Beijing, August 2005

Flavour Dynamics & ~~C~~P in the SM*: A Tale of Great Successes, Little Understanding -- and Promise for the Future!

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Lecture II (6)

CKM Phenomenology

Recap from Lecture I

The CKM description of flavour transitions:

an amazingly successful piece of `theoretical engineering' based on central mysteries of the SM -- mass generation for quark fields.

$$|V_{CKM}| \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

presumably profound message from nature -- in an encoded form

Menu for Lecture II

I Phenomenological Landscape → 1999

II Theoretical Technologies

Effective Field Theories
Operator Renormalization & Mixing
Nonperturbative Tool Chest

III The CKM Paradigm of Large ~~CP~~ in B Decays

Prelude '52 - '73
Growing up '73 - '94
Completion of a Heroic Era
Status of CKM Theory end of 2nd Millenium
CKM Exotica -- EDM's

IV Summary of Lecture II

I Phenomenological Landscape → 1999

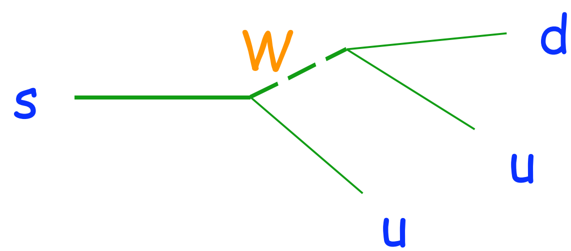
		understanding?
❑ \`$\theta-\tau$ puzzle': $\theta\rightarrow 2\pi$, $\tau\rightarrow 3\pi$	~~P~~	implemented
❑ production >> decay rates	associated production	quark families
❑ $\tau(K^+\rightarrow\pi^+\pi^0)$ >> $\tau(K\rightarrow\pi^+\pi^-)$	$\Delta I=1/2$ rule	??
❑ Cabibbo Universality:	$\|V(us)\|^2 << \|V(ud)\|^2$, $\|V(ud)\|^2 + \|V(us)\|^2 = 1$	
❑ K^0-K^0 oscillations	$\Delta\Gamma_K$	CP+phase space
	ΔM_K	GIM, quark box
❑ $K_L\rightarrow\mu^+\mu^-$, $\gamma\gamma$	suppression of FlChNC	~~GIM~~, quark box
❑ $K_L\rightarrow\pi^+\pi^-$	ε_K	CP+ quark box
$\rightarrow l^+\nu\pi^-$	δ_L	
❑ charm	$\|V(cs)\|^2 \sim \|V(ud)\|^2$, $\|V(cd)\|^2 \sim \|V(us)\|^2$	GIM
❑ beauty	$\|V(ub)\|^2 << \|V(cb)\|^2 << 1$	
	ΔM_B	GIM, quark box
❑ top	$m_t > M_Z$, $>> m_b$	inferred f.quantum corr.

II Theoretical Technologies

2.1 Electroweak Dynamics

Can be dealt with perturbatively

consider $\Delta S=1$



dim-6 $\rightarrow$ nonrenormalizable ?

effective coupling derived from

renorm. $L = g_W \, q_1 \gamma_\mu (1-\gamma_5) q_2 W_\mu$

with heavy fields -- W_μ -- `integrated out'

2.1.1 Effective Field Theories

Wilson prescription:

- define field theory $L(\Lambda)$ at UV scale Λ with

  Λ >> germane scales of theory like M_W, m_Q etc.

- for applications characterized by scales ~ μ integrate out the heavy d.o.f. to arrive at an effective low energy field theory using the Operator Product Expansion (OPE) as tool

$$L(\Lambda) \;\rightarrow\; L(\mu) = \Sigma_i\, c_i(\mu,\Lambda)\, O_i(\mu)$$

c numbers providing gateway for heavy d.o.f. with frequencies > μ (→ $c_i(\mu,\Lambda)$)

local operators containing dynamical, i.e. active fields with frequencies ≤ μ (→ $O_i(\mu)$)

- integrating out heavy d.o.f. induces higher-dimensional (d>4) operators

- $\mathcal{L}(\mu_1) \neq \mathcal{L}(\mu_2)$ for $\mu_1 \neq \mu_2$

in principle observables can*not* depend on value of μ --
it is just a labeling device:

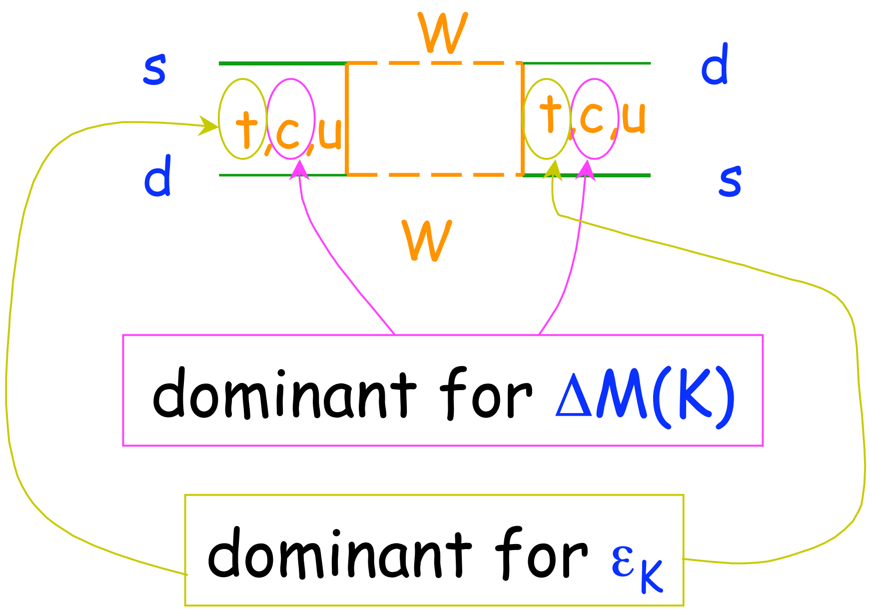
short distances < μ^{-1} < long distances

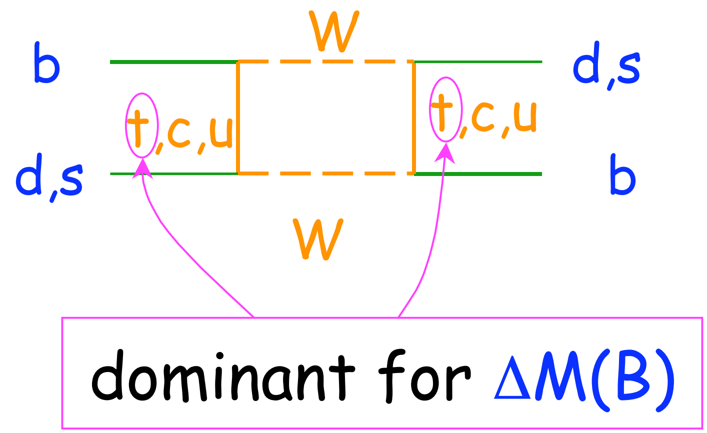
in practice, however, must be chosen judiciously due to limitations in our computational abilities
s.t.

- $\alpha_S(\mu) < 1$
- matrix elements can be evaluated

➥ $\mu \sim 1$ GeV

consider $\Delta S=2$ produced by iterating $\Delta S=2$

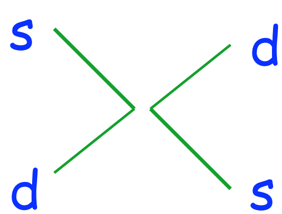




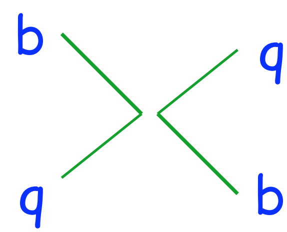
$m_t > M_B$

$m_t > m_c > M_K$

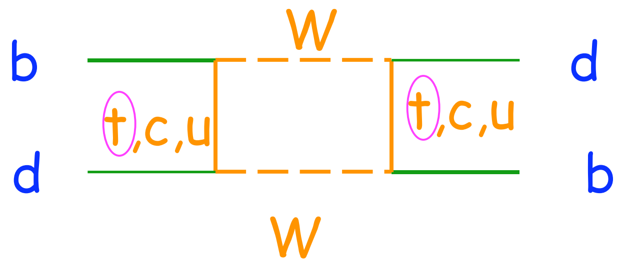
$L_{eff}(\Delta S=2) \propto$



$L_{eff}(\Delta B=2) \propto$



`food for thought' a.k.a. homework assignment

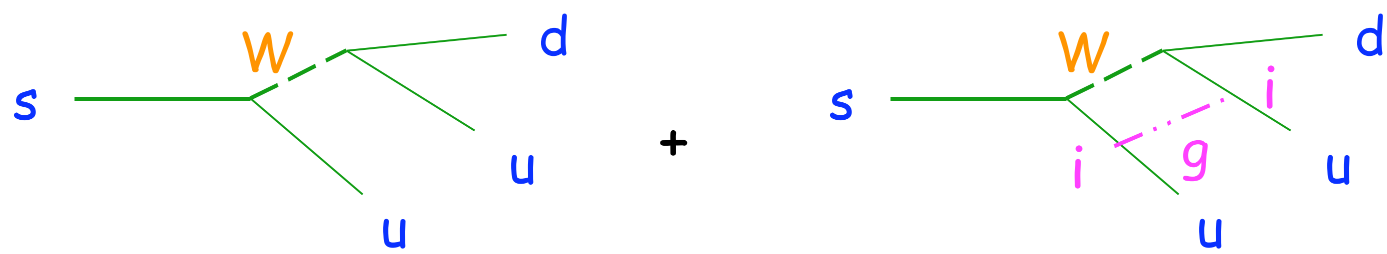


$\Delta M(B) \propto (m_t/M_W)^2$ for $m_t \gg M_W$

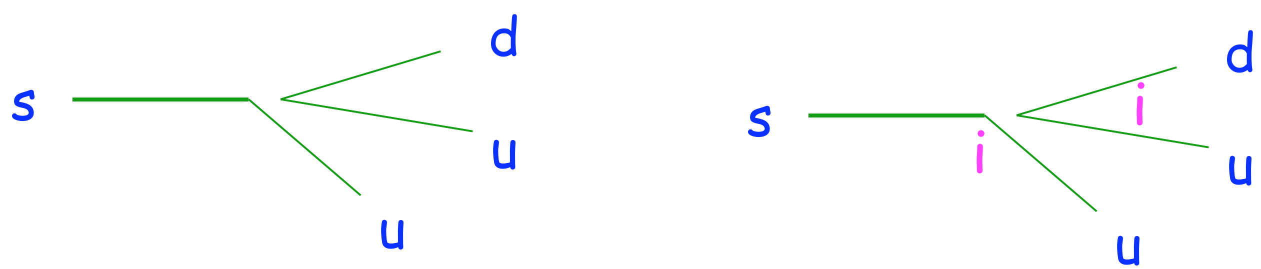
☹ "decoupling" ??

radiative QCD corrections affect the strength of these effective weak transition operators -- and create new & novel ones!

ΔS=1

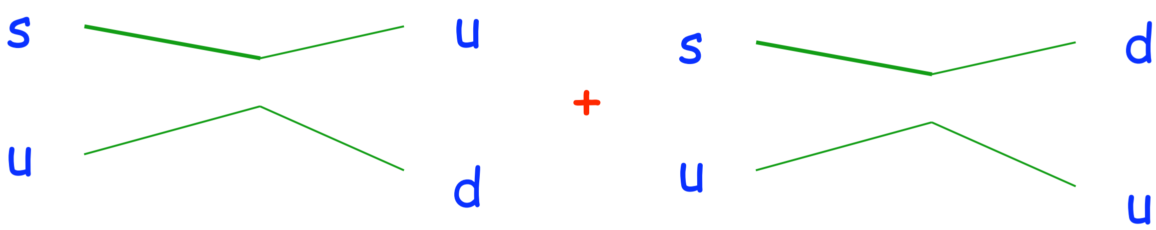


➥ under QCD renormalization the two operators



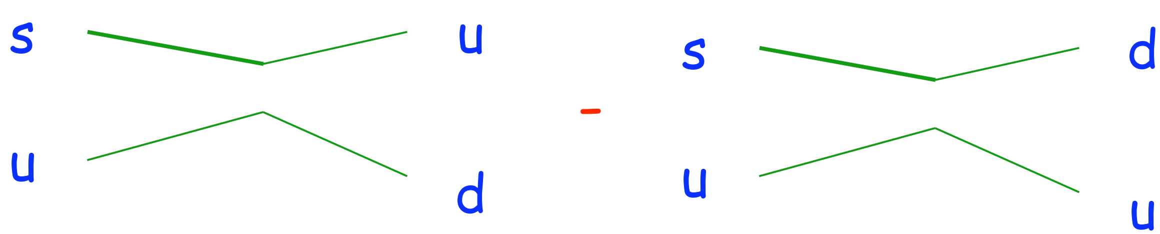
mix

$I_{init} = 1/2$



$I_{final} = 1$

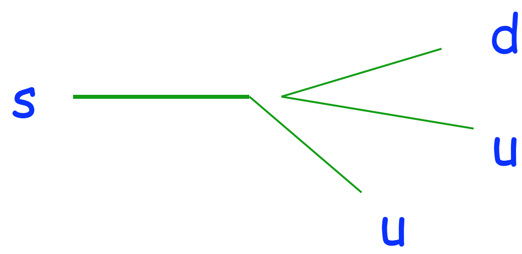
➥ $\Delta I = 1/2$ & $3/2$

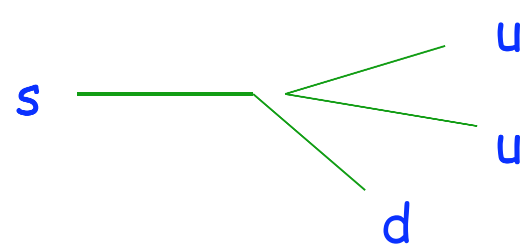


$I_{final} = 0$

➥ $\Delta I = 1/2$ only

- 2 multiplicatively renormalized operators

$O_{\pm} = 1/2 \times \Big($ 

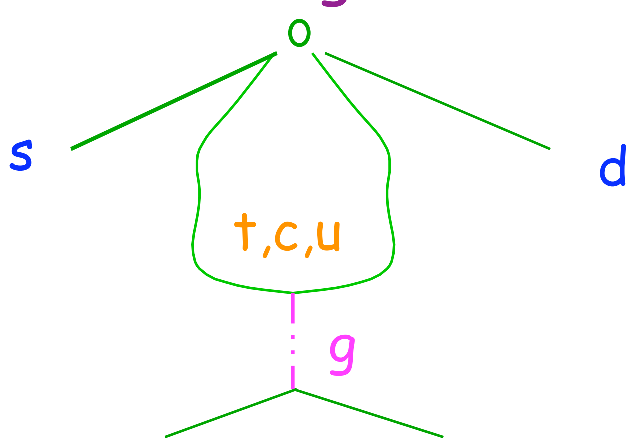
$\pm$ 

$\Big)$

➥ $\mathcal{L}_{eff} \propto c_- O_- + c_+ O_+$

with $c_- > 1 > c_+$ & $c_- c_+^2 \sim 1$, O_- pure $\Delta I=1/2$

☞ … the emergence of Penguins !



- pure $\Delta I=1/2$
- sensitive to three families in $\Delta S=1$
  - ➥ direct ~~CP~~

2.2 Nonperturbative Dynamics

to calculate rates need to evaluate on-shell hadronic ME:

$$T(H \to f) \propto \langle f|L_{eff}|H\rangle \propto \Sigma_i c_i(\mu) \langle f|O_i(\mu)|H\rangle,$$

μ = usual hadronic scale

challenge of nonperturbative dynamics

- ✍ quark models

  The `old war horse' -- can still get some mileage out of it, but do not overburden it: excellent for developing intuition, first answers, yet unsatisfactory for final answers

- ✍ chiral perturbation theory = QCD at low energies
- ✍ heavy quark theory = QCD for heavy flavours (see later)
- ✍ LQCD = the perceived Panacea
- ✍ QCD Sum Rules

a central example:

$$\langle K|(s_L\gamma_\mu d_L)\,(s_L\gamma_\mu d_L)|K\rangle,\ \langle B_q|(b_L\gamma_\mu q_L)\,(b_L\gamma_\mu q_L)|B_q\rangle$$

control K-K, B-B oscillations

Vacuum Saturation (VS)/`factorization'

$$\langle K|(s_L\gamma_\mu d_L)\,(s_L\gamma_\mu d_L)|K\rangle$$

$$\mathbf{1} = |0\rangle\langle 0| + \cancel{|had\rangle\langle had|}$$

$$\langle K|(s_L\gamma_\mu d_L)(s_L\gamma_\mu d_L)|K\rangle \sim \underbrace{\langle K|(s_L\gamma_\mu d_L)|0\rangle}_{if_K p_\mu}\underbrace{\langle 0|(s_L\gamma_\mu d_L)|K\rangle}_{if_K p_\mu}$$

$$= B_K f_K^2 M_K^2\,,$$

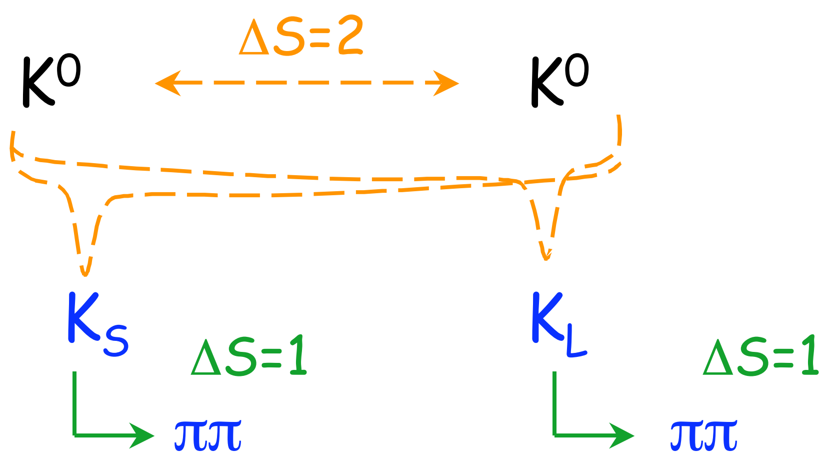
$$B_K^{VS}=1,\ B_K \sim O(1)$$

✍ fact. at $\mu_1 \neq$ fact. at μ_2 if $\mu_1 \neq \mu_2$

III The CKM Paradigm of Large ~~CP~~ in B Decays

- phenomenological distinction between $\Delta F=1$ & $\Delta F=2$ dynamics; yet underlying theory has to yield both!

- same interplay between $\Delta F=1$ & $\Delta F=2$ affects ~~CP~~



$$\eta_{+-,00} = \frac{A(K_L \to \pi^{+,0}\pi^{-,0})}{A(K_S \to \pi^{+,0}\pi^{-,0})}$$

$$\eta_{+-} = \epsilon + \epsilon', \quad \eta_{00} = \epsilon - 2\epsilon'$$

indirect (→ ϵ)   direct (→ ϵ')

~~CP~~

☞ as long as ~~CP~~ seen in a single decay of a neutral meson, distinction between direct & indirect ~~CP~~ arbitrary!

a general comment:

transitions like $K_L \to \pi\pi$ or $B_d \to \psi K_S$ involve two phenomenologically distinct dynamics, namely $\Delta F=1$ & $\Delta F=2$;

it is important to deduce from data to which degree both contribute to observed modes;

yet in the end the underlying theory has to explain both.

Lastly:

The `Superweak' Model is not a theory, not even a model --

it is merely a classification scheme.

3.1 Prelude: '52 $\to$ '73

- ~~CP~~ vs. ~~P~~

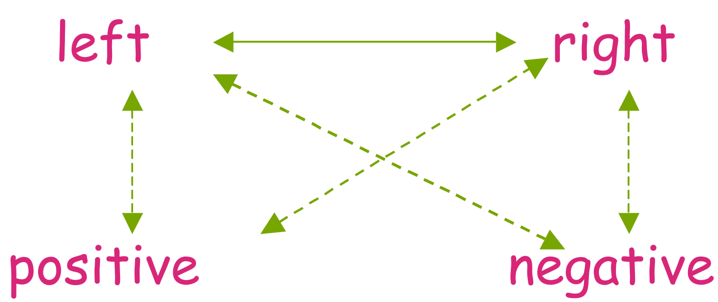
  Wick ND, Wightman, Wigner (1952):

  the "… disturbing possibility …" that

  CP √ , yet ~~P~~ and ~~C~~ is "remote at the moment"!

- discovery of ~~P~~ in '57 a great shock, yet theorists quickly recovered

"politics and ~~P~~"



$\pi^- \to e_L^- \nu$ or $\pi^+ \to e_R^+ \nu$

"L" = f ("-")

CP: $(\pi^- \to e_L^- \nu) \Rightarrow (\pi^+ \to e_R^+ \nu)$

If CP √ $\Rightarrow$ "L" pure convention!

"the thumb is left on the right hand!"

- '64: $\not{CP}$ discovered -- caused another even greater shock!

Attempts at evasion:

➻ $K_L \to \pi\pi$ implying CP requires Superposition Principle of QM -- give up SuPoPr!

➻ ∃ invisible CP odd particle U $K_L \to \pi^+\pi^-[U]$

a la Pauli's postulate for ν's in β decay $n \to p\ e\ [\nu]$

introduce new invisible particle to save conservation law

U	ν
CP	energy-momentum
did not work	did work

\`quod licet Jovi, non licet bovi'

= Pauli (Jovi) = non-Pauli (bovi)

- ~~CP~~ $\Rightarrow$ ~~T~~

- ~~CP~~ required to define matter vs. antimatter, L vs. R,
  + vs. - in convention independent way

- smallest observed violation of a symmetry

$$\mathrm{Im}\, M_{12} \approx 1.1 \times 10^{-8}\, \mathrm{eV} \Leftrightarrow \mathrm{Im}\, M_{12}/m_K \approx 2.2 \times 10^{-17}$$

☞ frustrating -- no `peccate fortiter'
CP invariance as a `near miss' vs. maximal ~~P~~

- '65: Sakharov conditions for baryogenesis
  - $\Delta N_{baryon} \neq 0$,
  - ~~C~~P
  - out-of-thermal equilibrium

- phenomenology of ~~C~~P quickly developed

$$\eta_{+-} = \varepsilon + \varepsilon', \ \eta_{00} = \varepsilon - 2\varepsilon'$$

- '64 - '72: lack of theory not realized

  even after renormalizibility of $SU(2)_L x U(1)$ recognized
  (except for short remark by Mohapatra in '72)

- '64 - '72:
  - 3 `quarks': u, d, s
    1 mixing angle θ_C
    2 charged leptons + 2 ν
  - charm -- suggested, yet common sentiment:
    "Nature is smarter than Shelley (Glashow) -- she can do without charm"
  - ☞ asymptotic freedom of QCD discovered & appreciated
- '74 `October Revolution'
  - quarks viewed as real d.o.f.
  - first `heavy' quark -- charm -- found
    open charm hadrons identified in '76
  - τ lepton found -- beginning of 3rd family

3.2 Growing up 1973 - 1994

- '76: discovery of Υ
- '79: prediction of large ~~CP~~ in $B_d \to K\pi$
- '80: prediction of large ~~CP~~ in B^0 decays involving qm state mixing & oscillations, in particular in $B_d \to \psi K_S$

➻ before a single B decay channel had been identified!

- \`beauty prefers charm': $|V(cb)|^2 \gg |V(ub)|^2$
- '82: discovery of \`long' B lifetime ~$\mathcal{O}$(1 psec): $|V(us)|^2 \gg |V(cb)|^2$

✍ the emerging pattern:

- $|V(us)| = \lambda$
- $\tau(B) \sim 1$ psec $\Longrightarrow$ $|V(cb)| \sim O(\lambda^2)$
- $|V(ub)|/|V(cb)| \sim O(\lambda)$

➥ Wolfenstein representation

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2 & \lambda & A\lambda^3(\rho - i\eta + \eta\lambda^2/2) \\ -\lambda & 1-\lambda^2/2 - i\eta A^2\lambda^4 & A\lambda^2(1+\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

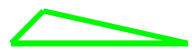
3 classes of 2 unitarity triangles each the sides of which have length

- $\lambda + \lambda + \lambda^5$

sd triangle: $V^*_{ud}V_{us} + V^*_{cd}V_{cs} + V^*_{td}V_{ts} = \delta_{sd} = 0$

cu triangle: $V^*_{ud}V_{cd} + V^*_{us}V_{cs} + V^*_{ub}V_{cb} = \delta_{cu} = 0$

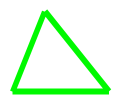
- $\lambda^2 + \lambda^2 + \lambda^4$



bs triangle: $V^*_{us}V_{ub} + V^*_{cs}V_{cb} + V^*_{ts}V_{tb} = \delta_{bs} = 0$

tc triangle: $V^*_{td}V_{cd} + V^*_{ts}V_{cs} + V^*_{tb}V_{cb} = \delta_{ts} = 0$

- $\lambda^3 + \lambda^3 + \lambda^3$



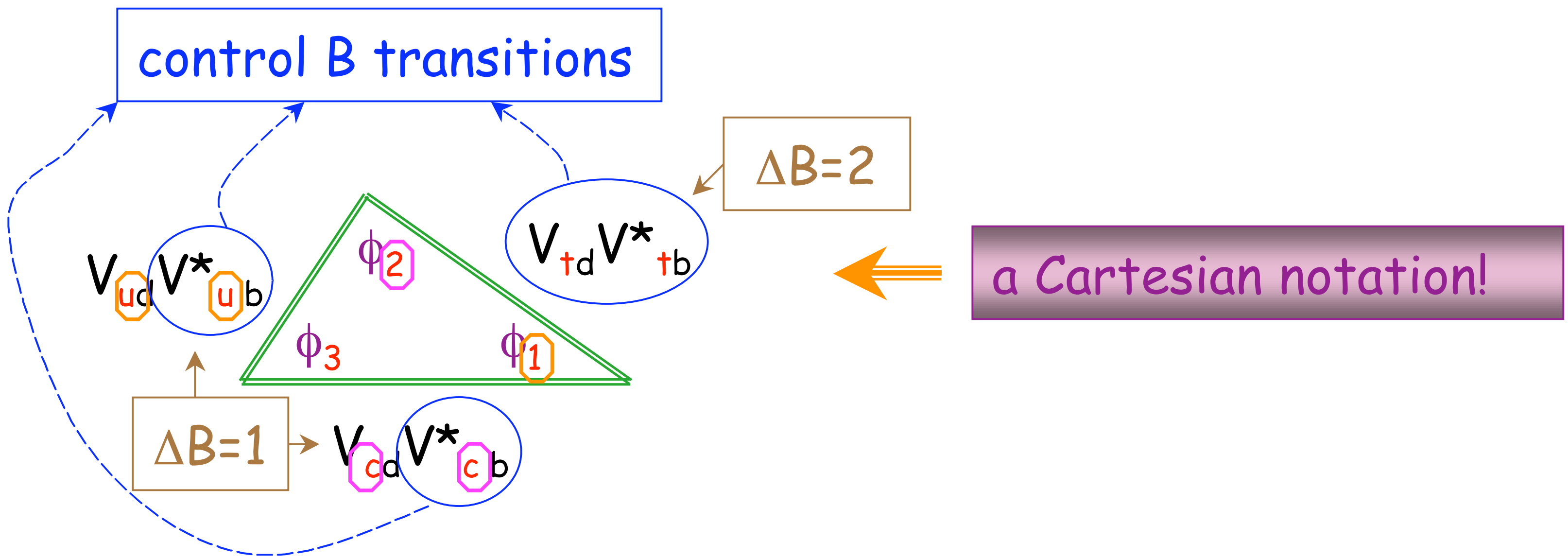
bd triangle: $V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = \delta_{bd} = 0$

tu triangle: $V^*_{ud}V_{td} + V^*_{us}V_{ts} + V^*_{ub}V_{tb} = \delta_{tu} = 0$

all six triangles have equal area!

last 2 triangles have all 3 sides of comparable length

➥ all their angles are naturally large



one more obstacle: due to CPT ~~CP~~ can enter only through complex phases

➥ to observe ~~CP~~ need 2 different, yet coherent amplitudes for a process

➥ best & most spectacular realization

B^0 - B^0 oscillations

- '86: discovery of B^0 oscillations: $x(B_d)=\Delta M(B_d)/\Gamma_B=0.75$
  - ➥ indirect bound $m_t > 100$ GeV

    [similar, though less precise than later LEP I findings]

CKM ⟹ ~~CP~~ in B^0 deccays with natural unit 10 %, not 0.1 %

predicted before discovery of top quarks

$$\sin 2\phi_1 \propto \epsilon_K/\Delta M(B)\ [=f(m_t)] \sim 0.6 - 0.7$$

- '94: top quarks discovered directly

data in '98

- all observed CP expressed by 1 number $|\eta_{+-}|$ ⟹ $\Phi(\Delta S=2)=\arg(M_{12}/\Gamma_{12})$
- intriguing, though not conclusive evidence for direct CP

  $\epsilon'/\epsilon = (2.30 \pm 0.65)\times 10^{-3}$ NA31 vs. $(0.74 \pm 0.59)\times 10^{-3}$ E731

  both launched by theory predictions and done in the '80's

3.3 The Completion of a Heroic Era

direct $\not{C}P$ established by '99

- WA '03: Re ϵ'/ϵ = $(1.66 \pm 0.16) \times 10^{-3}$

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\overline{K^0} \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\overline{K^0} \to \pi^+\pi^-)} = (5.5 \pm 0.6) \times 10^{-6}$$

standard for CPT tests!

- a discovery of the first rank -- irrespective of theory
- experimental groups earned our admiration
- not inconsistent with SM/CKM
  - CKM is not a superweak theory
  - ϵ'/ϵ suppressed by $\Delta I = 1/2$ rule, superheavy top mass, being a loop effect

do not expect quick conclusive reply from theory

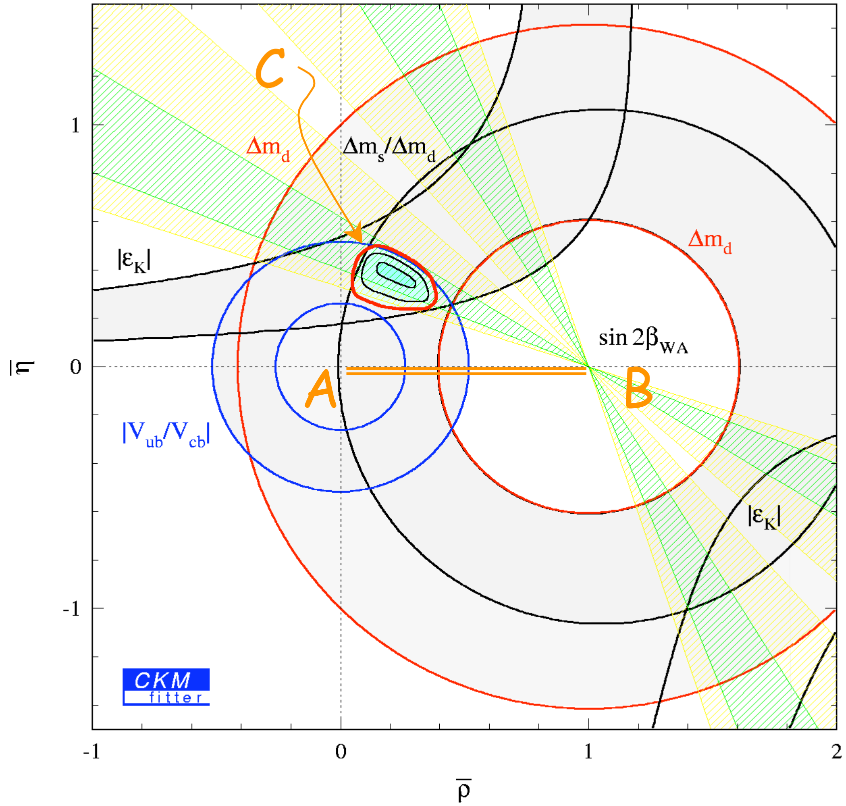
3.4 Status of CKM theory end of 2nd millenium

Yes, indeed …

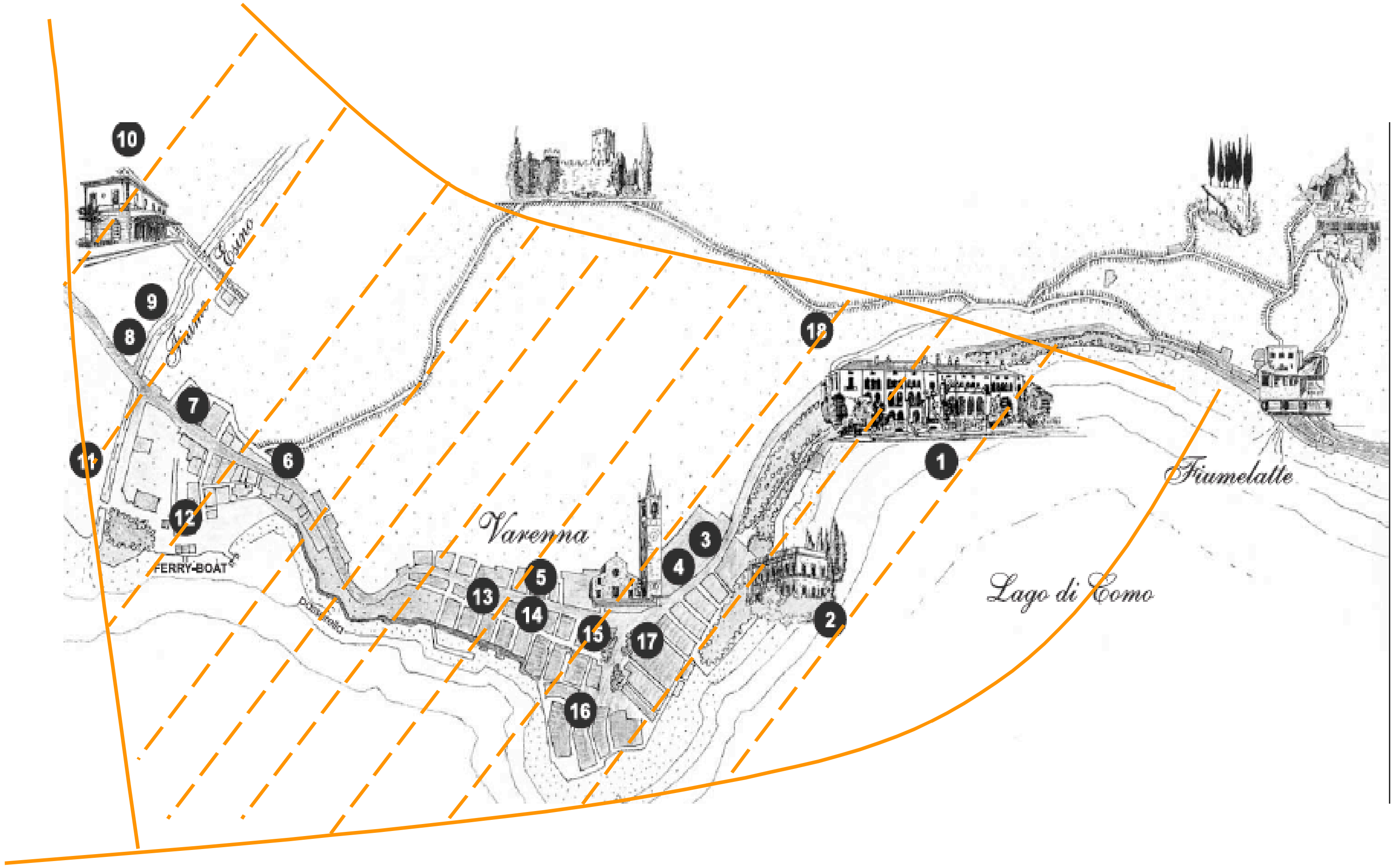
large fraction of Δm_K, ϵ_K, Δm_B } could be due
most of ϵ_K' } to New Physics

or equivalently

data constraints translate into `broad' bands
in unitarity triangle plots



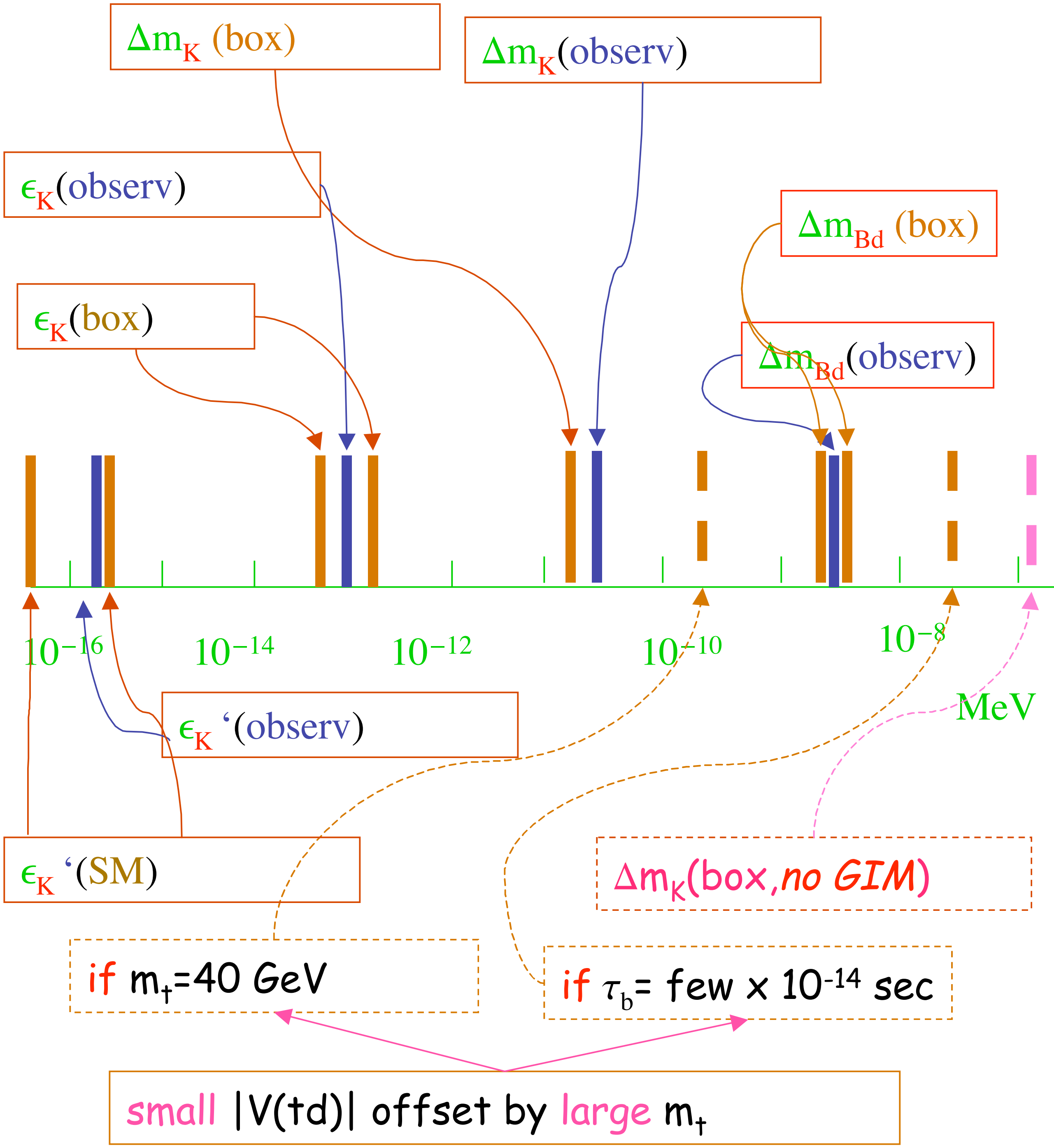
yet such a statement misses the real point!



broad bands, indeed, it seems …

… but look at the big picture!

… there must be a good reason!



can be reproduced with

|V(us)|~ 0.22,|V(ts)|~0.04

|V(td)|~ 0.004

m_u~5 MeV,m_c~1.2 GeV

m_t≈180 GeV,m_d ~10 MeV

m_s~0.15 GeV,m_b≈4.6 GeV

observables spanning several orders of magnitude accommodated with

parameter choices that a priori would seem frivolous!

There could easily have been inconsistencies!

Interlude: Singing the Praise of Hadronization

hadronization (& nonperturbative dynamics in general) usually viewed as unwelcome complication (if not outright nuisance);

case in point:

interpretation of

observed Δm_K, ϵ_K, Δm_B , ϵ_K'

contains sizeable uncertainties

correct --

yet such perspective again misses the deeper truth without hadronization no formation of bound states

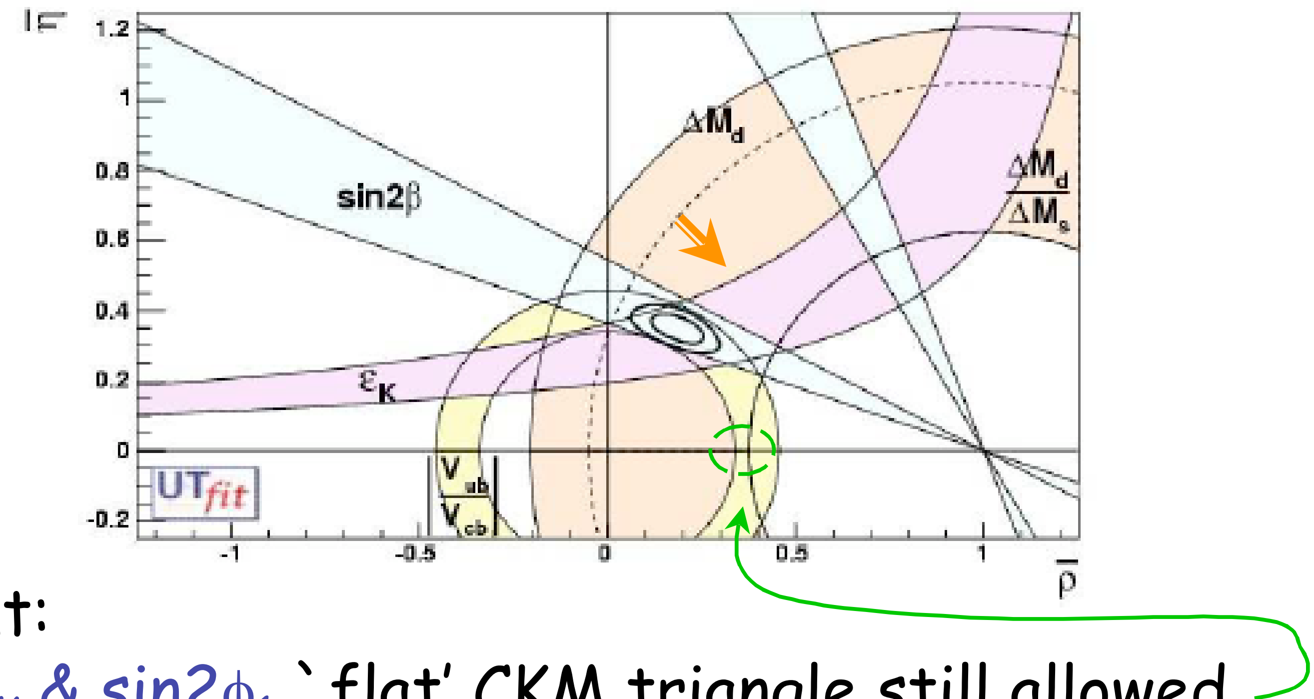
- ☞ no K^0-$\overline{K}^0$ oscillations
  - ➥ no indirect $\not{CP}$: Im $M_{12} \sim O(10^{-8}$ eV)!
  - ➥ no direct $\not{CP}$ a la ϵ'
- ☞ no B^0-$\overline{B}^0$ oscillations
  - ➥ no $\not{CP}$ in $\Delta B=2$: $\sim O(10^{-4}$ eV)
  - ➥ no New Physics in $\Delta B=2$

hadronization

- ☞ reduces CP √ $K_L \to 3\pi$ by ~ 500 due to hadronic PhSp
- ☞ awards `patience'; i.e. you can `wait' for pure K_L beam
- ☞ generates CP signal in existence rather than asymmetry

➻ hadronization -- the hero rather than the villain in the tale of $\not{CP}$!

another imminent CKM triumph (?)



at present:

without ε_K & sin2ϕ_1 \`flat' CKM triangle still allowed

[unless accept QCD Fact.'s verdict on BR($B \to K\pi$)]

if $\Delta M(B_s)$ measured \`soon':

|V(ub)/V(cb)| & $\Delta M(B_s)$ require non-trivial CKM triangle

\`CP insensitive observables imply ~~C~~P!'

- `arrival of the pure Penguins'

$B \to \gamma K^*$

$B \to \gamma X_s$

as 1-loop processes pure quantum effect in SM

☞ already by '98 CKM dynamics provided a surprisingly successful description of highly diverse phenomena

CKM fits yielded: $\sin 2\phi_1$ [β] = 0.72 ± 0.07

➼ cannot count on New Physics inducing large deviation from the SM

➥ need for precision experimentally & theoretically!

3.5 CKM `Exotica, Outliers, Leftfielders'

Electric dipole moments

static quantities

energy shift $\Delta\mathcal{E}$ of system inside electric field $\boldsymbol{E}$:

$$\Delta\mathcal{E} = d_i E_i + d_{ij} E_i E_j + \ldots$$

linear in E $\quad \mathbf{d} \propto \mathbf{s} \Rightarrow \mathbf{d} \neq 0 \Leftrightarrow$ T violation !

$d_N < 0.63 \times 10^{-25}$ ecm vs. $d_N^{CKM} < 10^{-30}$ ecm

from ultracold neutrons

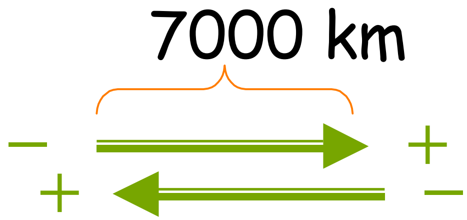
memento: Strong CP problem!

$d_e = (0.07 \pm 0.07) \times 10^{-26}$ ecm vs. $d_e^{CKM} < 10^{-32}$ ecm

from atomic EDM

✍ New Physics scenarios can yield ~ 10^{-26} - 10^{-28} ecm to visualize the sensitivity achieved

- $d_N = 6.3 \times 10^{-26}$ e cm $\Leftrightarrow$ radius $r_N \sim 10^{-13}$ cm



search for displacement of 10^{-12} $R_e \sim 7\,\mu$!

- $d_e = (-0.3 \pm 0.8) \times 10^{-26}$ e cm

$\Leftrightarrow \delta[(g-2)/2] \sim 10^{-11}$

$\Leftrightarrow \delta(F_2(0)/2m_e) \approx 2 \times 10^{-22}$ e cm !

$Pol_\perp(\mu)$ in $K_{\mu 3}$ decays

$K \to \mu^+ \nu \pi$

$Pol_\perp(\mu) = \langle \mathbf{s}_\mu \cdot (\mathbf{p}_\mu \times \mathbf{p}_\pi)/|\mathbf{p}_\mu \times \mathbf{p}_\pi| \rangle$ -- T odd moment

$K^+ \to \mu^+ \nu \pi^0$

$Pol_\perp(\mu) = (-1.7 \pm 2.3 \pm 1.1) \times 10^{-3}$ vs. $Pol_\perp^{SM}(\mu) < 10^{-6}$

➻ a clean search for CP via Higgs dyn.

$K_L \to \mu^+ \nu \pi^-$

$Pol_\perp^{SM}(\mu) \sim 10^{-3}$ ($\sim \alpha/\pi$) -- Coulomb FSI!

τ decays

most certainly not least!

see lecture VI

IV Summary of Lecture II

from a general perspective ...

take a model with a set of mass related basic quantities -- fermion masses, CKM parameters -- that any sober person would view as frivolous -- were they not forced upon us by data -- in particular since we have no deeper understanding of mass generation in particular for fermions --

you would have no reason to expect success in describing flavour dynamics proceeding on vastly different scales --

yet it does seem to work!

this model has to produce a host of large ~~CP~~ in B decays --

there is no plausible deniability

Some of us concluded that while the seemingly accidental structures in CKM theory strongly suggest a deeper level of dynamics underlying them, one cannot count on New Physics intervening in heavy flavour decays in a numerically massive and thus obvious way