Status of CP violation in Kaon systems

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- Short distance dominated $K \to \pi\bar{\nu}\nu$
- Minimal Flavour violation
- CP violation in $K \to \pi\pi\pi$, $K \to \pi\pi\gamma$, $K \to \pi\pi ee$
- Bell - Stenberger test, CPT
- Conclusions

Standard Model FCNC- CPviolation

- SM with 3 families $\Longrightarrow$ weak int. with an unit. mat. V_{ij}: 3 angles and 1 phase (CPV)

$$\overbrace{V_{ud}, V_{cb}, V_{td}}^{\text{Wolfenstein}} \Longrightarrow \lambda, A\lambda^2, A\lambda^3(1-\rho-i\eta)$$

- FCNC only at 1-loop

$$\mathcal{H}^{SM}_{\Delta F=2} \sim \frac{G_F^2 M_W^2}{16\pi^2}\left[\frac{(V_{td}^* m_t^2 V_{tb})^2}{v^4}(\bar{d}_L\gamma^\mu b_L)^2 + \frac{(V_{td}^* m_t^2 V_{ts})^2}{v^4}(\bar{d}_L\gamma^\mu s_L)^2\right] + \text{charm}$$

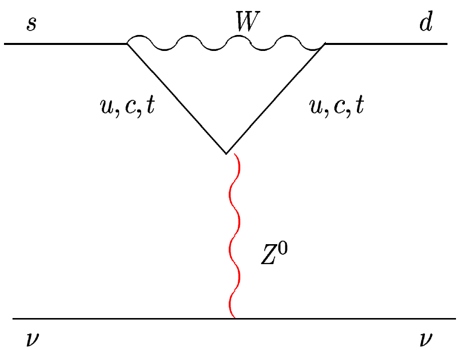
- The area of all possible CKM-unitarity triangles is an invariant:

$$|J_{CP}| \overset{Wolfenstein}{\simeq} A^2\lambda^6\eta$$

- As we shall see $B(K_L \to \pi^0\nu\overline{\nu})$ will measure this area

$K \to \pi\nu\overline{\nu}$

$$A(s \to d\nu\overline{\nu})_{\rm SM} \sim \overline{s}_L\gamma_\mu d_L \quad \overline{\nu}_L\gamma^\mu\nu_L \times \left[\sum_{q=c,t} V_{qs}^* V_{qd}\, m_q^2\right]$$



$$\sim \quad \left[A^2\lambda^5\,(1-\rho-i\eta)m_t^2 + \lambda m_c^2\right]$$

SM: $\underbrace{V - A \otimes V - A}_{\Downarrow}$ Littenberg

$$\Gamma(K_L \to \pi^0\nu\overline{\nu}) \quad \begin{cases} \text{CP violating} \\ \Rightarrow \quad J = A^2\lambda^6\eta \\ \text{Only } top \end{cases}$$

$K \to \pi\nu\overline{\nu}$: theory versus expts.

- K^+: $t >$ charm $\overset{\mathrm{NLO-QCD}}{\Longrightarrow}$ K^+ $\mathcal{O}(5\%)$, K_L $\mathcal{O}(1\%)$

- BR$(K \to \pi\nu\overline{\nu})_{\mathrm{TH}}$ K^+ $(0.8 \pm 0.1) \cdot 10^{-10}$ $K_L : (3.0 \pm 0.6) \cdot 10^{-11}$

- $B(K^+) = (1.73^{+1.15}_{-1.05}) \cdot 10^{-10}$ BNL-E787/E949 P326 at CERN

  $B(K_L) \leq 0.26 \times 10^{-7}$ at $90\% C.L.$ E391 at KEK

- K_L Model-independent bound, based on $SU(2)$ properties dim-6 operators for $\overline{s}d\overline{\nu}\nu$
  Grossman-Nir

$$B(K_L) \ \leq \frac{\tau_L}{\tau_+} \times B(K^{\pm})_{\mathrm{E949}} \leq 1.4 \times 10^{-9} \quad \text{at } 90\% C.L.$$

Supersymmetric Flavour Problem

- the SM Yukawa structure

$$\mathcal{L}^{Y}_{SM} \quad = \quad \bar{Q} Y_D D H + \bar{Q} Y_U U H_c + \bar{L} Y_E E H \ + \ \text{h.c.}$$

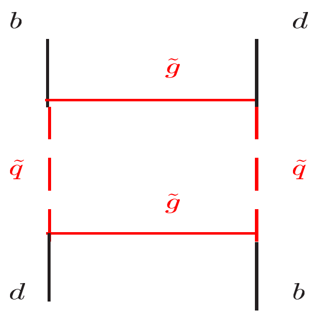
FCNC

$$\mathcal{H}^{SM}_{\Delta F=2} \sim \frac{G_F^2 M_W^2}{16\pi^2} \left[\frac{(V_{td}^* m_t^2 V_{tb})^2}{v^4} (\bar{d}_L \gamma^\mu b_L)^2 + \frac{(V_{td}^* m_t^2 V_{ts})^2}{v^4} (\bar{d}_L \gamma^\mu s_L)^2 \right] + \text{charm}$$

- Supersymmetry must be broken

$$-\mathcal{L}_{soft} = \tilde{Q}^\dagger m_Q^2 \tilde{Q} + \tilde{L}^\dagger m_L^2 \tilde{L} + \tilde{\bar{U}} a_u \tilde{Q}\ H_u + \ldots$$

- $m_Q^2, m_L^2, a_u, \ldots$ matrices in flavour space additional (to $Y_{u,d,l}$) non-trivial structures



$$\mathcal{H}^{\tilde{g}}_{\Delta F=2} \sim \frac{\alpha_s^2}{9M^2_{\tilde{Q}}}\left[(\delta^{LL}_{12})^2\,(\bar{s}_L\gamma_\mu d_L)^2 + \cdots\right]$$

δ^{LL}_{12} departure from identity matrix m^2_Q

Gabrielli,Masiero,Silvestrini

- $K - \bar{K} \Longrightarrow \quad \frac{(\delta^{LL}_{12})^2}{M^2_{\tilde{Q}}} \leq \frac{1}{(100\mathrm{TeV})^2} \Longrightarrow$ Naturalness?
- m^2_Q obey some Flavour symmetry so that GIM is realized $(\sim I)$:

$$\mathcal{L}_{\Delta F=2} = \frac{C}{\Lambda^2_{MFV}}\left[\frac{(V^*_{td}m^2_t V_{tb})^2}{v^4}(\bar{d}_L\gamma^\mu b_L)^2 + \frac{(V^*_{td}m^2_t V_{ts})^2}{v^4}(\bar{d}_L\gamma^\mu s_L)^2\right]$$

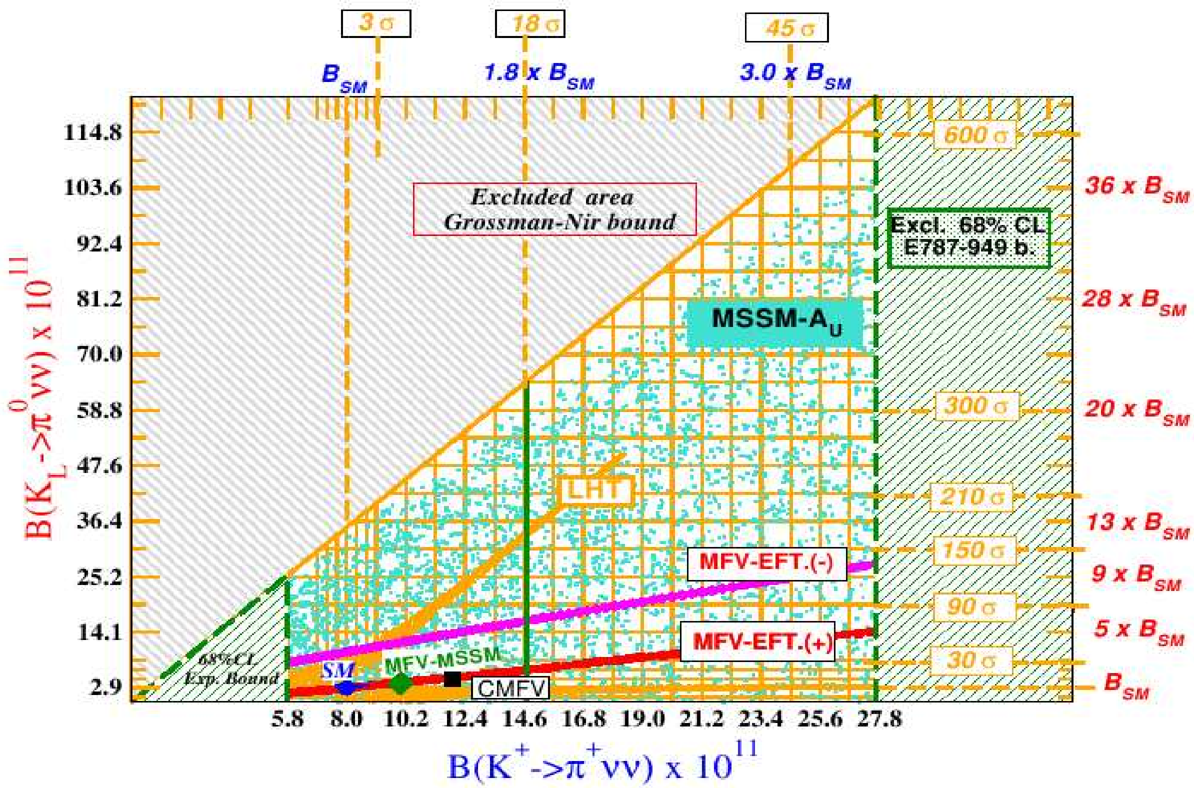
$C \sim 1 \Longrightarrow \Lambda_{MFV} > 5\mathrm{TeV}$ Ali, Buras

Theory

- There is a symmetry that New Physics must obey to satisfy FCNC -constraints

$$G_F = \overbrace{\mathrm{U}(3)_Q \otimes \mathrm{U}(3)_U \otimes \mathrm{U}(3)_D \otimes \mathrm{U}(3)_L \otimes \mathrm{U}(3)_E}^{\text{global symmetry}} + \overbrace{Y_{U,D,E}}^{\text{spurions}}$$

- Technicolour Chivukula, Georgi
- Gauge mediation Dine,Nelson, Shirman; Giudice, Rattazzi

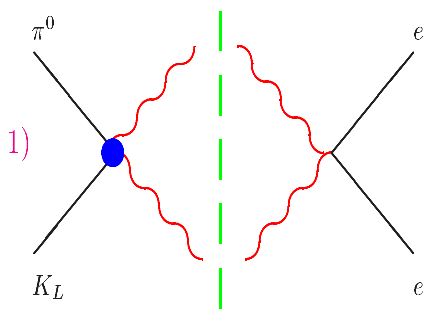


Mescia

P326 aims to have 100 $K^+ \to \pi^+ \nu \bar{\nu}$

$K_L \to \pi^0 e^+ e^-$: summary

$\mathrm{Br}(K_L \to \pi^0 e^+ e^-) \leq 2.8 \cdot 10^{-10}$ at 90% CL KTeV

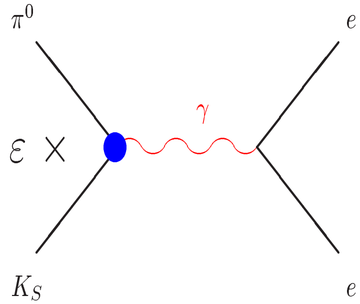


CP conserving NA48

Br$(K_L \to \pi^0 e^+ e^-) < 3 \cdot 10^{-12}$

V-A$\otimes$ V-A $\Rightarrow \langle \pi^0 e^+ e^- | (\bar{s}d)_{V-A} (\bar{e}e)_{V-A} | K_L \rangle$ violates CP

2) $\varepsilon\times$



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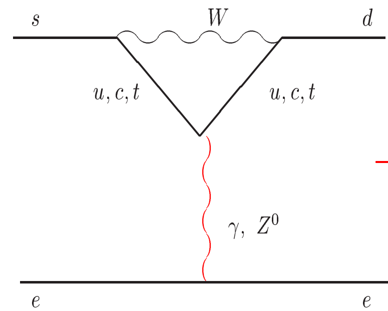


$\longrightarrow$ Im λ_t

$\lambda_t = V_{td}V_{ts}^*$

$\uparrow$ $\mathrm{B}(K_S \to \pi^0 e^+ e^-) = 4.6 a_S^2 \times 10^{-9}$

Possible large interference: $a_S < -0.5$ or $a_S > 1$; short distance probe even for a_S large

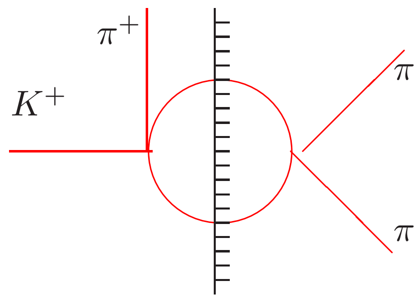
$$|2) + 3)|^2 = \left[15.3\, a_S^2 - 6.8\frac{Im\lambda_t}{10^{-4}}\, a_S + 2.8\left(\frac{Im\lambda_t}{10^{-4}}\right)^2\right]\cdot 10^{-12}$$

$$[17.7 \pm \quad 9.5 + \quad 4.7] \quad \cdot 10^{-12}$$

CP violation in in $K^\pm \to 3\pi$

- Dalitz distribution in X,Y $|A(K^\pm \to 3\pi)|^2 \sim 1 + g_\pm\, Y + j_\pm\, X$
- we can define the slope asymmetry $\Delta g/2g = (g_+ - g_-)/(g_+ + g_-)$
- Isospin+rescattering: $A(K^+ \to \pi^+\pi^+\pi^-) = a e^{i\alpha_0} + b e^{i\beta_0} Y$

Final State Interaction



Zeldovich,Grinstein et al
Isidori,Maiani,Pugliese

Compared to $K \to \pi\pi$

- two $\Delta I = 1/2$ transitions (a, b)
- final state small ($\alpha_0, \beta_0 \sim 0.1$)

- $\mathcal{O}(p^4)$ necessary for the slopes ($\frac{\Delta a}{a} \sim \frac{\Delta b}{b} \sim 30\%$) and for $\Delta g/2g \neq 0$

$$\Downarrow$$

- splitting $a = a^{(2)} + a^{(4)}$ and $b = b^{(2)} + b^{(4)}$ G.D.,Isidori,Paver

$$\frac{\Delta g}{2g} = \frac{\Im A^0}{\Re A^0} \ (\alpha_0 - \beta_0) \left(\frac{\Re b^{(4)}}{\Re b^{(2)}} - \frac{\Im b^{(4)}}{\Im b^{(2)}} + \frac{\Im a^{(4)}}{\Im a^{(2)}} - \frac{\Re a^{(4)}}{\Re a^{(2)}} \right)$$

$$|\frac{\Im A^0}{\Re A^0}| \sim 22\epsilon' \sim 10^{-4} \qquad (\alpha_0 - \beta_0) \sim 0.1$$

- to maximize Δg, we take $\mathcal{O}(p^4) \sim \mathcal{O}(p^2) \Longrightarrow \Delta g/2g \leq 10^{-5}$

New Physics to have large $\Delta g/2g$

- an operator which affects $K \to 3\pi$ but not $K \to 2\pi$, limited by expt. size of ϵ'

- Actually Masiero- Murayama:new flavour structures to only the $\Delta S = 1$ and not $\Delta S = 2$

$$(\delta^D_{LR})_{ij} = (M^2_D)_{i_L j_R}/m^2_{\tilde{q}}$$

- Through the gluino box diagram

$$C^{\pm}_g(m_{\tilde{g}}) = \frac{\pi\alpha_s(m_{\tilde{g}})}{m_{\tilde{g}}} \left[\left(\delta^D_{LR}\right)_{21} \pm \left(\delta^D_{LR}\right)^*_{12} \right] G_0(x_{gq})$$

$$\mathcal{H}_{\rm mag} = C^+_g Q^+_g + C^-_g Q^-_g + {\rm h.c.}$$

$$Q_g^{\pm} = \frac{g}{16\pi^2} \left(\bar{s}_L \sigma^{\mu\nu} t^a G^a_{\mu\nu} d_R \pm \bar{s}_R \sigma^{\mu\nu} t^a G^a_{\mu\nu} d_L \right)$$

- Q_g^+ is affects only $K \to 3\pi$; Q_g^- only $K \to 2\pi$

G.D,Isidori,Martinelli

- As a result by tuning properly $C_g^{\pm}$ we can generate large $\Delta g/2g$ $(\leq 10^{-4})$

- NA48/2 has measured

$$\frac{\Delta g}{2g} \quad \overset{\text{NA48}}{<} 10^{-4} \qquad \overset{\text{SM}}{<} 10^{-5} \qquad \overset{\text{PDG}}{<} 7 \cdot 10^{-3} \qquad \overset{\text{NP}}{<} 10^{-4}$$

$$K(p_K) \to \pi(p_1)\pi(p_2)\gamma(q)$$

- Lorentz + gauge invariance $\Rightarrow$ Electric (E) and Magnetic(M) amplitude

$$A(K \to \pi\pi\gamma) = F^{\mu\nu}\left[E\partial_\mu K\partial_\nu\pi + M\varepsilon_{\mu\nu\rho\sigma}\partial^\rho K\partial^\sigma\pi\right]$$

- Unpolarized photons

$$\frac{d^2\Gamma}{dz_1 dz_2} \sim |E|^2 + |M|^2$$

$$|E^2| = |E_{IB}|^2 + 2Re(E^*_{IB}E_D) + |E_D|^2$$

$$\downarrow$$

Low Theorem $\Rightarrow E_{IB} \sim \dfrac{1}{E^*_\gamma}$ + c $\qquad E_D$, M chiral tests

We need FIGHT DE/IB$\sim 10^{-3}$

	IB	DE_{exp}	
$K_S \to \pi^+\pi^-\gamma$	10^{-3}	$< 9 \cdot 10^{-5}$	$E1$
$K^+ \to \pi^+\pi^0\gamma$	10^{-4} ($\Delta I = \frac{3}{2}$)	$(0.44 \pm 0.07)10^{-5}$ PDG	$M1$,$E1$
$K_L \to \pi^+\pi^-\gamma$	10^{-5} (CPV)	$(2.92 \pm 0.07)10^{-5}$ KTeVnew	$M1$, VMD

CPV is only from IB K_L (also measured in $K_L \to \pi^+\pi^-e^+e^-$)

BUT IB suppressed in K^+ and K_L.

$K^+ \to \pi^+\pi^0\gamma$

$$A(K \to \pi\pi\gamma) = F^{\mu\nu}\left[E\partial_\mu K\partial_\nu\pi + M\varepsilon_{\mu\nu\rho\sigma}\partial^\rho K\partial^\sigma\pi\right]$$

$E1$ and $M1$ are measured with Dalitz plot

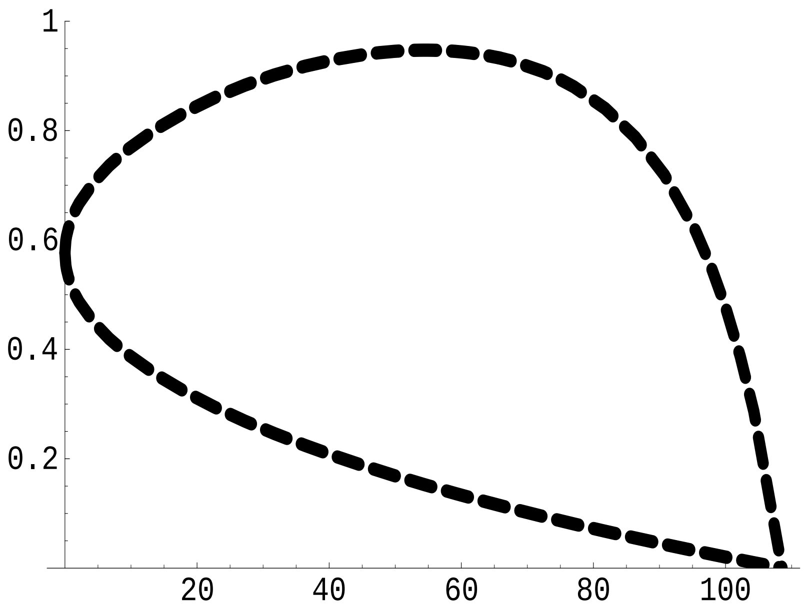
$$\frac{\partial^2\Gamma}{\partial T_c^*\partial W^2} = \frac{\partial^2\Gamma_{IB}}{\partial T_c^*\partial W^2}\left[1 + \frac{m_{\pi^+}^2}{m_K}2Re\left(\frac{E1}{eA}\right)W^2 + \frac{m_{\pi^+}^4}{m_K^2}\left(\left|\frac{E1}{eA}\right|^2 + \left|\frac{M1}{eA}\right|^2\right)W^4\right]$$

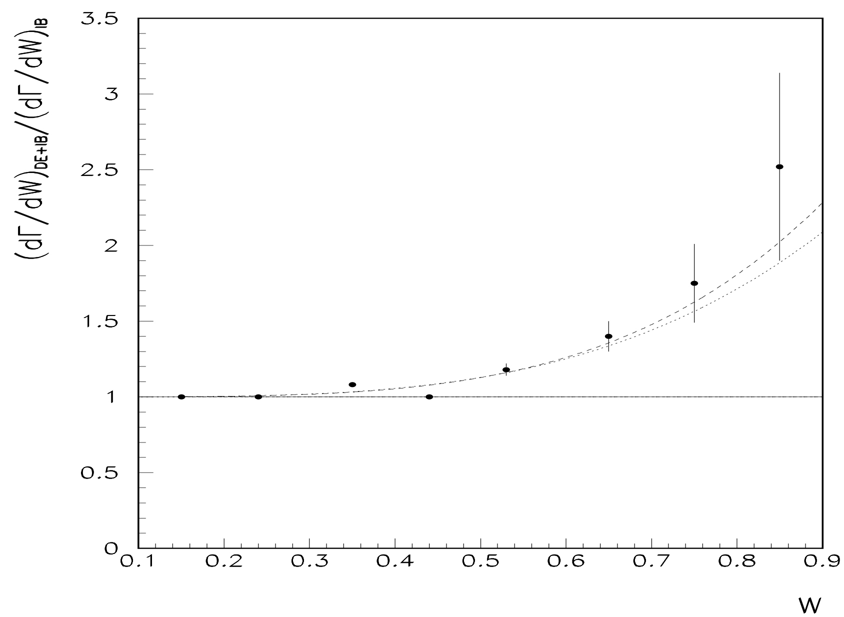
$$W^2 = (q\cdot p_K)(q\cdot p_+)/(m_\pi^2 m_K^2)$$

$A = A(K^+ \to \pi^+\pi^0)$

$K^+ \to \pi^+\pi^0\gamma$ $W - T_c$ **Dalitz plot**

Integrating over T_c deviations from IB measured





CP asymmetry

- In the asymmetry in the slope, $\frac{\partial^2\Gamma^\pm}{\partial T_c^* \partial W^2}$ select a favourable kin. region (large W^2)

- This asymm., Ω, in extensions of SM $\sim \mathcal{O}(10^{-4})$ Colangelo et al.

- SM $\leq \mathcal{O}(10^{-5})$ Paver et al.

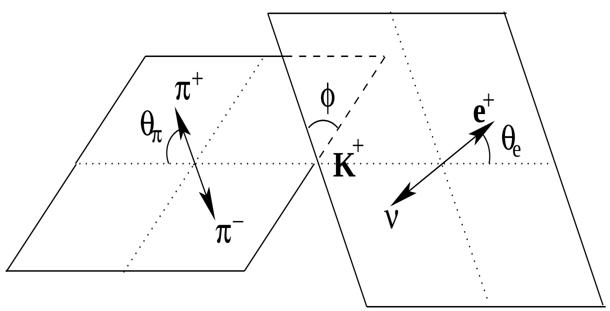
- Assuming the expts. are almost seeing the CP conserving $E1$ Statistics seems tough but previous limit (Smith eta l. 76) weak

- Similar analysis for CPV in K_L: but time interf. required

$K^+ \to \pi^+\pi^0\gamma^* \to \pi^+\pi^0 e^+e^-$: **Cappiello, Cata,G.D. and Gao, EPJC**

- $K_L \to \pi^+\pi^- e^+e^-$: extra kin. variables compared to $K_L \to \pi^+\pi^-\gamma \Longrightarrow$ interesting interference among E_B and M

- CP violating effect and since $E_B \sim M$ the observable $\dfrac{\Re(E_B\ M^*)}{|E_B|^2 + |M|^2}$ is maximal, suppressed only by phase space ($\sim 14\%$)



- Look angular plane asymmetry $\pi\pi$ e^+e^-

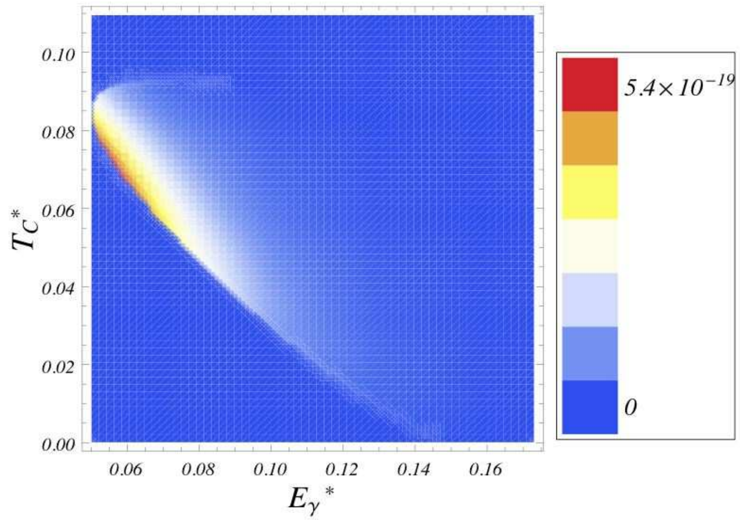
- CP asymmetry generated, purely LD Not SD

$K^+ \to \pi^+\pi^0 e^+ e^-$

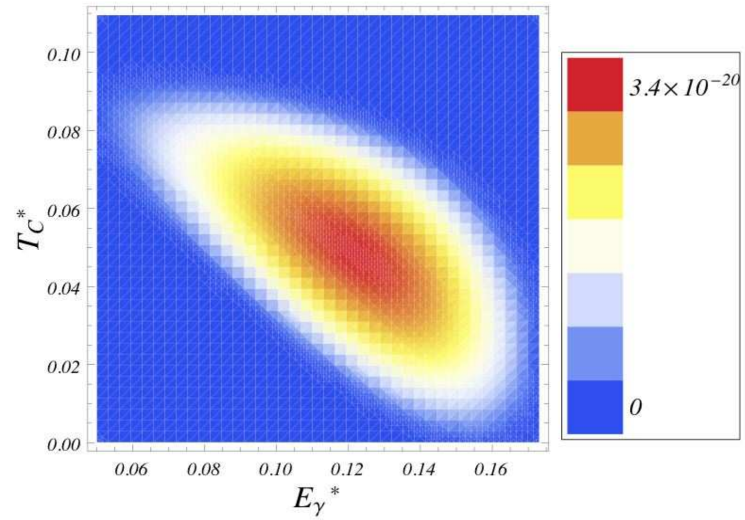
,

- the asymm. , $\dfrac{\Re(E_B\ M^*)}{|E_B|^2 + |M|^2}$, as in K_L, not as lucky $E_B >> M$: $B(K^+ \to \pi^+\pi^0 e^+ e^-)_B \sim 3.3 \times 10^{-6} \ \sim\ 50\ B(K^+ \to \pi^+\pi^0 e^+ e^-)_M$
- Still CP asymmetry generated, without having simultaneously K^+ and K^-, asymm. in phase space, Also P-violation in interesting:
- Interesting for weak CT"s:
- Chosen variables as in $K^+ \to \pi^+\pi^0\gamma$, $W - T_c$ plus dilepton invariant mass, q^2
- interesting Dalitz plots (at fixed q^2) to disentangle M from E_B

$K^+ \to \pi^+ \pi^0 e^+ e^-$: Dalitz plot



IB



DE

In different portions of Dalitz plots also other inteferences (magnetic -electric)

How to extract SD from $K^+ \to \pi^+\pi^0 e^+ e^-$

- LD: e^+e^--pair coupled through "γ^* $\Longrightarrow$ P-violation in the lepton pair signature of short distance , important for NA62

- Novel CP violation contributions (compared to $A_{CP}(K^+ \to \pi^+\pi^0\gamma)$)

$$A_{CP} = \frac{\Gamma(K^+ \to \pi^+\pi^0 e^+e^-) - \Gamma(K^- \to \pi^-\pi^0 e^+e^-)}{\Gamma(K^+ \to \pi^+\pi^0 e^+e^-) + \Gamma(K^- \to \pi^-\pi^0 e^+e^-)}$$

μ-Polarization in $K^+ \to \pi^0 \mu^+ \nu$

- $\langle P_\perp \rangle \sim \langle \vec{s_\mu} \cdot (\vec{p_\mu} \times \vec{p_\pi}) \rangle$ is T-odd, $\Longrightarrow$ CP violation

- FSI $\langle P_\perp \rangle \sim 10^{-6}$ Zhitniskii,Hiller-Isidori

$$M_{K_{\mu 3}} = G_F \sin\theta_c f_+(q^2)[p_\alpha \overline{u_\mu}\gamma^\alpha(1-\gamma_5)u_{\nu_\mu} + f_s(q^2) m_\mu \overline{u_\mu}(1-\gamma_5)u_{\nu_\mu}]$$

$$\langle P_\perp \rangle \sim 0.2 \quad Im(f_s)$$

- Bounds on models $\langle P_\perp \rangle \leq 10^{-2}$ Peccei

  but interesting models (multi-Higgs, leptoquarks) $\langle P_\perp \rangle \sim 10^{-4}$ Garisto-Kane

- KEK E246 $\langle P_\perp \rangle < 5 \cdot 10^{-3}$

Bell Steinberger relations

$$\left[\frac{\Gamma_S+\Gamma_L}{\Gamma_S-\Gamma_L}+i\tan\phi_{\rm SW}\right]\left[\frac{\Re(\epsilon)}{1+|\epsilon|^2}-i\Im(\Delta)\right]=\frac{1}{\Gamma_S-\Gamma_L}\sum_f \overset{(\alpha_f)}{A_L(f)A_S^*(f)}$$

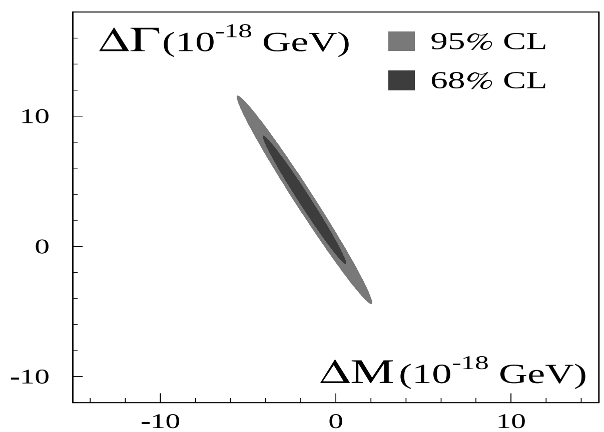
$$\begin{aligned}\epsilon_{S,L} &= \frac{-i\Im\left(M_{12}\right)-\frac{1}{2}\Im\left(\Gamma_{12}\right)\mp\frac{1}{2}\left[M_{11}-M_{22}-\frac{i}{2}\left(\Gamma_{11}-\Gamma_{22}\right)\right]}{m_L-m_S+i(\Gamma_S-\Gamma_L)/2}\\ &= \epsilon\mp\Delta\end{aligned}$$

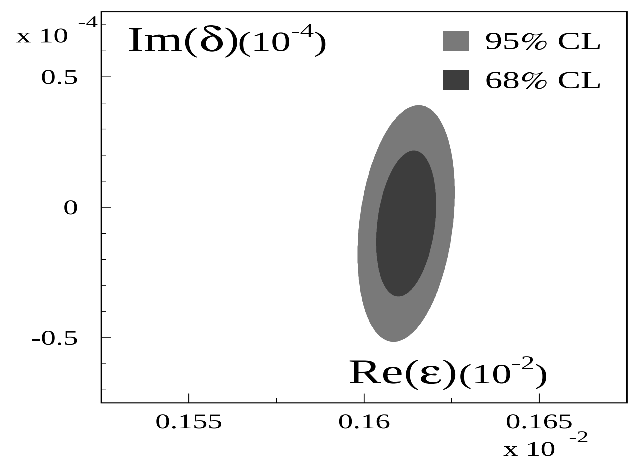
$$\epsilon\equiv|\epsilon|e^{i\varphi_{SW}} \qquad \tan\varphi_{SW}=\frac{2(m_L-m_S)}{\Gamma_S-\Gamma_L}$$

Bell Steinberger relations: CPLEAR,KTeV,NA48,KLOE

$$\Re(\epsilon) = (161.1 \pm 0.5) \times \ 10^{?5} \qquad \Im(\Delta) = (-0.7 \pm 1.4) \times \ 10^{?5}$$

$$-4.0 \times 10^{-19} \text{ GeV} < m_{K^0} - m_{\overline{K}^0} < 4.0 \times 10^{-19} \text{ GeV} \quad \text{at 95 \% C.L.}$$





Important K-physics still to be done: impact of expts. on CKM

- 2004: $|V_{us}|$: 2.2 σ 's discrepancy from unitarity reconciliated after semileptonic measurement from BNL, KTeV, KLOE, NA48
- 2006 KLOE measures τ_{K^+} confirming in-flight measurements vs at rest mesurements
- 2006 All KL's branching fractions changed due KTeV measurements

Conclusions

- Connection CP violation D- and K-physics departure from MFV
- Looking forward to have data from NA62
- check also less ambitious channels
- Many interesting chiral tests ($K^+ \to \pi^+\pi^0\gamma$, $K^+ \to \pi^+\pi^0 e^+e^-$,..)
- Bell Steinberger tests

Chiral Perturbation Theory

χPT effective field theory based on the two assumptions

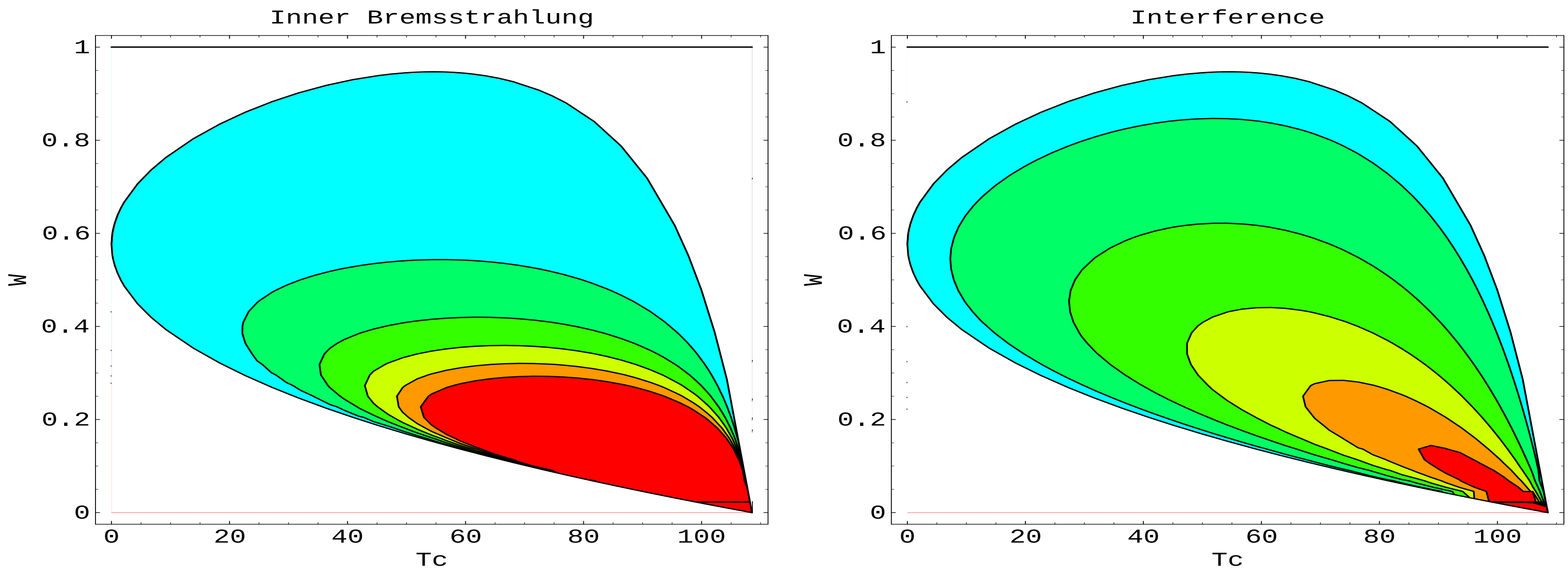
- π's are the Goldstone boson of $SU(3)_L \otimes SU(3)_R \to SU(3)_V$
- *(chiral) power counting* i.e. the theory has a small expansion parameter: $p^2/\ \Lambda^2_{\chi SB}$: $\Lambda_{\chi SB} \sim 4\pi F_\pi \sim 1.2$ GeV

$$\mathcal{L}_{\Delta S=0} = \mathcal{L}^2_{\Delta S=0} + \mathcal{L}^4_{\Delta S=0} + \cdots = \frac{{F_\pi}^2}{4} \overbrace{\langle D_\mu U D^\mu U^\dagger + \chi U^\dagger + U \chi^\dagger \rangle}^{\pi\to l\nu,\ \pi\pi\to\pi\pi,\ K\to\pi..} + \overbrace{\sum_i L_i O_i}^{K\to\pi..} + \cdots$$

Fantastic chiral prediction $A_{\pi\pi} \sim (s - m_\pi^2)/{F_\pi}^2$ Weinberg, Colangelo *et al*

$$\mathcal{L}_{\Delta S=1} = \mathcal{L}^2_{\Delta S=1} + \mathcal{L}^4_{\Delta S=1} + \cdots = G_8 F^4 \underbrace{\langle \lambda_6 D_\mu U^\dagger D^\mu U \rangle}_{K\to 2\pi/3\pi} + \underbrace{G_8 F^2 \sum_i N_i W_i}_{K^+\to\pi^+\gamma\gamma,\, K\to\pi l^+ l^-} + \cdots$$

$K^+ \to \pi^+ \pi^0 \gamma$



- E787 has measured M1 and $\mathrm{Re}\left(\frac{E1}{E_{IB}}\right) \sim (-0.4 \pm 1.6)\%$

$$\downarrow$$

- E1 dominated by CT $\Rightarrow$ E787 constrains models $(k_f < 1)$ NA48/2$\Longrightarrow$

$k_f = -0.4$