Flavour Dynamics -- Central Mysteries of the Standard Model

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Notre Dame du Lac

3 mysteries

- ∃ family structure ! ?

  quarks ↔ leptons
- family replication ! ?

  why 3 families? Is 3 fundamental?
- pattern of masses & mass related quantities ← CKM
  - appears highly nonaccidental
  - neutrinos massless?

2 strategies for obtaining answers

Strategy (A)

- have enough data!
- solve remaining fundamental challenge: bring gravity into quantum world!
  - ⇒ family structure as side effect

"Le Penseur"

Strategy (B)

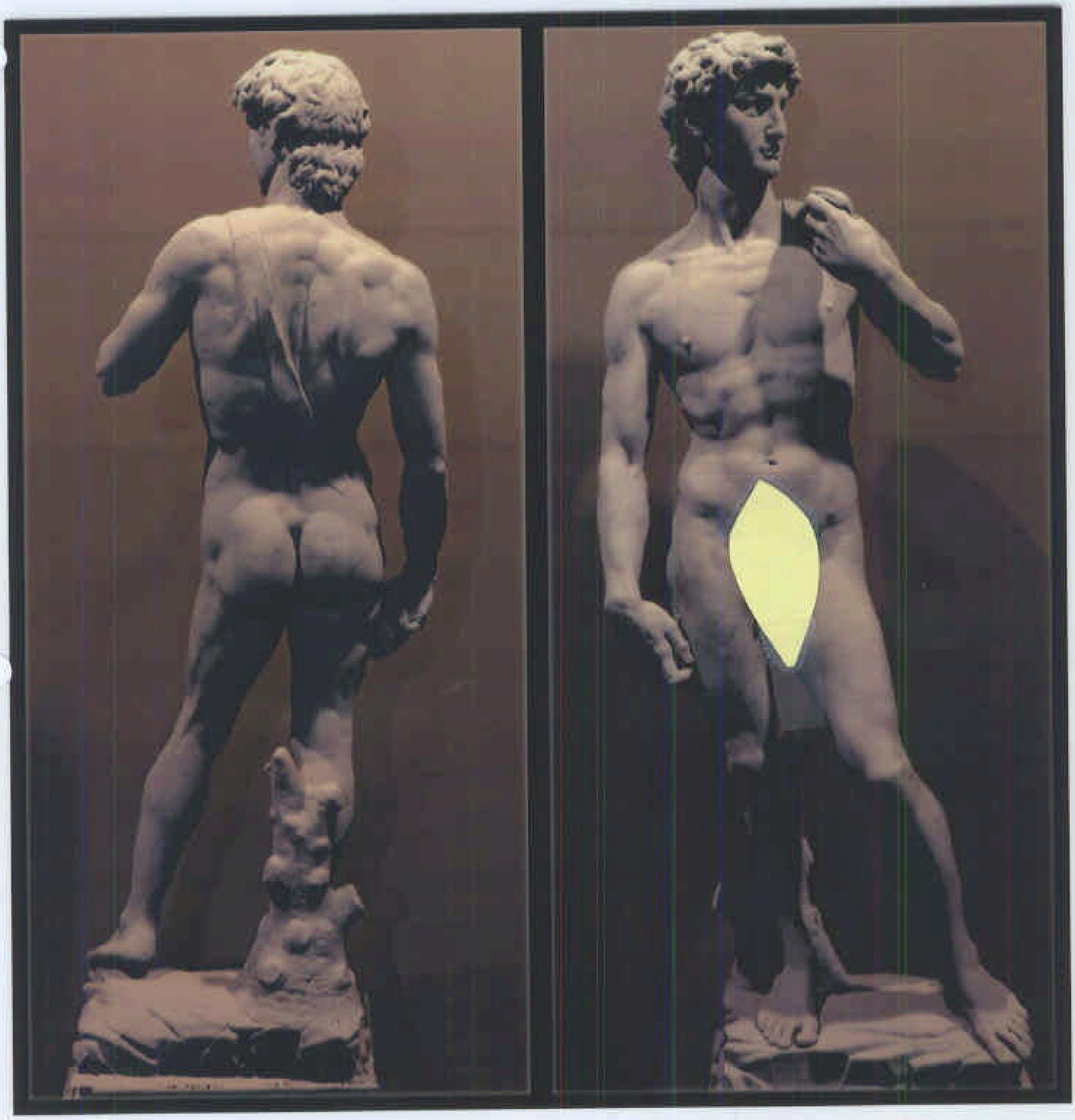
nature might have a few more surprises up her sleeves -- need more hints from nature!

"David"

this talk: Strategy (B)

20

http://www.musee-rodin.fr/images/imagre/5788.jpg



New Landmarks

- Direct $\cancel{CP}$ established in K decays!
- On the brink of observing $\cancel{CP}$ in B decays -- a first outside $\Delta S \neq 0$!
- Reaching fertile ground for finding New Physics in D^0 - D^0 and $\cancel{CP}$

on the theory side:

☹ learning lessons of humility

☺ increasing sophistication of theoretical technologies

☺ pushing back new frontiers

New Challenges (to Theory)

- regain theoretical control over ϵ'/ϵ!
- develop reliable quantitative predictions for CP asymmetries in B decays!
- refine those predictions into precise ones!
- establish theoretical control over D^0 - D^0 oscillations and CP violation!
- develop comprehensive strategies to distinguish between different New Physics scenarios!

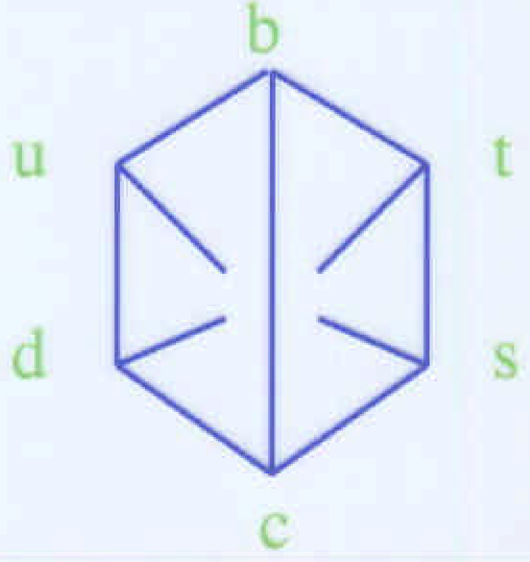
topics

- Charged Current Couplings of Quarks
    - the unreasonable success of CKM
    - extracting CKM parameters
- Nonleptonic Decays
    - H_b & H_c lifetimes as validation studies
    - exclusive NL decays $B \to M_1\, M_2$
    - quark-hadron duality
- CP Violation
    - ϵ'/ϵ
    - $\Delta B \neq 0$
- The Search for New Physics
- comments on theoretical uncertainties
    - future CKM trigonometry
    - "exotica": $K_{\mu 3}$, EDM's, $\Delta C \neq 0$
    - "Textures"

1:50,000 Scale Topographic Map/地形図

http://www.gsi-mc.go.jp/ENGLISH/MAPS/VARIETIES/FROM_THE_SKY/3d-e.html

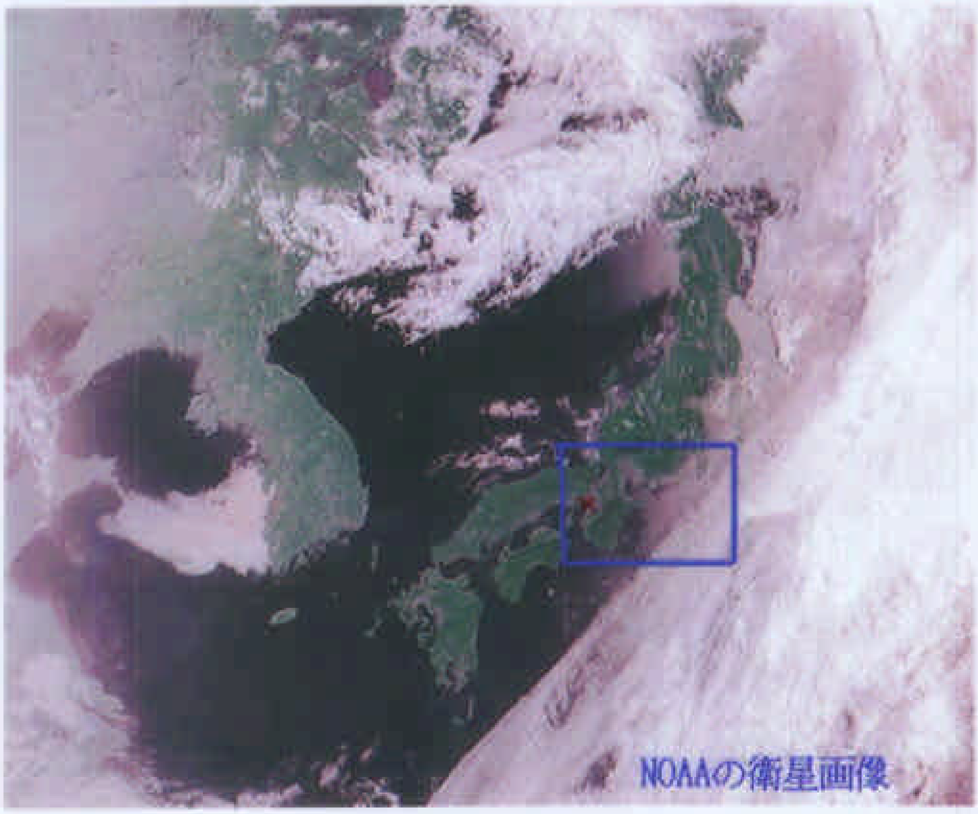
I. The Charged Current Couplings of Quarks



- $\tau(b) \sim 10^{-12}$ sec >> 10^{-14} sec
- $|b \Rightarrow c|^2 >> |b \Rightarrow u|^2$

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

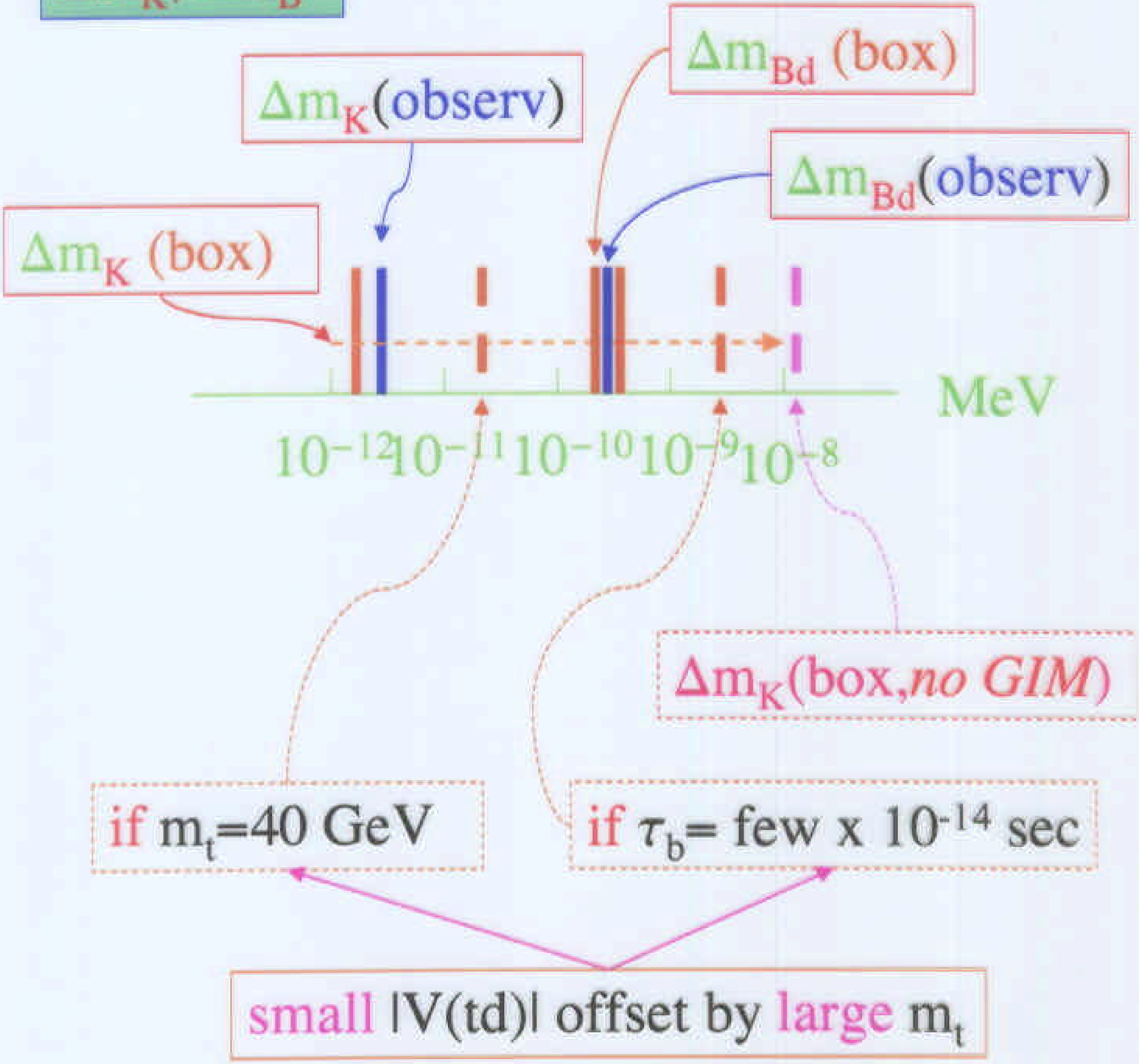
14 5.2



http://www.gsi-mc.go.jp/ENGLISH/MAPS/VARIETIES/FROM_THE_SKY/noaa.html

I.1 The unreasonable success of the CKM description

$\Delta m_K, \Delta m_B$



Δm_{Bd} (box)

Δm_K(observ)

Δm_{Bd}(observ)

Δm_K (box)

Δm_K(box, *no GIM*)

if m_t=40 GeV

if τ_b= few x 10^{-14} sec

small |V(td)| offset by large m_t

$\boxed{\epsilon_K}$

could always be "accommodated" --

whether

$|V(td)| \sim \lambda^2$, $|V(ts)| \sim \lambda$ and $m_t \sim 40$ GeV

or

$|V(td)| \sim \lambda^3$, $|V(ts)| \sim \lambda^2$ and $m_t \sim 180$ GeV

yet

$|V(td)| \sim \lambda^2$, $|V(ts)| \sim \lambda$ and $m_t \sim 180$ GeV

or

$|V(td)| \sim \lambda^3$, $|V(ts)| \sim \lambda^2$ and $m_t \sim 40$ GeV

would have been a clear inconsistency!

I.2 The (important) Details

PDG 2000:

- without imposing 3 family unitarity

$$\begin{pmatrix} |V(ud)| & |V(us)| & |V(ub)| & \\ 0.9735\pm0.0013 & 0.220\pm0.004 & 0.003\pm0.002 & \cdots \\ & & & \\ |V(cd)| & |V(cs)| & |V(cb)| & \\ 0.226\pm0.007 & 0.880\pm0.096 & 0.040\pm0.003 & \\ |V(td)| & |V(ts)| & |V(tb)| & \\ 0.05\pm0.04 & 0.28\pm0.27 & 0.5\pm0.49 & \\ & & & \\ \cdots & & & \cdots \end{pmatrix}$$

- with imposing 3 family unitarity

$$\begin{pmatrix} |V(ud)| & |V(us)| & |V(ub)| \\ 0.9750\pm0.0008 & 0.223\pm0.004 & 0.003\pm0.002 \\ |V(cd)| & |V(cs)| & |V(cb)| \\ 0.222\pm0.003 & 0.9742\pm0.0008 & 0.040\pm0.003 \\ |V(td)| & |V(ts)| & |V(tb)| \\ 0.009\pm0.005 & 0.039\pm0.004 & 0.9992\pm0.0002 \end{pmatrix}$$

I.2.a. Theoretical Technologies for QCD

s	$m_s < \Lambda$	chiral pert. th.
c	$m_c > \Lambda$	$1/m_c$ expans. (?)
b	$m_b >> \Lambda$	$1/m_b$ expans. !
t	$\Gamma_t \sim O(\Lambda)$	perturb. dynamics

lattice QCD

- ○ $1/m_Q$ expansions
- ○ lattice QCD (⇒ Kenway's lecture)
- ○ quark models (properly used)

→ ground prepared for fruitful feedback

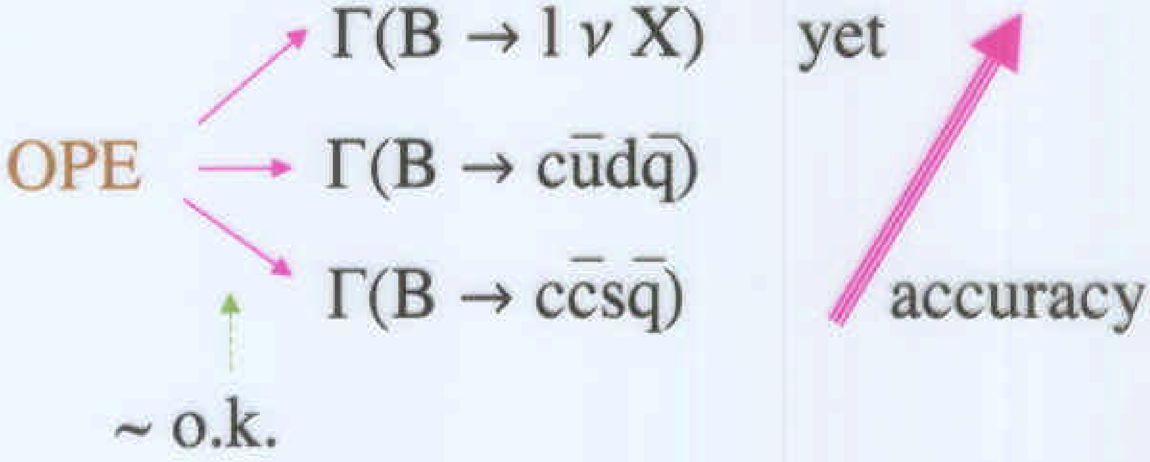
- ➡ both defined in Euclidean space
- ➡ both "mature"
- ➡ similar as well as different expansion parameters
- ➡ lattice QCD provides input to $1/m_Q$ expansion

I.2.b. Extracting CKM Parameters

main tool (so far): $1/m_Q$ expansions

- conceptual convergence

e.g.:



OPE

$\Gamma(B \to l\,\nu\,X)$ yet

$\Gamma(B \to c\bar{u}d\bar{q})$

$\Gamma(B \to c\bar{c}s\bar{q})$

accuracy

~ o.k.

- numerical convergence in basic quantities

(kinetic) $$m_b(1\,\text{GeV}) = \begin{cases} 4.56 \pm 0.06\ \text{GeV} & \text{MeYe} \\ 4.57 \pm 0.04\ \text{GeV} & \text{Ho} \\ 4.59 \pm 0.06\ \text{GeV} & \text{Be Si} \end{cases}$$

error estimates quite possibly overly optimisitc, but not foolish

Caveat:

all three analyses based on Y(4S) region;
i.e. not truly independent!

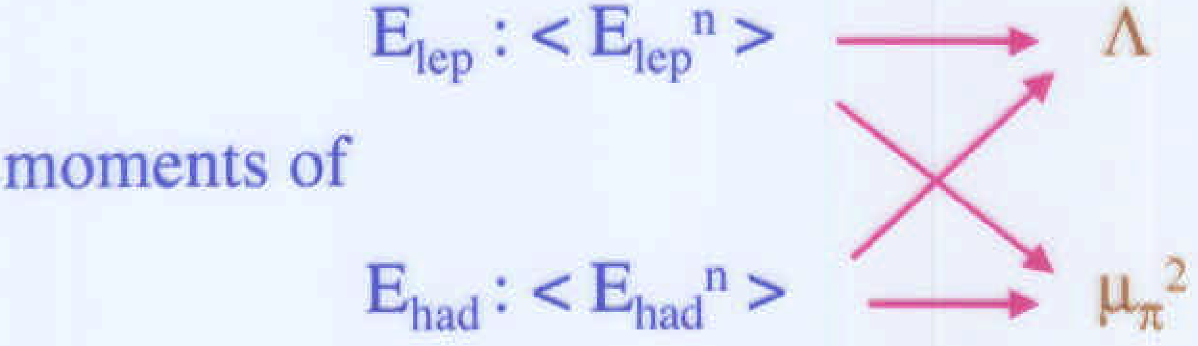
essential quality/selfconsistency check

shape of spectra in SL B decays

depend on m_b, $m_b - m_c$, μ_π^2 $[\lambda_1]$

- $\bar{\Lambda}(\mu) \equiv M(H_b) - m_b(\mu)$ as $m_b \to \infty$
- $\mu_\pi^2 \equiv \left\langle B \middle| \bar{b}(iD)^2 b \middle| B \right\rangle / 2M_B$

$B \to l\, \nu X$ Fa Lu Sa



moments of

$E_{lep} : < E_{lep}{}^n >$ → Λ

$E_{had} : < E_{had}{}^n >$ → μ_π^2

jury still out ...

V(cb)

2 methods with best theoretical justification

➲ *`exclusive'*

$B \Rightarrow l\,\nu\,D^*$ at zero recoil

→ $|V(cb)\,F_{D^*}(0)\,|$

→ $= 1 + O\,(1/m_c^2) + O\,(\alpha_s)$

→ the challenge!

$$F_{D^*}(0) = \begin{cases} 0.89 \pm 0.08 & \text{Uraltsev et al.} \\ 0.913 \pm 0.042 & \text{BaBar Book} \\ 0.935 \pm 0.03 & \text{prelim. lattice:} \end{cases}$$

$(0.935 \pm 0.022 {}^{+0.008}_{-0.011} \pm 0.008 \pm 0.020)$

AK et al.

[illegible]

will use: $F_{D^*}(0) = 0.90 \pm 0.05$

data:

- CLEO for ICHEP2000

$|V(cb)\, F_{D*}(0)| = (42.4 \pm 1.8|_{stat} \pm 1.9|_{syst}) \times 10^{-3}$

$|V(cb)| = (47.1 \pm 2.0\, |_{stat} \pm 2.1|_{syst} \pm 2.1|_{th}) \times 10^{-3}$

- LEP for ICHEP2000:

$|V(cb)\, F_{D*}(0)| = (34.9 \pm 0.7|_{stat} \pm 1.6|_{syst}) \times 10^{-3}$

$|V(cb)| = (38.8 \pm 0.8\, |_{stat} \pm 1.8|_{syst} \pm 1.7|_{th}) \times 10^{-3}$

- $\Delta |V(cb)\, F_{D*}(0)| = 7.5 \times 10^{-3}$
- keeps me sitting on the fence

  concerning the observation of B_s oscill.

Future:
very hard to reduce theoretical uncertainty!

- `inclusive' -- total SL B width

$\Gamma_{SL}(B) \propto m_b^5 (1+O(1/m_b^2) + O(\alpha_S))$

→ the challenge!

[actually $\Gamma_{SL}(B) \propto (m_b - m_c)^3 m_b^2$]

lots of new CLEO data on tape -- but not analyzed!

new LEP data:

$$V(cb)|_{incl} = (40.76 \pm 0.41|_{exp} \pm 2.0|_{th}) \times 10^{-3}$$

$$|V(cb)| = 0.0411 \sqrt{\frac{1.55}{0.105}\Gamma(b \to l \nu X_c)} \times$$

$$\times \left(1 - 0.024\left(\frac{\mu_\pi^2 - 0.5}{0.2}\right)\right) \times$$

Bi Sh Ur Va

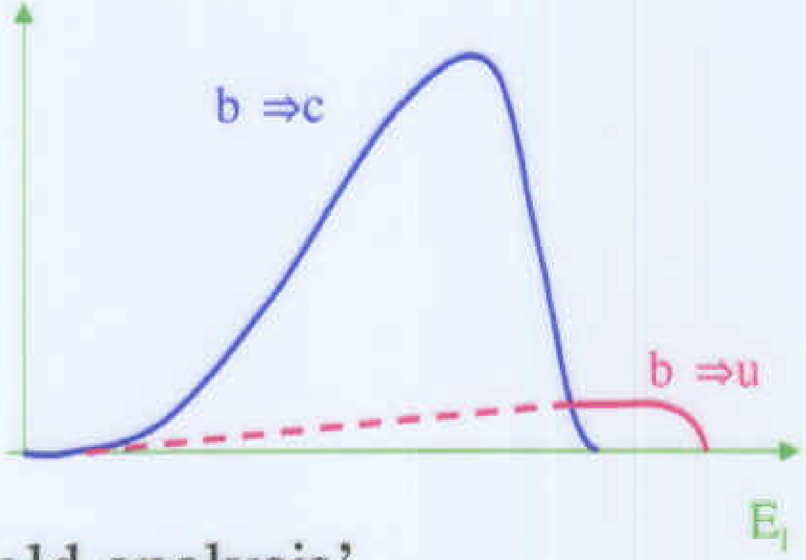
$$\left(1 \pm 0.030|_{pert} \pm 0.020|_{m_b} \pm 0.024|_{1/m_b^3}\right)$$

Future: not unrealistic to reduce theoretical uncertainty down to ~2%!

V(ub)

1. first methods

   - energy endpoint spectrum
     (i.e., kinematical discrimination)



`old analysis'

$V(ub)|_{endp} = (3.2 \pm 0.8) \times 10^{-3}$

- strong model dependance *so far*
- yet can be reduced considerably!
- endpoint different for B_d and B^+!

- exclusive semileptonic modes

$$B \Rightarrow l \nu \pi, l \nu \rho$$

$V(ub)|_{excl}=$

$(3.25 \pm 0.14|_{stat} \pm 0.27|_{syst} \pm 0.55|_{th}) \times 10^{-3}$

- strong model dependance *so far*
- input from QCD sum rules
- waiting for lattice QCD

❷ new method on the scene:

determine $\Gamma_{SL}(B \to l\nu X_u)$

$$V(ub)|_{\Gamma_{SL}} = (4.04 \pm 0.44|_{stat} \pm 0.46|_{b\to c,syst} \pm$$

$$\pm 0.25|_{b\to u,syst} \pm 0.02|_{\tau_b} \pm 0.19|_{HQE}) \times 10^{-3}$$

➲ good theoretical control BiShUrVa

➲ experimentally very challenging

❸ future method

measure the hadronic recoil mass spectrum

$$\frac{\mathrm{d}}{\mathrm{d}\,M_X}\Gamma(B \to l\nu X)$$

Ba Ph Ki

QCD compatible descript:

DiUr,BiUrDi,FaLiWi

mild dependance on cut-off $M_{X,max}$ for

$M_{X,max} \sim 1.6$ GeV

- theoretical refinements under construction to improve experimental feasibility Ba Li Lu
- large statistics required
- 10% uncertainty not unrealistic

resume on V(ub)

- considerable improvements in the near future quantitatively and qualitatively

more reliable error estimates

- an uncertainty not exceeding 10 % appears achievable through dedicated efforts

- one can entertain hopes (dreams?) beyond that in the long run

V(td)

- B_d vs. B_s oscillations

$x_d/x_s \approx \ |V(td)/V(ts)|^2 \times |Bf(B_d)/Bf(B_s)|^2$

- ☛ could be sensitive to New Physics!

- $K^+ \Rightarrow \pi^+ \nu \nu$

its width is dominated by virtual top quark contribution

$$\Gamma(K^+ \Rightarrow \pi^+ \nu \nu) \Rightarrow |V(td)V(ts)|^2$$

- exclusive radiative decays

$\Gamma(B \Rightarrow \rho\, \gamma)/\ \Gamma(B \Rightarrow K^* \gamma) \sim |V(td)/V(ts)|^2$

- ☛ could be sensitive to New Physics
- ☛ could be quite sensitive to long distance dynamics

II. Nonleptonic Heavy Flavour Decays

II.1 Quark-hadron duality

systematic theoretical uncertainties?

quark-hadron duality!

$$\langle d\sigma(\text{quark\&gluon d.o.f.})\rangle \underset{\text{duality}}{=} \langle d\sigma(\text{hadr.d.o.f})\rangle$$

general expectations:

- duality cannot be exact
- limitations to duality will depend on the process
- duality violations larger in NL than SL decays

beyond?

lots of folklore

→ fruitful concepts -- but no theory

3 phases of QCD

❶ perturb. effects

❷ nonpert. effects -- in heavy flavour decays

❸ limitations to duality a new frontier!

different realizations of duality

- global duality
- duality
- local duality

averaging/"smearing"

physical origins of limitations to duality

-- exact positions of hadronic thresholds implementation through `oscillating terms'

Euclidean $\exp\{-m_Q/\Lambda\}$

→ Minkowskian $\sin(m_Q/\Lambda)$

-- sensitivity to `distant cuts'

-- validity of $1/m_c$ expans. in $B \to l \nu D^*$

theoretical tools

- OPE insensitive to duality violations

  (yet indirect qualitative lessons)

- exactly solvable model field theories

  e.g., ‘t Hooft model

  QCD in 1+1 dimensions, $N_C \to \infty$

  Le Gr numerical analysis suggested significant or even large violations of duality

  Bi Sh Ur Va analytical analysis

  → truly tiny violations only!

  Le Ur duality obeyed even in spectra etc.

other tools? redundant determinations!

determine m_b, $m_b - m_c$, μ_π^2 in different ways

- extract V(cb), V(ub), V(td)/V(ts) from B_s decays `hic Rhodus, hic salta!'

  more telling than B_d vs. B_u

  V(cb)

  - $\Gamma_{SL}(B_s)$
  - lepton spectra/moments in B_s decays
  - $B_s \Rightarrow l \nu D_s^*$ at zero recoil

  V(ub)

  - hadronic recoil mass spectrum in

    $$B_s \Rightarrow l \nu X$$

  - exclusive semileptonic modes

    $$B_s \Rightarrow l \nu K, B_s \Rightarrow l \nu K^*$$

II.2 Weak lifetimes as validation studies

Charm

$\tau(D^+) > \tau(D^0) \sim \tau(D_s^+) \geq \tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^+)$

	1/mc expect.	comments	data
$\tau(D^+)/\tau(D^0)$	~ 2 + 10 - 20% from WA	PI in $\tau(D^+)$ consistent treatment of momenta in 'wavefunction'	2.55 ± 0.034 updated BELLE $2.51 \pm 0.06 \pm 0.04$
$\tau(D_s)/\tau(D^0)$	1.0 – 1.07 0.9 – 1.3 B&U 1.08 ± 0.04 Cheng & Yang	without WA with WA " " use QCD SR for ME	"old" 1.125 ± 0.042 "new WA" 1.180 ± 0.017 BELLE $1.15 \pm 0.04 \pm 0.02$
$\tau(\Lambda_c^+)/\tau(D^0)$	~ 0.5	Quark model matrix elem.	0.489 ± 0.008 updated
$\tau(\Xi_c^+)/\tau(\Lambda_c)$	~ 1.3	"	1.75 ± 0.36
$\tau(\Xi_c^+)/\tau(\Xi_c^0)$	~ 2.8	"	3.57 ± 0.91
$\tau(\Xi_c^+)/\tau(\Omega_c)$	~ 4	"	3.9 ± 1.7
$2y = \Delta\Gamma/\Gamma\|_{D^0}$	$\leq O(1\%)$	test bed for duality	$-12 < 2y < 0.6\%$

- observed pattern reproduced/predict. semiquantitatively!
- PI main effect for mesons
  - "old" data on $\tau(D_s)/\tau(D^0)$

    ⇨ WA *not* leading, possibly irrelevant
  - "new" data

    ⇨ WA -- while not leading --

    still significant in D decays!
- description for baryonic widths helped by generous errors

$$\delta\tau(\Xi_c)\backslash\tau(\Lambda_c) \sim 10 - 15\ \%$$

highly informative!

- semileptonic BR's for baryons do not reflect lifetime ratios!

$\Gamma_{SL}(D) \neq \Gamma_{SL}(\Lambda_c) \neq \Gamma_{SL}(\Xi_c) \neq \Gamma_{SL}(\Omega_c)$

constructive PI in SL Ξ_c and Ω_c decays —>

$BR_{SL}(\Xi_c^0) \sim BR_{SL}(\Lambda_c)$ vs. $\tau(\Xi_c^0) \sim 0.5\cdot\tau(\Lambda_c)$

$BR_{SL}(\Xi_c^+) \sim 2.5\cdot BR_{SL}(\Lambda_c)$ vs. $\tau(\Xi_c^+) \sim 1.3\cdot\tau(\Lambda_c)$

$BR_{SL}(\Omega_c) < 15\ \%$

beauty

	$1/m_b$ predict.	comment	data
$\tau(B^+)/\tau(B_d)$	$1 + 0.05(f_B/200\ \mathrm{MeV})^2$	PI in $\tau(B^+)$ factorization at low scale (1 GeV)	1.070 ± 0.020 updated ICHEP
$\tau(B_s)/\tau(B_d)$ $\Delta\Gamma(B_s)/\Gamma(B_s)$	$1 \pm O(0.01)$ $0.18(f_B/200\mathrm{MeV})^2$	Voloshin et al., Sov.J.Nucl. Phys. 46 (1987)112	0.945 ± 0.039 updated ICHEP < 0.31 (95 % C.L.)
$\tau(B_c)$	~ 0.5 psec	largest lifetime diff. !	0.46± 0.17 psec
$\tau(\Lambda_b)/\tau(B_d)$	0.9 – 1.0	quark model matrix elem.	0.79 ± 0.05

- Predictions for meson life times on the mark!
- recent lattice study (Di Piero & Sachrajda):

$$\frac{\tau(B^+)}{\tau(B_d)} = 1.03 \pm 0.02 \pm 0.03$$

- need more precise data on $\tau(B_s)$ (see later)
- $$\frac{\tau(B_c)}{\tau(B_d)} \sim \frac{1}{3}$$
  - largest lifetime difference by far!
  - absence of $1/m_Q$ contribution crucial!
- serious challenge from "short" baryon lifetime

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} \equiv 1 - \Delta$$

- $\Delta_{th} \simeq 0.03 - 0.12$ quark model Uraltsev

  $\Delta_{th} \approx 0.13 - 0.21$ QCD SR Huang et al.

  $\Delta_{exp} \simeq 0.21 \pm 0.05$
- pilot lattice study

  $$\Delta_{lattice} \simeq \left(0.07 - 0.09\right) \pm ?$$
- $\tau(\Xi_b^-)$ vs. $\tau(\Lambda_b)$ vs. $\tau(\Xi_b^0)$?
  - $\tau(\Xi_b^-) > \tau(\Lambda_b)$, $\tau(\Xi_b^0)$
  - $[\tau(\Xi_b^-) - \tau(\Lambda_b)]/\tau(\Lambda_b) \sim 14\ \%$ Volosh.,Gub.et al.

  from observed $\tau(\Xi_c^+) - \tau(\Lambda_c)$

Heresy

- $\Gamma(H_Q) \propto M^5(H_Q)$ rather than m^5_Q Al et al.
  - ⇨ $\tau(\Lambda_b)/\tau(B_d) \sim 0.75$
- anathema to the OPE!
  - represents large contribution of $O(1/m_Q)$
  - sum rules in OPE enforce Bi Sh Ur Va

quark phase space + nonperturb. corrections

=

hadronic phase space + boundstate corrections

⇨ would constitute rather massive violation of duality

- other predictions
  - $\tau(B_s)/\tau(B_d) \sim 0.94$!
  - $\tau(B_c)$??
  - $\frac{\tau(\Xi_b^0)}{\tau(\Lambda_b)} \simeq \frac{\tau(\Xi_b^-)}{\tau(\Lambda_b)} \simeq \left(\frac{M(\Xi_b)}{M(\Lambda_b)}\right)^5 \sim 0.86$!

II.3 Exclusive NL decays $B \to M_1\, M_2$

- guidance by symmetry considerations

  SU(2) [SU(3)]

- phenomenological models

  central *assumption* --

  concept of factorization

$$<M_1 M_2|JJ'|B> \approx <M_1|J|B> <M_2|J'|0>$$

- invoke $1/N_C$ counting rules to justify factorization;

  however

  - no realistic hope to evaluate nonleading terms (no FSI!)
  - $N_C = 3$

- yet models still very useful if used with awareness and common sense

  host of well-measured BR's: referee for the games Fl,Ho,HY C
- theoretical treatment -- new frontier!

  puts the bar higher for models
  - *conditio sine qua non*

    large energy release ⇒ hard process
  - `colour transparency' …

elements have been around -- but now are combined into comprehensive and detailed framework

2 groups

- Beneke Buchalla Neubert Sachrajda

  \`QCD factorization'
- Keum Li Sanda

  \`pQCD factorization'

ring of truth

factorization theorem:

  - non-universal
  - sometimes not the leading effect

apparent differences between 2 approaches

  - BBNS: FSI mostly small in B → $K\pi,\pi\pi$;

    WA suppressed
  - KLS: WA important, FSI not small

Beneke

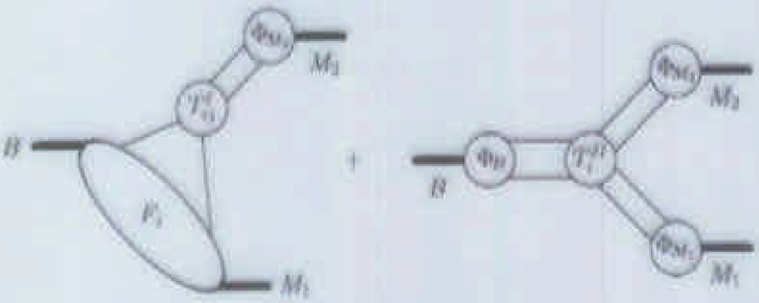
QCD factorization formula

Hard gluon effects ($k > m_b$) can be calculated and lead to the effective hamiltonian:

$$\mathcal{H}_{\mathrm{eff}} = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i^{\mathrm{CKM}} C_i(\mu) Q_i(\mu)$$

Principal idea: factorize systematically the remaining hard effects ($k \sim m_b$) from long-distance effects ($k \sim \Lambda_{\mathrm{QCD}}$) – heavy quark expansion. Result is:

$$\begin{aligned} \langle \pi K | Q_i | B \rangle \;&=\; f_+^{B\to\pi}(0)\, f_K\, T^{\mathrm{I}}_{K,i} * \Phi_K \\ &+ f_+^{B\to K}(0)\, f_\pi\, T^{\mathrm{I}}_{\pi,i} * \Phi_\pi + \underbrace{f_B f_K f_\pi\, T_i^{\mathrm{II}} * \Phi_B * \Phi_K * \Phi_\pi}_{\text{spectator interaction}} \end{aligned}$$



- long-distance: form factor, decay constant, light-cone distribution amplitudes
- short-distance: kernels $T^{I,II} = \alpha_s^0 + \alpha_s^1 + \ldots$, contain all "non-factorizable" corrections and strong phases.

Beneke

III: CP averaged branching fraction ratios

Despite significant corrections to naive factorization, the qualitative pattern that emerges for the set of $\pi\pi$ and πK decay modes is similar to that of naive factorization:

the penguin–tree interference is constructive (destructive) in $B \to \pi^+\pi^-$ ($B \to \pi^- K^+$) decays if $\gamma < 90°$.

Taking the currently favoured range $\gamma = (60 \pm 20)°$, we find [CLEO, hep-ex/0001010 in brackets]:

$$
\begin{aligned}
\frac{\mathrm{Br}(\pi^+\pi^-)}{\mathrm{Br}(\pi^\mp K^\pm)} &= 0.5\text{–}1.9 \quad [0.25 \pm 0.10] \\
\frac{\mathrm{Br}(\pi^\mp K^\pm)}{2\mathrm{Br}(\pi^0 K^0)} &= 0.9\text{–}1.4 \quad [0.59 \pm 0.27] \\
\frac{2\mathrm{Br}(\pi^0 K^\pm)}{\mathrm{Br}(\pi^\pm K^0)} &= 0.9\text{–}1.3 \quad [1.27 \pm 0.47] \\
\frac{\tau_{B^+}}{\tau_{B^0}}\,\frac{\mathrm{Br}(\pi^\mp K^\pm)}{\mathrm{Br}(\pi^\pm K^0)} &= 0.6\text{–}1.0 \quad [1.00 \pm 0.30]
\end{aligned}
$$

0.36±0.26 BE
0.94±0.29 BA

0.94±0.32 BE

2.26±1.42 BE

[R_*^{-1} – Neubert-Rosner]

1.44±0.42 BE

[R – Fleischer-Mannel]

The near equality of the second and the third ratios is a result of isospin symmetry.

We find (almost independently of γ):

$$\mathrm{Br}(B \to \pi^0 K^0) = (4.5 \pm 2.5) \times 10^{-6}\,(V_{cb}/0.039)^2 (f_+^{B\to\pi}(0)/0.3)^2$$

W.S. Hou et al. (99) factorization approach

$m_0 \sim 4.0$ GeV

FIGURES

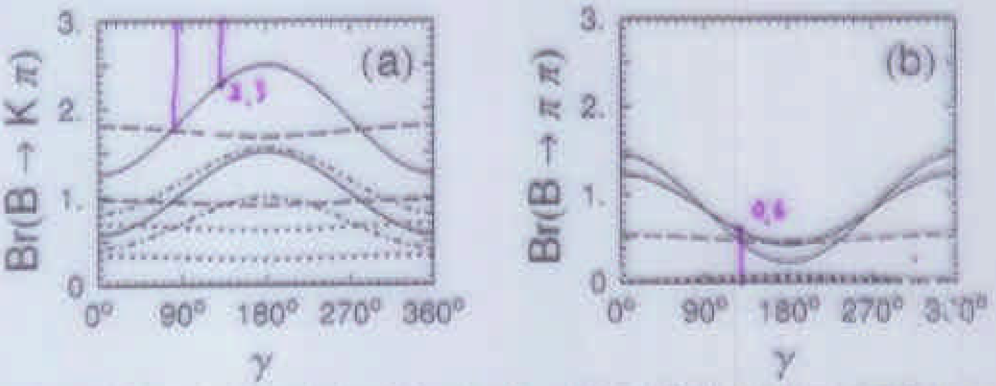


FIG. 1. (a) Solid, dash, dotdash and dots for $B \to K^+\pi^-$, $K^0\pi^+$, $K^+\pi^0$ and $K^0\pi^0$, for $m_s =$ 105 (upper curves) and 200 MeV. (b) Solid, dash and dots for $B \to \pi^+\pi^-$, $\pi^+\pi^0$ and $\pi^0\pi^0$ for $m_d = 2m_u = 3$ and 6.4 MeV, where the lower (upper) curve at $\gamma = 180°$ for $\pi^+\pi^-$ ($\pi^0\pi^0$) is for lower $m_{u,d}$. In all figures Brs are in units of 10^{-5}, and $|V_{ub}/V_{cb}| = 0.08$.

CLEO data (central values) PQCD ($\phi_3 \sim 90°$)

$B(B^\pm \to K^0\pi^\pm) \sim 18.2 \times 10^{-6}$ (20×10^{-6}) Keum, Li, Sanda

$B(B^0 \to K^\pm\pi^\mp) \sim 17.2 \times 10^{-6}$ (19×10^{-6})

$B(B^0 \to \pi^\pm\pi^\mp) \sim 4.3 \times 10^{-6}$ (4.6×10^{-6}) Lu, Ukai, Yang

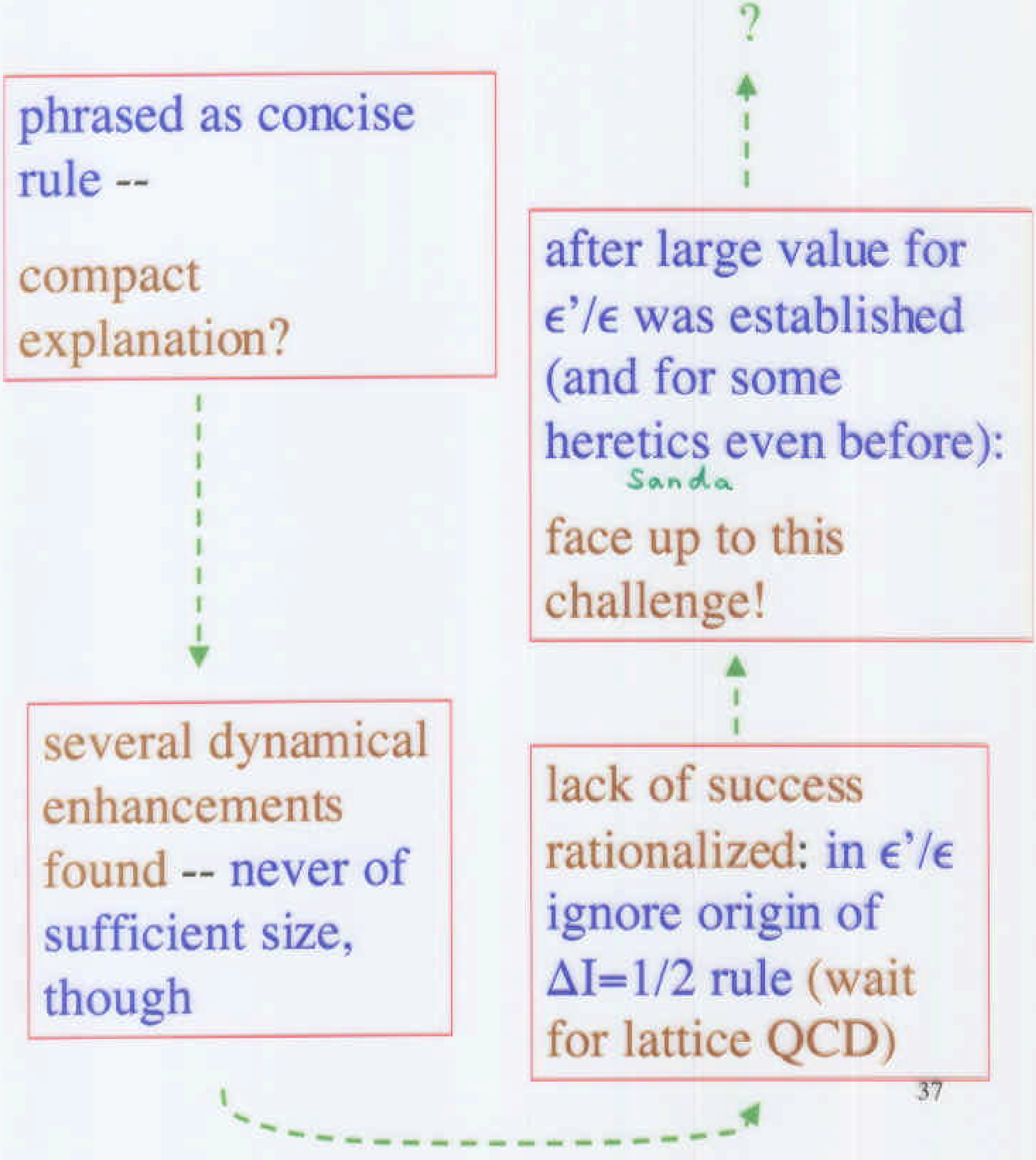
(6.3×10^{-6}, Belle) (9.3×10^{-6}, BaBar)

$$R = \frac{B(B^0 \to K^\pm\pi^\mp)}{B(B^\pm \to K^0\pi^\pm)} \sim 1 \Rightarrow \phi_3 \sim 90°$$

$$R_\pi = \frac{B(B^0 \to K^\pm\pi^\mp)}{B(B^0 \to \pi^\pm\pi^\mp)} \sim \underset{(3)}{4} \Rightarrow \phi_3 \sim 130°$$

The ΔI = 1/2 Saga

Pa,So,HY
Ch,Fa



phrased as concise rule --

compact explanation?

several dynamical enhancements found -- never of sufficient size, though

lack of success rationalized: in ϵ'/ϵ ignore origin of ΔI=1/2 rule (wait for lattice QCD)

after large value for ϵ'/ϵ was established (and for some heretics even before):
Sanda

face up to this challenge!

Pr,Pa,HY C,Fa,Go,Va

exact value of ϵ'/ϵ -- much harder question (and history does not represent one of the glory pages of theor. HEP)!

- $\mathcal{L}(\Delta S=1)$ under good theoretical control

Bu et al.

Fabb: `educated guess'

$$\epsilon'/\epsilon \sim 10^{-3}$$

- considerable uncertainties in the size of hadronic matrix elements
- magnified by the presence of several relevant operators.

III. Rare ΔS=1 & ΔB=1 Decays

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

BNL E787, Komat.

$BR(K^+ \to \pi^+ \nu \nu) = (1.5 + 3.4 - 1.2) \times 10^{-10}$

sensitivity will be 0.7×10^{-10}

E949 sensitivity expected $(8\text{-}14) \times 10^{-12}$

SM: $(0.82 \pm 0.32) \times 10^{-10}$

$B \to \gamma X, l^+ l^- X$

the first ~ correctly predicted Penguin!

$BR(H_b \to \gamma X_{\text{no charm}}) =$
$(3.15 \pm 0.35 \pm 0.32 \pm 0.26) \times 10^{-4}$ CLEO

$BR(H_b \to \gamma X_{\text{no charm}}) =$
$(3.34 \pm 0.5 \pm 0.35 \pm 0.28) \times 10^{-4}$ BELLE

35a

$BR(B \to \gamma X_s)|_{SM} = (3.29 \pm 0.33) \times 10^{-4}$ Misiak

- central value & uncertainty hardly changed

$\left.\begin{array}{l}\text{many new calculations}\\ \text{new contrib.} \sim \text{cancel}\end{array}\right\}$ impressive theor. machinery

- careful analysis of γ spectrum

- $BR(B \to \ell^+\ell^- X_s)_{\hat{s} \in [0.05, 0.25]} = (1.46 \pm 0.19) \times 10^{-6}$

- impact of New Physics different

  for $B \to \gamma X$ and $B \to \ell^+\ell^- X$

IV. CP Violation in $\Delta S \neq 0$ Decays

ϵ' / ϵ

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

$$\frac{\varepsilon'}{\varepsilon} = \frac{1}{\sqrt{2}} \left(\frac{\langle (\pi\pi)_{I=2} | H_W | K_L \rangle}{\langle (\pi\pi)_{I=0} | H_W | K_L \rangle} - \frac{\langle (\pi\pi)_{I=2} | H_W | K_S \rangle}{\langle (\pi\pi)_{I=0} | H_W | K_S \rangle} \right)$$

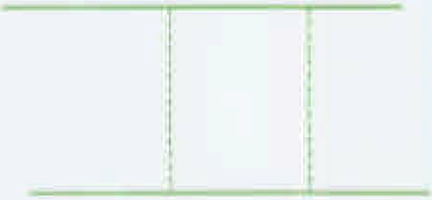
- ○ $\Delta I = 1/2$ rule
- ○ single KM phase
- ○ m_t large

$\}\ 0 \neq \epsilon'/\epsilon << 1/20$

ϵ'

$\propto$ log m_t

ϵ

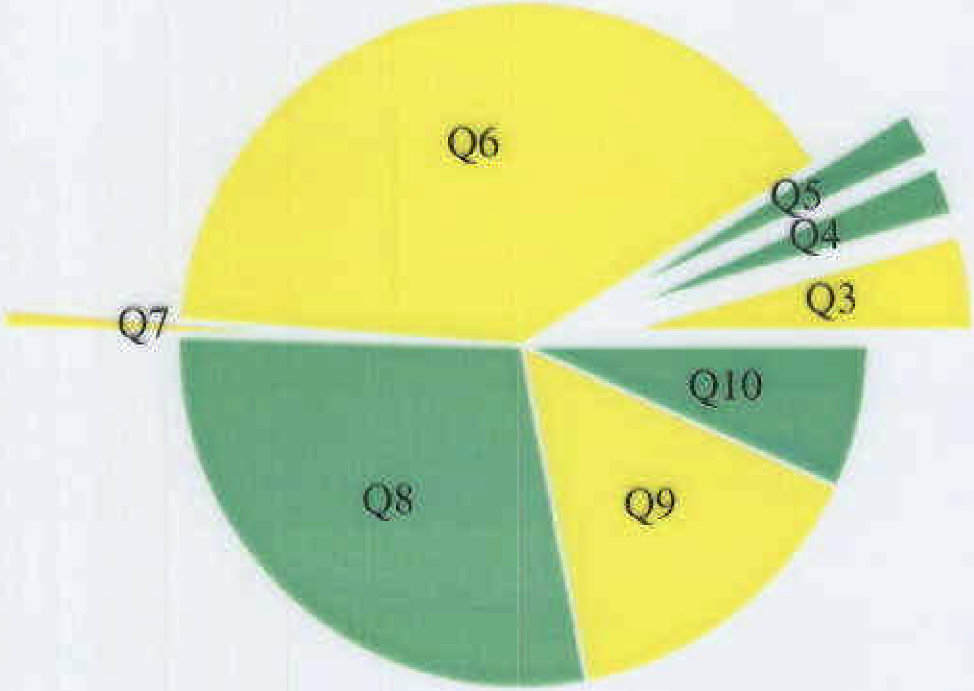


$\propto m_t^2$

Fabb.

THE ε'/ε PIE

Gluonic Penguins



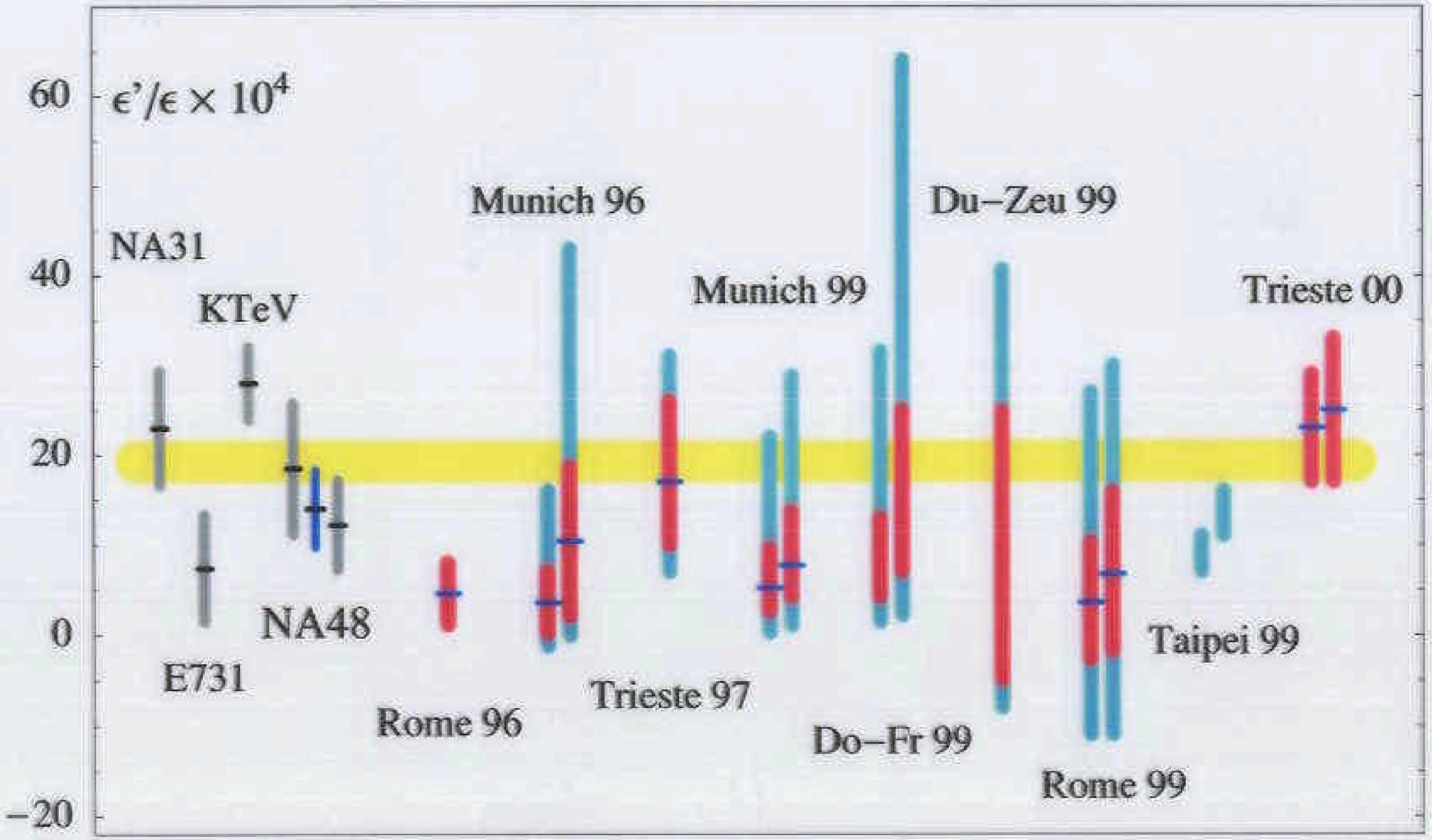
Electroweak Penguins and Box

Vacuum Saturation Approximation to the hadronic matrix elements of the effective four-quark operators.

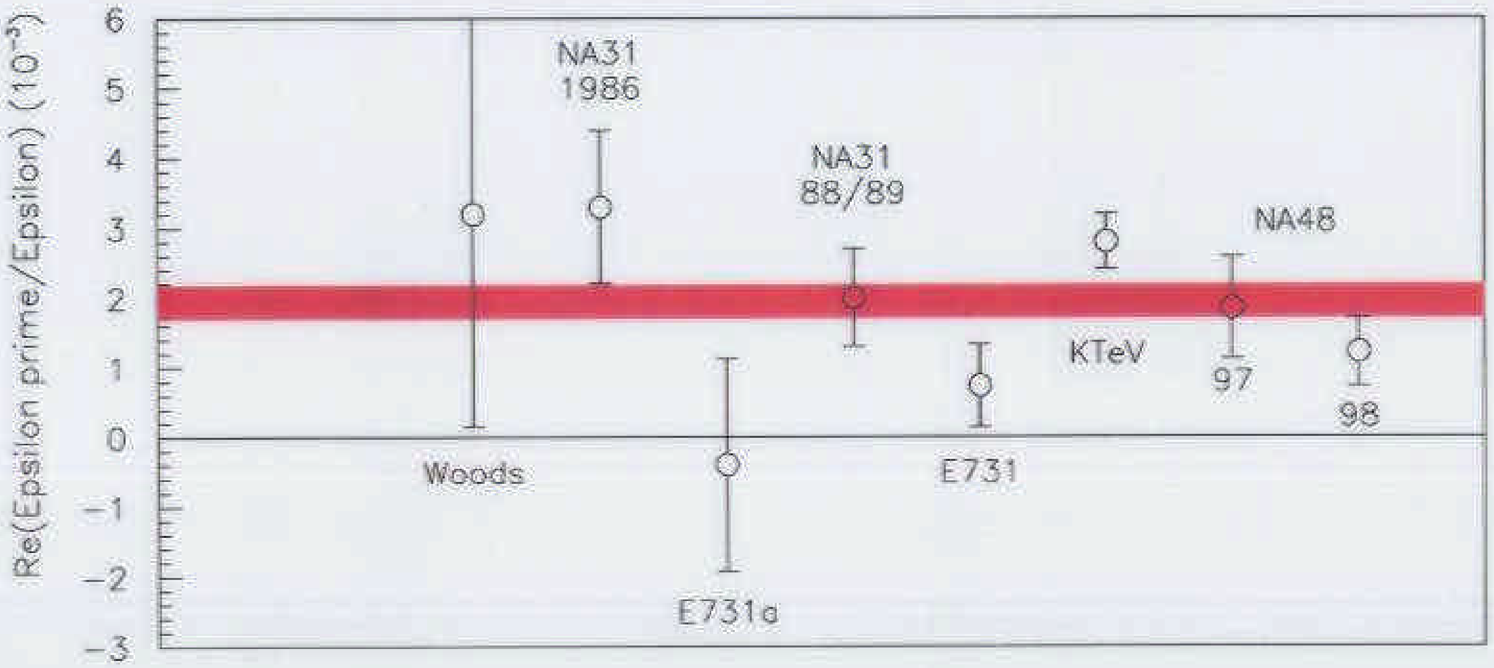
In Yellow (Green) the Positive (Negative) contributions.

Fabb.

Experiment vs. Theory



New world average



New world average:

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (19.3 \pm 2.4) \times 10^{-4}}$$

$(\chi^2/ndf = 11.1/5)$

Direct Evidence for T Violation

of course $\cancel{CP} \Rightarrow \cancel{T}$

CPT √

$K^0 \Rightarrow K^0$ vs. $K^0 \Rightarrow K^0$

The `Kabir Test'

associated production √

$$A_T = \frac{\Gamma(K^0 \rightarrow \overline{K^0}) - \Gamma(\overline{K^0} \rightarrow K^0)}{\Gamma(K^0 \rightarrow \overline{K^0}) + \Gamma(\overline{K^0} \rightarrow K^0)}$$

semilept. $K_{neut} \rightarrow l^{\pm} \nu \pi$, CPT √

CPLEAR:

$A_T = (6.6 \pm 1.3 \pm 1.0) \times 10^{-3} \neq 0$

vs. $(6.54 \pm 0.24) \times 10^{-3}$ √

$K_L \to \pi^+\pi^- e^+e^-$ and its T odd correlation

$\phi = \angle(\mathbf{n}_l, \mathbf{n}_\pi)$

$\mathbf{n}_l = \mathbf{p}(e^+) \times \mathbf{p}(e^-) / |\mathbf{p}(e^+) \times \mathbf{p}(e^-)|$

$\mathbf{n}_\pi = \mathbf{p}(\pi^+) \times \mathbf{p}(\pi^-) / |\mathbf{p}(\pi^+) \times \mathbf{p}(\pi^-)|$

$$d\Gamma/d\phi = \Gamma_1 \cos^2\phi + \Gamma_2 \sin^2\phi + \Gamma_3 \cos\phi \sin\phi$$

$$\Gamma_3 \cos\phi \sin\phi \xrightarrow{T,CP} -\cos\phi \sin\phi$$

$$A = \frac{2\Gamma_3}{\pi(\Gamma_1 + \Gamma_2)} = \begin{cases} (13.6 \pm 2.5 \pm 1.2)\%, & \text{KTeV} \\ (14.3 \pm 1.3)\%, & \text{Se Wa} \end{cases}$$

η_{+-} effect!

can be made consistent with T √ -- Bi Sa at the price of ~~CPT~~ ~ 10^{-3} in

$K^\pm \to \pi^\pm\pi^0$!

V. CP Violation in $\Delta B \neq 0$ Decays

wide-spread attitude:

- observing a CP asymmetry in

  $$B_d \rightarrow \psi K_S$$

  no big deal since expected -- unless its value falls clearly outside predicted range;

- observing a CP asymmetry in

  $$B_d \rightarrow \pi^+ \pi^-$$

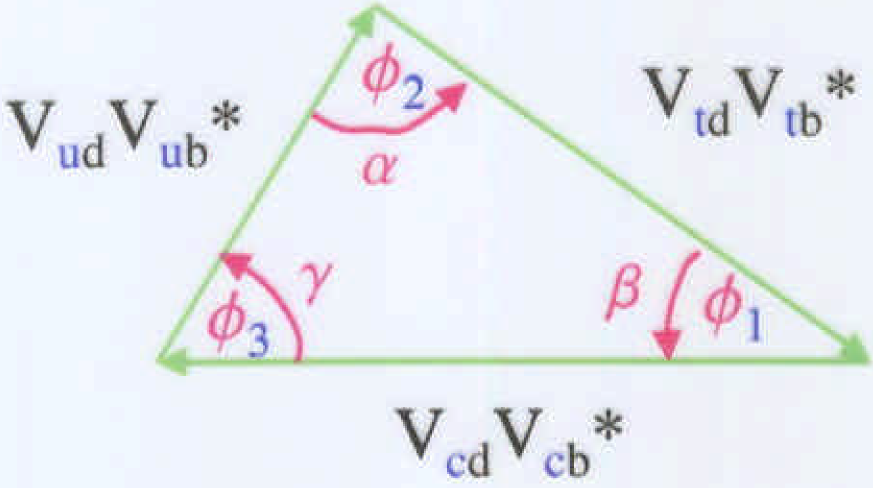
  no big deal either, since it cannot be interpreted cleanly in terms of CKM parameters and its value is hardly constrained.

such sentiments miss the paradigmatic character of such observations:

- an asymmetry in $B_d \rightarrow \psi K_S$
  - ⊃ would be the first CP violation directly observed outside K_L decays,
  - ⊃ would have to be big to be established in the near future and
  - ⊃ would establish the KM ansatz as a -- if not the -- major agent of CP violation!
- likewise an asymmetry in $B_d \rightarrow \pi^+ \pi^-$
  - ⊃ again would have to be big to be established in the near future and
  - ⊃ would probably reveal direct CP violation to be huge in beauty decays!

V.1 CKM Trigonometry, Part I

`the' KM unitarity triangle



ϕ_i opposite side with $V_{id}V_{ib}^*$

$$\phi_1 = \pi - \arg\left(\frac{-V_{tb}^* V_{td}}{-V_{cb}^* V_{cd}}\right)$$

$$\phi_2 = \arg\left(\frac{V_{tb}^* V_{td}}{-V_{ub}^* V_{ud}}\right)$$

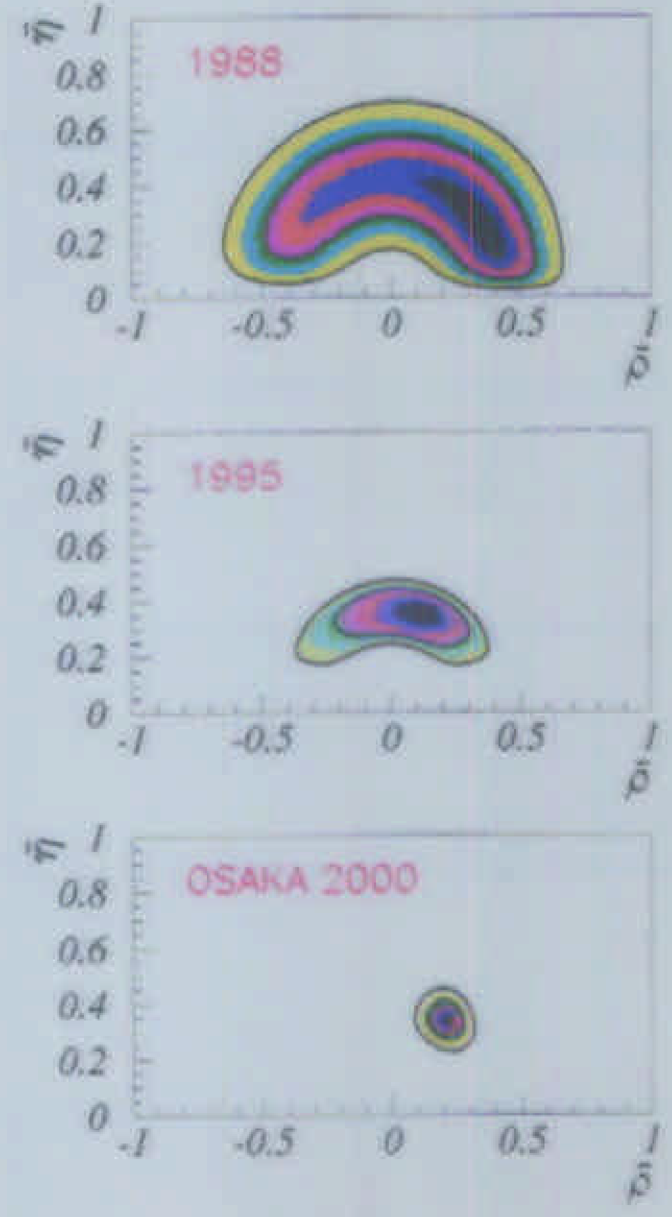
$$\phi_3 = \arg\left(\frac{V_{ub}^* V_{ud}}{-V_{cb}^* V_{cd}}\right)$$

2 classes of observables:

- CP insensitive rates ⇒ sides
  - $b \to l \nu u / b \to l \nu c$ ⇒ $|V_{ub}/V_{cb}|$
  - $\Delta m(B_d)/\Delta m(B_s)$ ⇒ $|V_{td}/V_{ts}|$
  - $K^+ \to \pi^+ \nu \nu$ ⇒ $|V_{td}/V_{ts}|$
- CP asymmetries ⇒ angles
  - $\epsilon_K/\Delta m(B_d)$ ⇒ $\sim \phi_1$

  - $B \to \psi K_S$ ⇒ ϕ_1

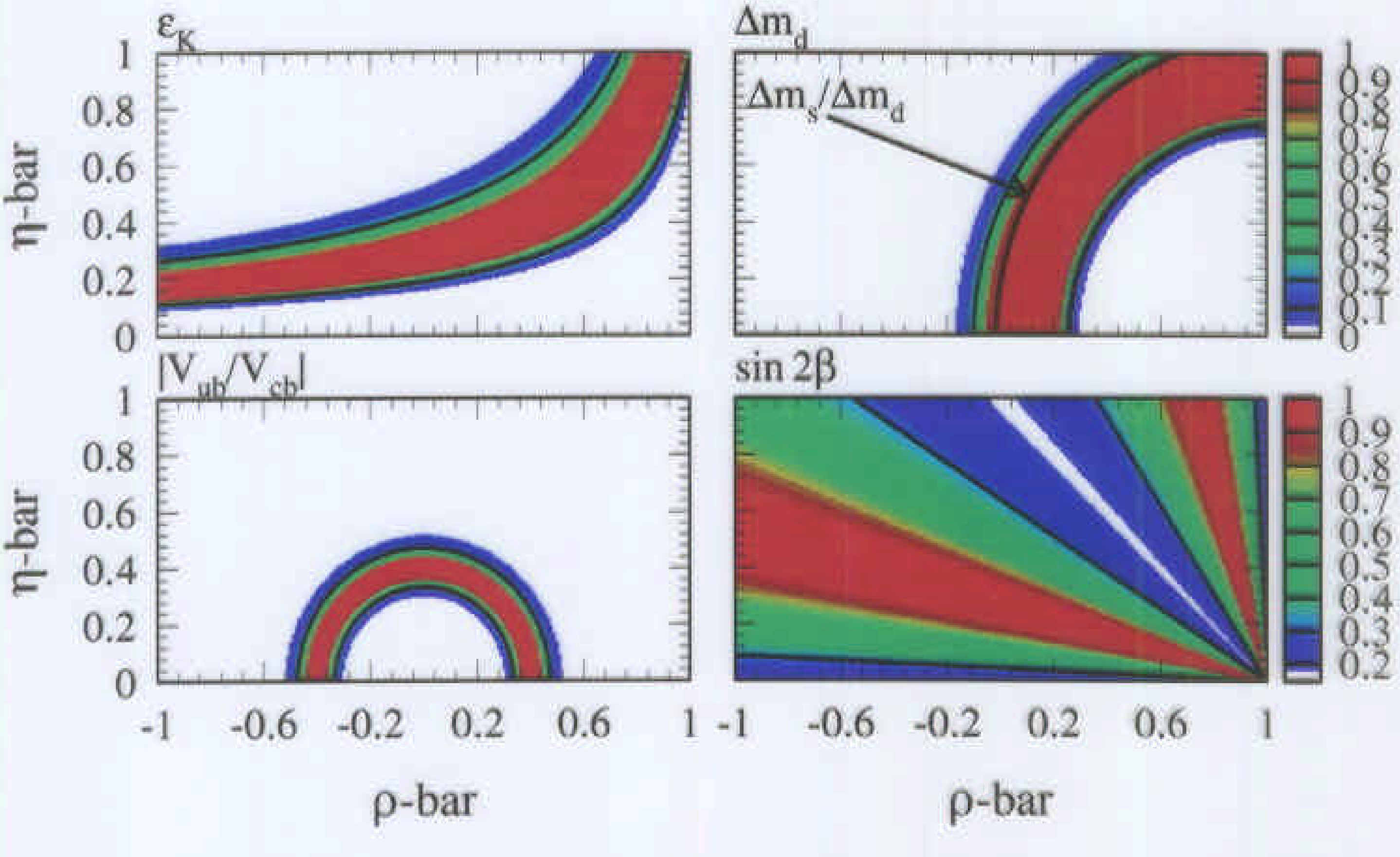
plots


1988
1995
OSAKA 2000
$\bar{\eta}$
1
0.8
0.6
0.4
0.2
0
-1
-0.5
0
0.5
1
$\bar{\rho}$

[illegible]

CKM-FITTER:

CONSTRAINTS IN THE $\rho - \eta$ PLANE



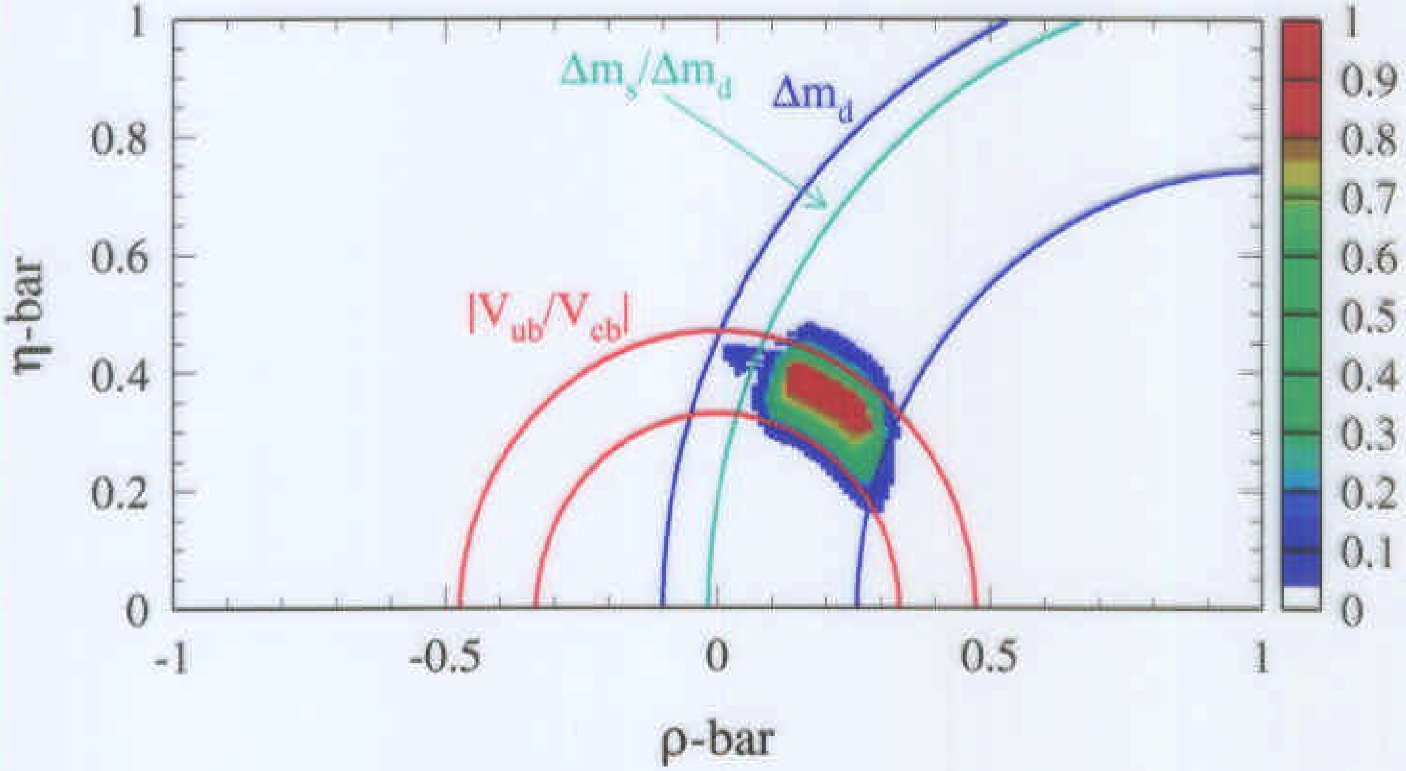
Andreas Höcker, Heiko Lacker, Sandrine Laplace and Fran cois Le Diberder

CKM-FITTER:

CONSTRAINTS IN THE $\rho - \eta$ PLANE

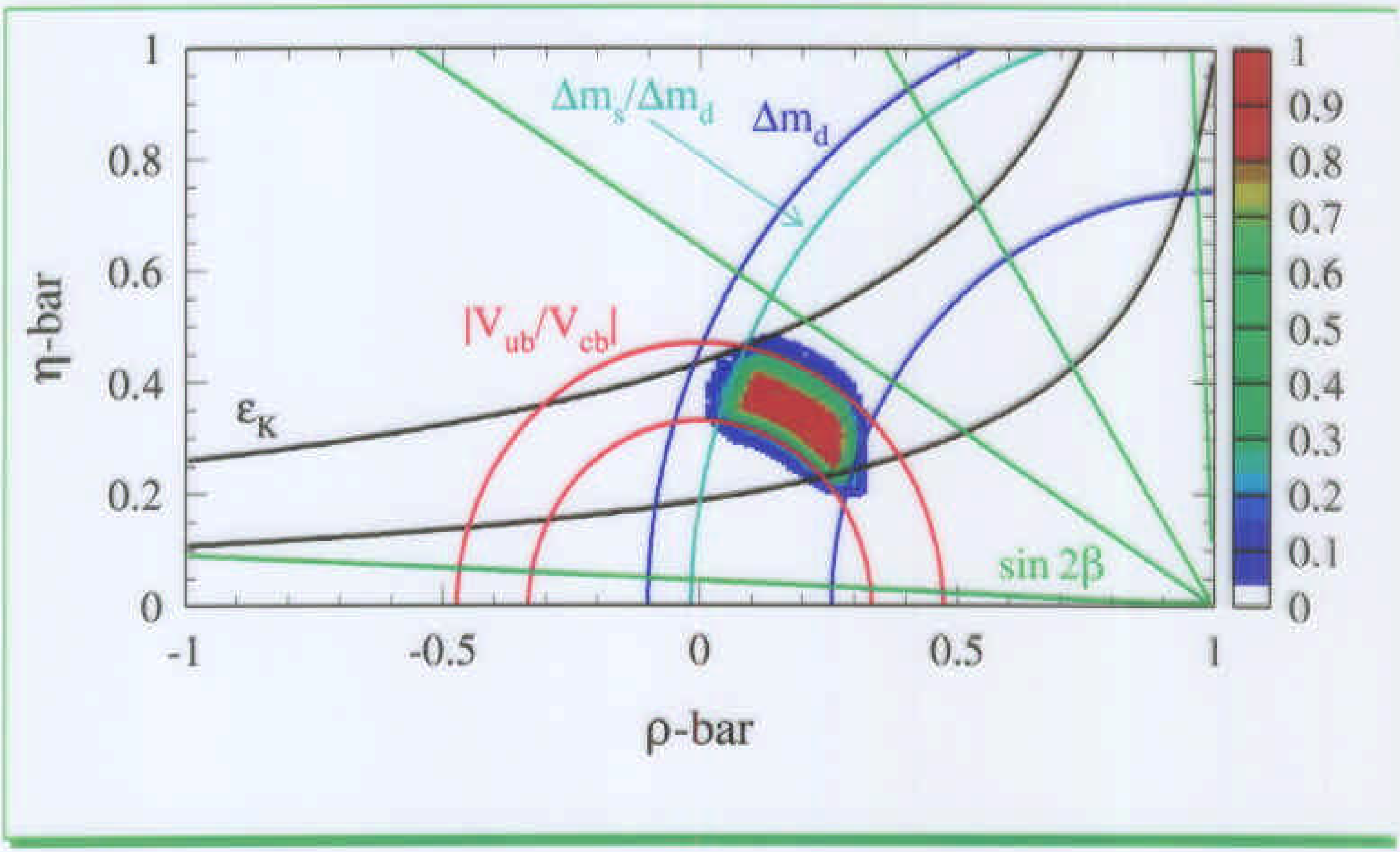
Indirect Evidence for CP-violation:

- Constraints without ϵ_K and $\sin 2\beta$



CKM-FITTER:

CONSTRAINTS IN THE $\rho - \eta$ PLANE



with caveats to be discussed below

present analyses (e.g. Stoc, DiLe) suggest:

$\sin 2\phi_1 = 0.716 \pm 0.070 \leftrightarrow 0.7 \pm 0.2$

$\sin 2\phi_2 = -0.26 \pm 0.28 \leftrightarrow -0.25 \pm 0.7$

$\phi_3 = 59.3^{\circ} \pm 7.3^{\circ}$

$B \to \psi K_S$

- CDF: $\sin 2\phi_1 = 0.79 \pm 0.44$
- BELLE: $\sin 2\phi_1 = 0.45 \begin{cases} +0.43 & +0.07 \\ -0.44 & -0.09 \end{cases}$
- BaBar: $\sin 2\phi_1 = 0.12 \pm 0.37 \pm 0.09$

what if `Michelson-Morley outcome'

$\sin 2\phi_1 \leq 0.1$!?

➡ CKM ruled out as major player in

$K_L \to \pi\pi$

no plausible deniability!

➡ new puzzle: why is CKM phase so small?

VI. Probing for New Physics

- historic precedent $\Delta S \neq 1,2$

⇒ instrumental for emergence of SM

through `qualitative' discrepencies

- can happen again
  - $\Delta C \neq 0$
  - EDM's
  - $K_{\mu 3}$ …
- different situation in $\Delta B \neq 1,2$

more complex

more opportunities

more challenges

quantitative discrepencies

control over uncertainties!

VI.1 KM Trigonometry, Part II

3x3 unitary matrix ⇒ 6 triangles with same area!

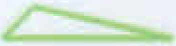
① *bd* triangle

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

② *tu* triangle

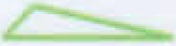
$$V^*_{ud}V_{td} + V^*_{us}V_{ts} + V^*_{ub}V_{tb} = \delta_{tu} = 0$$

③ *bs* triangle



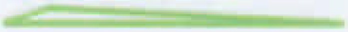
$$V^*_{us}V_{ub} + V^*_{cs}V_{cb} + V^*_{ts}V_{tb} = \delta_{bs} = 0$$

④ *tc* triangle



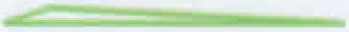
$$V^*_{td}V_{cd} + V^*_{ts}V_{cs} + V^*_{tb}V_{cb} = \delta_{tc} = 0$$

⑤ *sd* triangle



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

⑥ *cu* triangle



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

there are three classes of angles:

❶ angles of order unity like ϕ_1, ϕ_2 and ϕ_3;
they differ from each other in $O(\lambda^2)$.

❷ angles that are themselves $\sim O(\lambda^2)$;
the most accessible representative is an angle in the *bs* triangle, often referred to as χ:

$$\chi = \phi_1{}^{bs} = \pi + \arg\left(\frac{V^*_{cs}V_{cb}}{V^*_{ts}V_{tb}}\right) \approx \lambda^2 \eta$$

it controls the CP asymmetry in

$$B_s \to \psi\,\eta,\ \psi\,\phi$$

B S '80

❸ angles that are themselves $\sim O(\lambda^4)$;
the least un accessible representative is an angle in the *cu* triangle, often referred to as χ':

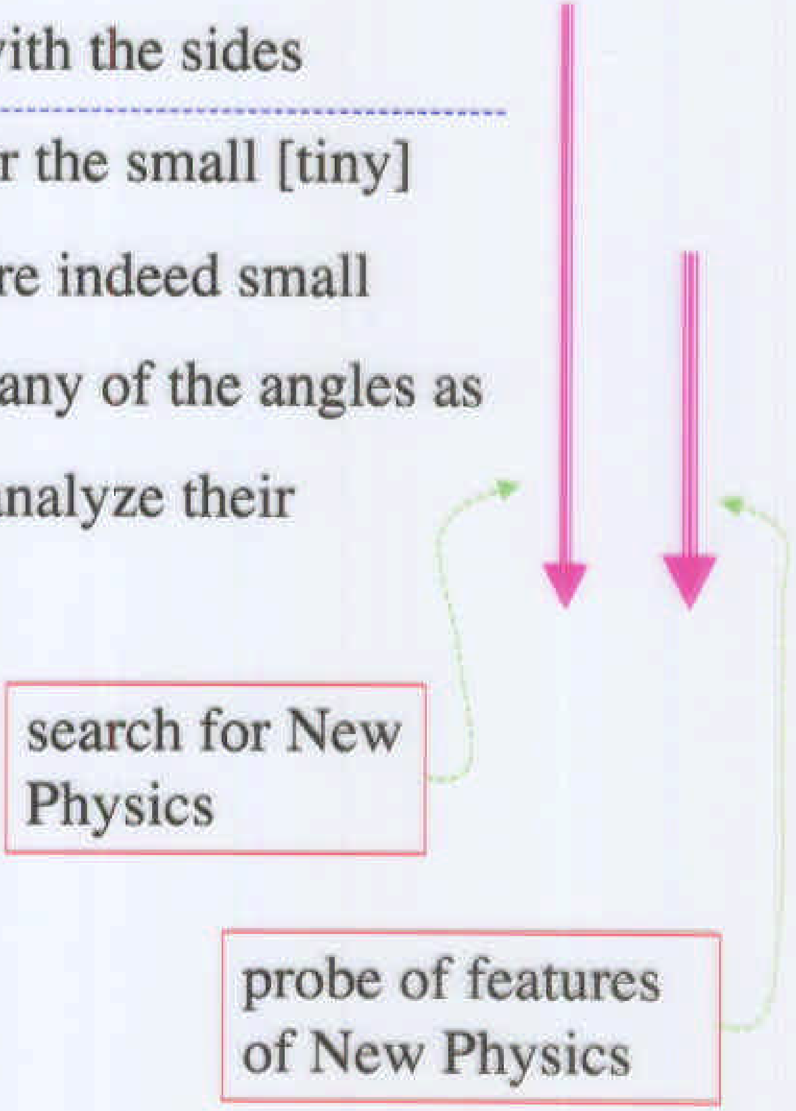
$$\chi' = \phi_3{}^{cu} = \arg\left(\frac{-V^*_{ud}V_{cd}}{V^*_{us}V_{cs}}\right) \approx -\lambda^4 A^2 \eta$$

B '89

it controls CP asymmetries in D decays

⇒ 3 step strategy:

- measure the large angles ϕ_1, ϕ_2, ϕ_3 and their `cousins' and check their correlations with the sides
- check whether the small [tiny] angle χ [χ'] are indeed small
- measure as many of the angles as possible and analyze their correlations.



search for New Physics

probe of features of New Physics

Peskin, LP '99

32

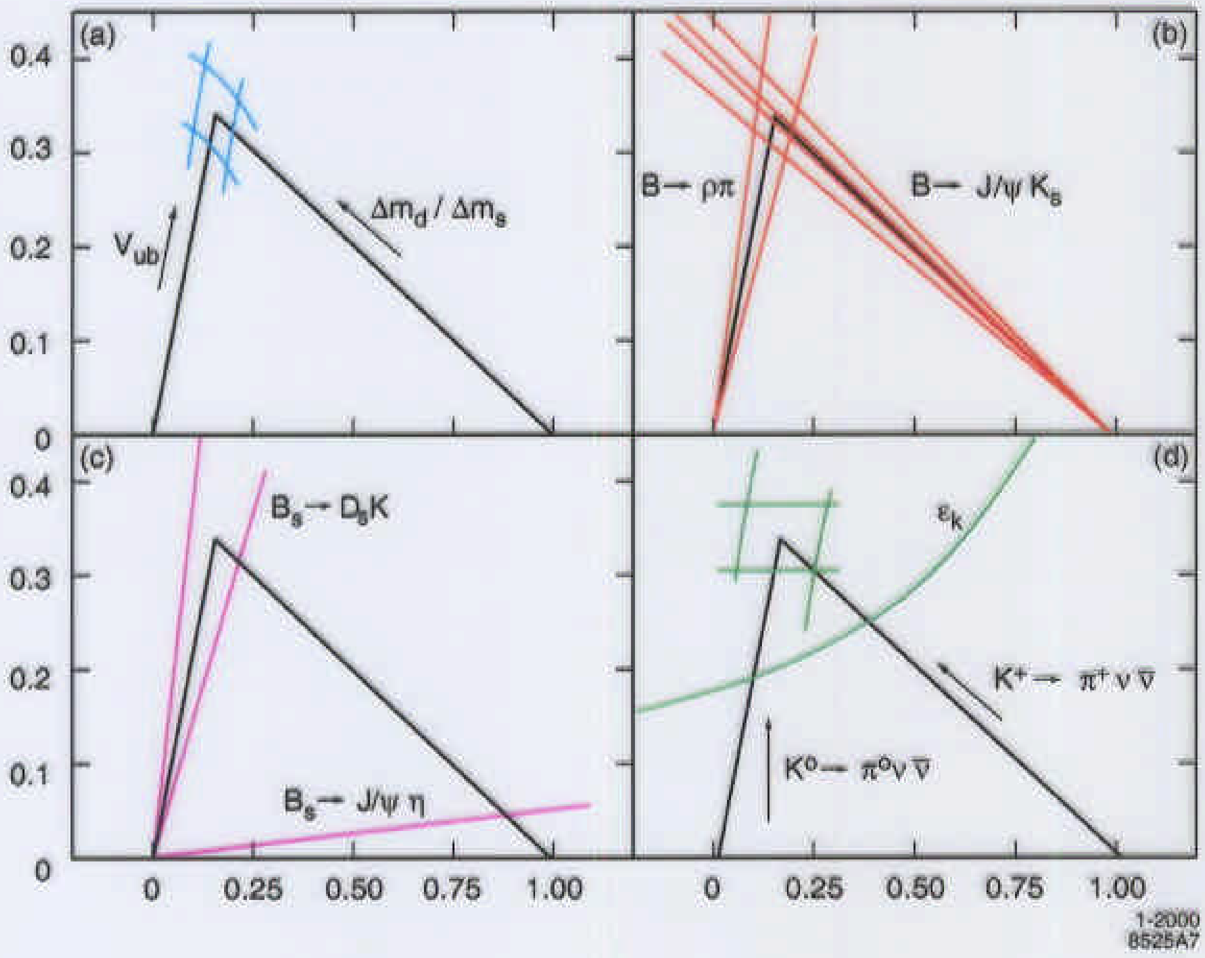


Figure 8: Illustration of four determinations of the unitarity triangle, by (a) non-CP observables, (b) B asymmetries, (c) B_s asymmetries, (d) K rare decays. See the text for more details.

easier said than done

- systematic experimental uncertainties!
- experiments could be wrong!

`Combiner' Hoecker,Laplace,Le Diberder

- theoretical uncertainties!

meaning of theoretical uncertainties?

my `definition' for stating theor. uncertainties:

"I would be very surprised if the true value would fall outside the stated range."

obviously hard to quantitfy

remember ϵ'/ϵ! Be Fa plot

- theoret. uncertainties mostly like systematic uncertainties with hidden correlations

- they can be evaluated only through overconstraints or `redundant'extractions

- prior to that predictions should be considered `preliminary'

a triangle analysis better be much more sturdy than a bunraku stage!

`good decisions derive from experience that often is based on bad decisions'

VI.2 D^0-D^0 Oscillations and CP Violation

charm usually seen as the dull cousin of beauty

- CKM parameters V_{cs} & V_{cd} `known' due to unitarity
- slow D^0 - D^0 oscillations
- tiny CP asymmetries

➥ ~ zero background search for New Physics

however …

? how slow is slow?

? how tiny is tiny?

VI.2.a D^0-D^0 Oscillations

2 quantities control D^0-D^0 oscillations:

$$x_D = \frac{\Delta m_D}{\Gamma_D} \qquad y_D = \frac{\Delta \Gamma_D}{2\Gamma_D}$$

$$r_D = \frac{\Gamma\left(D^0 \to l^- X\right)}{\Gamma\left(D^0 \to l^+ X\right)} \approx \frac{x_D^2 + y_D^2}{2} \qquad \text{for } x_D, y_D << 1$$

- x_D and y_D Cabibbo suppressed
- $x_D = 0 = y_D$ in the $SU(3)_{Fl}$ limit

➡ $x_D, y_D < 0.05$

a conservative estimate

$$x_D, y_D \sim O\,(0.01)$$

popular claims

- $x_D(SM)|_{OPE} << x_D(SM)|_{LD}$

  $y_D(SM)|_{OPE} << y_D(SM)|_{LD}$
- $x_D(SM)|_{LD}, y_D(SM)|_{LD} \sim 10^{-4} - 10^{-3}$

general expectations

- $\Delta\Gamma$: on-shell contributions
  - ➡ ~ insensitive to New Physics
- Δm: virtual intermediate states
  - ➡ sensitive to New Physics

    $x_D \sim O$ (few %) conceivable

more careful analysis

- $x_D(SM)|_{OPE}, y_D(SM)|_{OPE} \sim O(10^{-3})$
- central theoretical issue: does quark-hadron duality hold at the charm scale already?
- more averaging in x_D than in y_D
  - ➡ duality better in x_D than in y_D

data

E791

$y_{CP} = 0.8 \pm 2.9 \pm 1.0\ \%$

CLEO

$-5.8\ \% < y'_{CP} < 1\ \%$ (95 % C.L.)

FOCUS

$y_{CP} = 3.42 \pm 1.39 \pm 0.74\ \%$

$$\text{if } y_D \sim 0.01 \begin{cases} \text{for } x_D \leq \text{few} \times 10^{-3}\text{: } 1/m_c \text{ expan. okay!} \\ \text{for } x_D \sim 0.01\text{: theor. conundrum} \end{cases}$$

sobering lesson:

case for New Physics based on x_D uncertain!

VI.2.b CP Violation in Charm Decays

- ~~CP~~ involving D^0 - $\bar{D}^0$ oscillations
  - ➡ $D^0 \to K^+K^-$ vs. $\bar{D}^0 \to K^+K^-$
  - ➡ $D^0 \to K^+\pi^-$ vs. $\bar{D}^0 \to K^-\pi^+$

CP asymmetry given by

$$\underbrace{\sin\Delta m_D t}_{\uparrow}\ \underbrace{\mathrm{Im}\,\rho(D \to f)}_{\uparrow}$$

small

in

SM KM

➡ strong case
for New Physics!

- direct ~~CP~~ in Cabibbo supp. modes

KM ⟶ $O(10^{-3})$ effects

unclear case ?!

VI.3 Probe for New Physics in $\Delta S = 1$

$P_T(\mu)$ in $K^+ \Rightarrow \mu^+ \pi^0 \nu$

T odd correlation

$$P_\perp \equiv < \mathbf{s}_\mu \cdot (\mathbf{p}_\mu \times \mathbf{p}_\pi) / | \mathbf{p}_\mu \times \mathbf{p}_\pi | >$$

can be `faked' by final state interactions

$$P_\perp \propto \mathrm{Im}\,\xi\,,\ \ \xi = f_- / f_+$$

New Physics ~ Higgs-X!

- `ancient' result:

$$\mathrm{Im}\,\xi = -\,0.01 \pm 0.019 \Leftrightarrow P_\perp = (-1.85 \pm 3.6) \cdot 10^{-3}$$

- $P_\perp \sim 10^{-6}$ from final state interactions
- new result: Aoki

$$\mathrm{Im}\,\xi = -\,0.013 \pm 0.016 \pm 0.003$$

VI.4 Electric Dipole Moments

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

$$\Delta\mathcal{E} = \underset{\overset{\uparrow}{\text{linear in } E}}{d_i E_i} + d_{ij}\, E_i E_j + \dots$$

$\mathbf{d} \propto \mathbf{s} \;\Rightarrow\; \mathbf{d} \neq 0 \Leftrightarrow$ T violation !

- experim. bounds
  - ➲ $d_{\text{neutron}} < 9.7 \cdot 10^{-26}$ e cm
  - ➲ $d_{\text{elektron}} = (-0.3 \pm 0.8) \cdot 10^{-26}$ e cm
- theoret. expectations
  - ➲ CKM: $d_{\text{neutron}} < 10^{-30}$ e cm
  - ➲ SM: $d_{\text{neutron}} \sim 10^{-9} \cdot \theta_{\text{QCD}}$ e cm
  - ➲ many New Physics scenarios:

    $d_{\text{neutron}}, d_{\text{elektron}} > 10^{-27}$ e cm

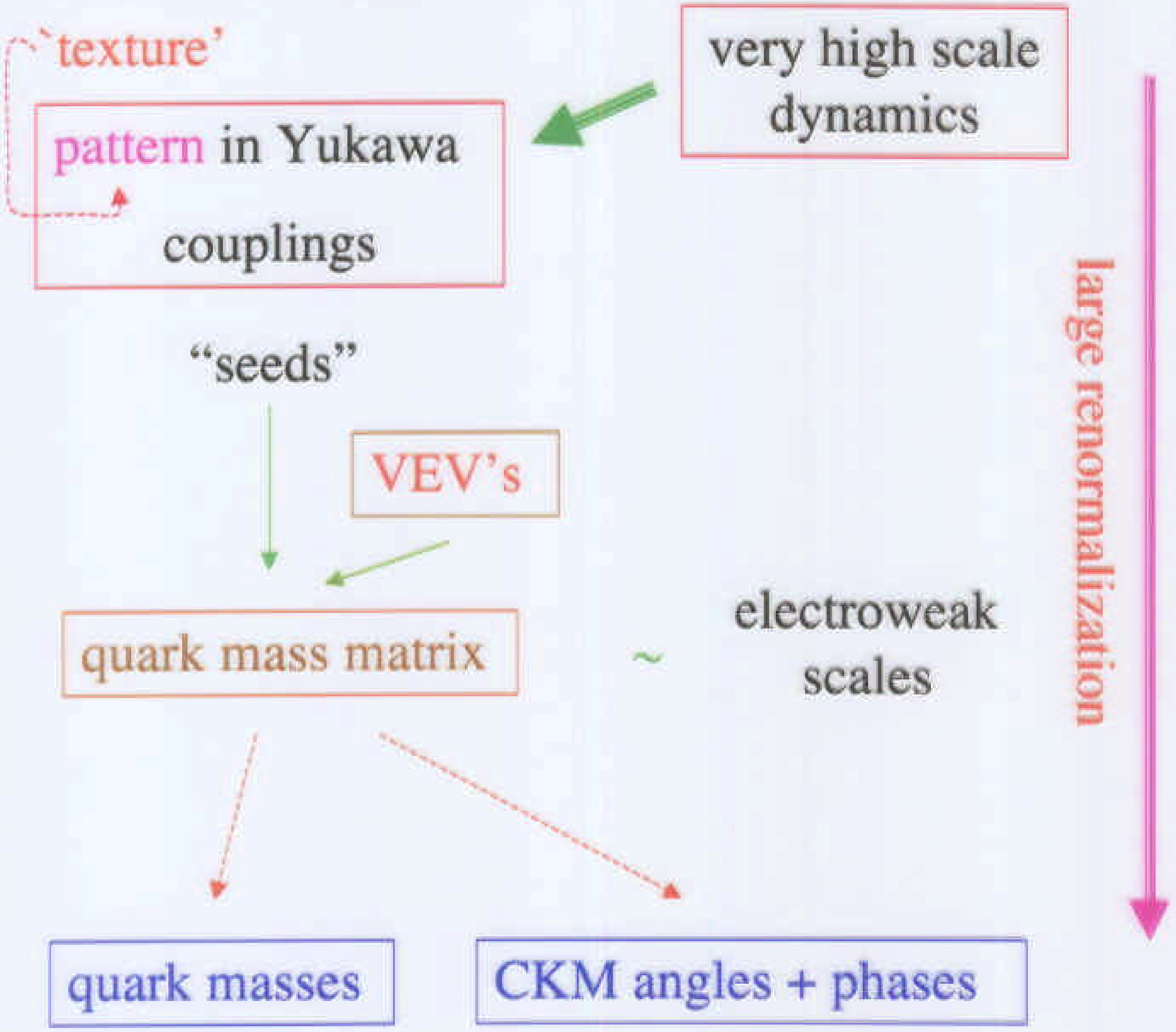
→ a definite must for experimental study!

VI.5 Glazing into the Crystal Ball

- my own expectation on beauty physics:
  - ➡ various large (> 10 %) CP asymmetries will be found in B decays
  - ➡ including direct CP violation
  - ➡ that agree with the CKM expectation to first order
  - ➡ yet exhibit some smallish, though definite deviations ⇒ New Physics!
- however it is conceivable that the whole future beauty phenomenology can be accommodated in the CKM ansatz --

were our efforts for naught then?

an emphatic NO!



`texture'

very high scale dynamics

pattern in Yukawa couplings

large renormalization

"seeds"

VEV's

quark mass matrix

~ electroweak scales

quark masses

CKM angles + phases

personal conjecture/bias:

simple pattern ⇒ special CKM parameters!

yet

high scale → low scale

washes out

VII. Conclusions & Outlook

exciting & even decisive phase in flavour dynamics

- phenom. success of CKM description quite unreasonable ⇒ hidden message!
- new (sub-)paradigms established or about to be established:

❶ direct $\cancel{CP}$ in $\Delta S=1$: $\epsilon'/\epsilon \neq 0$

❷ first evidence for $\cancel{CP}$ outside K_L decays

❸ CKM predictions for $\cancel{CP}$ in B decays

about to be tested

high sensitivity probes of dynamics

many possible portals for New Physics!

- basic quantities known with good accuracy -- and the promise for even better:
  - $\delta m_b \sim 1.5$ % most precise quark mass
  - $\delta m_t \sim 3$ % [10 %] direct [rad.corr.]
  - $\delta V(cb) \sim 5+$ % → 2% feasible
  - $\delta V(ub) \sim 40$ % → 10% feasible
    → 5% not impossible
  - $\delta V(td) \sim 60$ % → 10% not impossible

  high precision probes of dynamics!

- greatly improved practical theoret. technologies
  - increasing sophistication in treating SL & radiat. decays
  - new frontier: exclusive NL $B \rightarrow M_1 M_2$
    - compreh. classif. scheme based on QCD
    - promise to evaluate even non-leading effects in the real world

- need experimental program that allows precise measurements in a comprehensive way
- *other portals for New Physics*:
  - ➡ d_N, d_e: any improvement in experim.

    sensitivity could reveal effect!
  - ➡ $P_\perp$ in $K \to \mu \nu \pi$
  - ➡ charm decays:

    CP & D^0-D^0 oscillations

… and: evidence for neutrino oscillations

➡ neutrino masses non-degenerate

➡ lepton flavour ES ≠ lepton mass ES

➡ as analogue of CKM matrix

the M(aki-)N(akagawa-)S(akata) matrix

"leptons exactly like quarks -- only different"

colour singlets

ν masses extremely tiny

↖ see-saw mechanism

➡ atm. ν's $\Leftrightarrow$ $\tau \to \mu\gamma$

solar ν's $\Leftrightarrow$ $\mu \to e\gamma$ Okada

(H)OPE: the Effective Lagrangian

$$\boxed{\mathcal{L}_{\Delta S=1} = -\frac{G_F}{\sqrt{2}} V_{ud}\, V_{us}^{*} \sum_i [z_i(\mu) + \tau \;\; y_i(\mu)] Q_i(\mu)}$$

$$\tau = -V_{td}V_{ts}^{*}/V_{ud}V_{us}^{*}$$

For $\mu < m_c$ $(q = u, d, s)$:

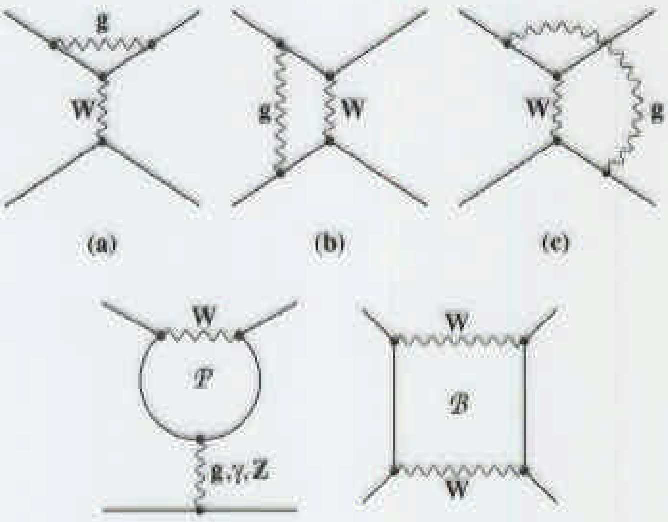
$$\left.\begin{array}{lcl} Q_1 & = & (\overline{s}_\alpha u_\beta)_{\text{V}-\text{A}} \, (\overline{u}_\beta d_\alpha)_{\text{V}-\text{A}} \\ Q_2 & = & (\overline{s}u)_{\text{V}-\text{A}} \, (\overline{u}d)_{\text{V}-\text{A}} \end{array}\right\} \quad \text{Current-Current}$$

$$\left.\begin{array}{lcl} Q_{3,5} & = & (\overline{s}d)_{\text{V}-\text{A}} \sum_q (\overline{q}q)_{\text{V}\mp\text{A}} \\ Q_{4,6} & = & (\overline{s}_\alpha d_\beta)_{\text{V}-\text{A}} \sum_q (\overline{q}_\beta q_\alpha)_{\text{V}\mp\text{A}} \end{array}\right\} \quad \text{Gluon ``penguins''}$$

$$\left.\begin{array}{lcl} Q_{7,9} & = & \frac{3}{2}\, (\overline{s}d)_{\text{V}-\text{A}} \sum_q \hat{e}_q \, (\overline{q}q)_{\text{V}\pm\text{A}} \\ Q_{8,10} & = & \frac{3}{2}\, (\overline{s}_\alpha d_\beta)_{\text{V}-\text{A}} \sum_q \hat{e}_q (\overline{q}_\beta q_\alpha)_{\text{V}\pm\text{A}} \end{array}\right\} \quad \text{Electroweak ``penguins''}$$

"Penguins" feel all three quark families in the loop:
they are sensitive to the CP phase.

Standard model contributions to the matching of the quark operators in the effective flavor-changing Lagrangian



(a) (b) (c)

(d) (e)

$\mu = m_W$	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
Tree		✓								
Tree + g	✓	✓								
Tree + γ		✓								
$\mathcal{P}_g$			✓	✓	✓	✓				
$\mathcal{P}_\gamma$							✓		✓	
$\mathcal{P}_Z$			✓				✓		✓	
$\mathcal{B}$			✓						✓	

Calculation of four-quark matrix elements

The ideal approach

A: Consistent definition of renormalized operators: correct scheme and scale matching with short-distance.

B: Self-contained calculation of all hadronic matrix elements (including B_K).

C: It reproduces simultaneously the $\Delta I = 1/2$ selection rule and ε'/ε .

- VSA:

$$\begin{aligned}\langle\pi^+\pi^-|Q_6|K^0\rangle &= 2\langle\pi^-|\overline{u}\gamma_5 d|0\rangle\langle\pi^+|\overline{s}u|K^0\rangle\\ &- 2\langle\pi^+\pi^-|\overline{d}d|0\rangle\langle 0|\overline{s}\gamma_5 d|K^0\rangle\\ &+ 2\left[\langle 0|\overline{s}s|0\rangle - \langle 0|\overline{d}d|0\rangle\right]\langle\pi^+\pi^-|\overline{s}\gamma_5 d|K^0\rangle\end{aligned}$$

- Generalized Factorization: Scale and scheme independent Wilson coefficients, matched with factorized matrix elements at the scale μ_F (H-Y Cheng, 1999).

- Phenomenological $1/N$: Fix some of the matrix elements by fitting the $\Delta I = 1/2$ rule and vary others around the $1/N$ values (München).

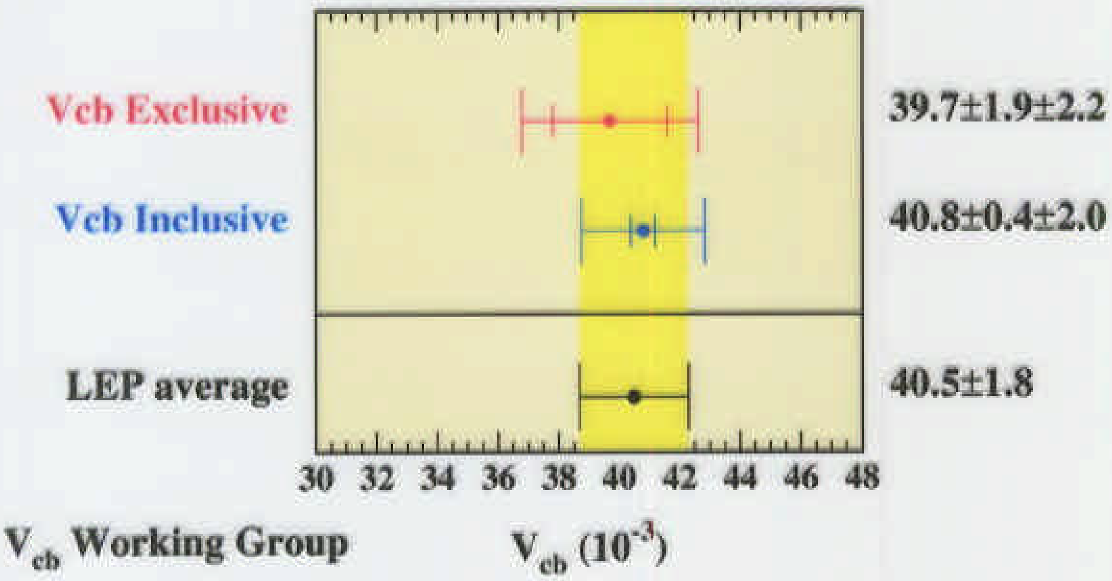
- Chiral Quark Model: All matrix elements at $O(p^4)$ in terms of $\langle\overline{q}q\rangle$, $\langle\frac{\alpha_s}{\pi}GG\rangle$, M, phenomenologically fixed via the $\Delta I = 1/2$ rule (Trieste).

- Phenomenological NJL: Chiral loops up to $O(p^6)$ and fit to the $\Delta I = 1/2$ rule. It includes scalar, vector and axial-vector resonances (Dubna).

- 1/N: Chiral loops regularized via cutoff, partial $O(p^4)$ (Dortmund).

- 1/N and NJL: It includes scalar, vector and axial-vector resonances, good scale stability (Bijnens and Prades, 1999).

- Lattice: $K \to \pi$ matrix elements of four-quark operators. Use chiral symmetry to obtain $K \to \pi\pi$ (Roma, RBC).


Vcb Exclusive
39.7±1.9±2.2
Vcb Inclusive
40.8±0.4±2.0
LEP average
40.5±1.8
30
32
34
36
38
40
42
44
46
48
V_{cb} Working Group
V_{cb} (10^{-3})