m_ℓ^n arise both from couplings in loops as well as the need to flip helicity in the loop to generate a $\sigma_{\mu\nu}$ term

$\therefore$ Try to get some other <u>heavy</u> fermion to flip helicity in a 1-loop graph

Imagine $\delta_\tau^\gamma = e\,\dfrac{\delta}{M_Z} \approx 2.2(\delta)\cdot 10^{-16}$ e-cm

$\sim$ present limit

⇒ what <u>δ's can we</u> get ?

{Bernreuther, Brandenburg + Overmann , Chang, Pal + Nieves}

<u>Survey of models</u>

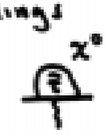
Basic Idea , at 1-loop $\quad \delta \sim \frac{\alpha}{\pi} \cdot \underbrace{\frac{m_F}{m_Z}}_{\text{O(1) or larger}}$

- multi-Higgs $\quad \delta \sim 10^{-4}$ ("$\tan\beta$"-type enhancements)

  1-loop $\sim \frac{\alpha}{\pi}\left(\frac{m_Z}{v}\right)^3$, 2-loop $\sim (\alpha/\pi)^2 (m/v)$

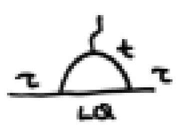
- non-MSSM SUSY $\quad \cancel{CP}$ phase in $\tau \tilde{\tau} \chi_i^0$ couplings

  χ_i^0 plays role of F



  $\rightarrow \delta \sim$ few $\cdot 10^{-4}$

- LQ's or $\cancel{R}$ violation $\left\{ \begin{array}{l} \text{Couplings } \underline{\text{NOT}} \text{ as constrained} \\ \text{as for 1st 2 generations} \end{array} \right.$



etc $\qquad m_F$ role played by m_t

$\delta \sim 10^{-3}$! $\qquad d_e^\gamma : d_\mu^\gamma : d_\tau^\gamma \overset{?}{=}$ "suggestive"

$m_e m_u^2 : m_\mu m_c^2 : m_\tau m_t^2$

<u>is</u> 'faster' than m_ℓ^3

• Left-Right : W-W' mixing, heavy RH neutrinos
Model

N plays role of F

→ highly suppressed by mixing angles

$\delta \sim 10^{-6}$ at best

• Ad-Hoc heavy ν + Charged Higgs

· N play role of F
· couplings enhanced by large N mass

$\delta \sim$ few $\cdot 10^{-3}$

e.g.

I conclude ~~from~~ this special operator Bizzare survey that

$\delta_\tau^\gamma \sim 10^{-18}$ e-cm for τ's is "best" you can hope

for not e or μ unless NP not is very bizarre ...

{ Perhaps a more Some discrete/family symmetry exhaustive survey would be useful !? }

Kühn + Mirkes
Choi, Lee + Song

→ $\cancel{CP}$ in τ decays : e.g, $\underline{\tau \to K \pi \nu}$

{ Here, constraints from the quark sector play the most important role

$$M = \sqrt{2} G_F \left[(1+\underline{\underline{\chi}}) \bar{\nu} \gamma^\mu P_- \tau J_\mu + \underline{\underline{\eta}} \bar{\nu} P_+ \tau J_s \right]$$

$$J_\mu = \sqrt{2} s_c \left[F_K(q^2) \left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2} \right) (q_1 - q_2)^\nu + \frac{m_{K^*}^2}{q^2} c_K F_S(q^2) q_\mu \right]$$

$$J_s = \sqrt{2} s_c \frac{m_{K^*}^2}{m_s - m_u} c_K F_S(q^2)$$

$F_i \leftrightarrow$ resonance saturation

c_K by models

Figure of merit $\quad \underline{\mathrm{Im}\, \xi}$, $\quad \xi = \dfrac{m_{K^*}^2}{(m_s - m_u) m_\tau} \cdot \dfrac{\eta}{1+\chi}$

• Scalars ? MHD or LQ's

$$\mathcal{L}_{MHD} = a \sqrt{2} G_F s_c \frac{m_\tau m_s}{m_H^2} \left[X^* Z (\bar{s}_R u_L)(\bar{\nu}_L \tau_R) + \frac{m_u}{m_s} Y^* Z (\bar{s}_L u_R)(\bar{\nu}_L \tau_R) \right] + h.c.$$

$$\mathrm{Im}\,\xi_{MHD} \simeq -\frac{m_{K^*}^2}{m_H^2}\left\{\mathrm{Im}(XZ^*) + \frac{m_u}{m_s}\,\mathrm{Im}(YZ^*)\right\}$$

$$\simeq -3.2\cdot 10^{-4}\left(m_W/m_H\right)^2\left[\mathrm{Im}(XZ^*) + \frac{1}{50}\,\mathrm{Im}(YZ^*)\right]$$

<u>Grossman</u> : $|\mathrm{Im}\,\xi_{MHD}| \leq 0.27$ for $m_H = 60$ GeV
from B SL decays $[B \to \tau \nu_\tau X]$

$$\mathcal{L}_{LQ} \sim -\frac{\lambda_{23}\lambda_{13}'^*}{2M^2}(\bar{s}_L u_R)(\bar{\nu}_L \tau_R) + \cdots$$

$$\mathrm{Im}\,\xi_{LQ} = -\frac{m_{K^*}^2}{m_s m_\tau}\cdot\frac{\mathrm{Im}(\lambda_{23}\lambda_{13}'^*)}{4\sqrt{2}G_F s_c M^2}$$

<u>Davies</u> + <u>He</u>

$D-\bar{D}$ mixing $\to$ $|\mathrm{Im}\,\xi_{LQ}| \leq 0.14$ <u>if</u>
LQ couplings to q's + ℓ's of same generation are similar in size

Choi et al estimate: $\gtrsim 10^7$ τ's needed to probe to this level whether polarized or not

Summary

- We may know less about the players in the lepton sector than the quark sector

- $\not{CP}$ probed by

  edm's, decays, ν osc. asymmetries

  small but 'pay dirt'

  involves input from quark sector

  probes phases in mixing matrix <u>directly</u>

  in lepton sector

- Keep looking – surprises do happen.