CP Violation: SM & Beyond

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INT, Seattle, March’07
OUTLINE

• Status of SM CKM paradigm
• Why is precision of paramount importance?
• Possible signs of BSM-CP-odd phase?
• Illustrative candidates for BSM
• Prospects for needed precision.
• BSMs & EDMs
• Summary
B-factories help attain an important milestone

- CKM constraints using expts. \([\epsilon_K, b \rightarrow ul\nu, \Delta m_d, \Delta m_s/\Delta m_d]\) + lattice + phenom. \(\Rightarrow (\sin 2\beta)_{SM} \approx 0.70 \pm 0.10\)
- \(a_{CP}(B \rightarrow \psi K^0) [\text{BELLE/BABAR/CDF...}] \Rightarrow \sin 2\beta = 0.731 \pm 0.055 \Rightarrow \text{CKM phase is the dominant contributor to } a_{CP}\)
- \(\Rightarrow \text{CP-odd phase(s) due BSM (}[\chi_{BSM}]\text{) may well cause only small deviations from SM in B-Physics}\)

Search must go on

Search for CP-odd phase(s) \([\chi_{BSM}]\) due BSM-physics is especially well motivated as there are essentially compelling reasons that they exist:

Extensions of SM invariably lead to new phase(s), besides baryogenesis is difficult to account for by the CKM paradigm
1st Hints of confirmation
Of CKM-CP violation

Most bands due
To theory errors

Atwood&A.S,
hep-ph/0103197
Measurement of $\lambda(\Phi_2)$

Overall result, including $\rho\pi$

Indirect: $\alpha = [100^{+5}_{-7}]^\circ$  $\alpha$ (deg)  Combined: $\alpha = [93^{+11}_{-9}]^\circ$

Youngjoon Kwon
Measurement of $\gamma (\Phi_3)$

**Overall result**

![Graph showing measurements]

- Indirect: $\gamma = [59^{+9}_{-4}]^\circ$
- Combined: $\gamma = [62^{+38}_{-24}]^\circ$

Youngjoon Kwon
Celebration I: SPECTACULAR PERFORMANCE of 2 Machines! (each several times better than design lumi!!)
Overall CKM agreement

\[ S(t)(B^0 \to 4 K) \approx 70\% \]

Frequentist

\[ \epsilon_K (K_L \to \pi\nu\bar{\nu}) \approx 10^{-3} \]

Both accounted by the KM phase!!

Bayesian

Conclusion is the same:
All measurements agree with SM picture of CKM matrix within errors
Celebration II: A beautiful theory paper which not only suggested the need for the 3rd family, before the discovery of charm and tau, its framework is vindicated in detail through exhaustive experimentation ~35 years later!!

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

**CP-Violation in the Renormalizable Theory of Weak Interaction**

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.
UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

We present here an analysis of leptonic decays based on the unitary symmetry for strong interactions, in the version known as “eighthfold way,” and the V-A theory for weak interactions. \(^2,3\) Our basic assumptions on \(J_\mu\), the weak current of strong interacting particles, are as follows:

1. \(J_\mu\) transforms according to the eightfold representation of SU\(_3\). This means that we neglect currents with \(\Delta S = -\Delta Q\), or \(\Delta I = 3/2\), which should belong to other representations. This limits the scope of the analysis, and we are not able to treat the complex of \(K^0\) leptonic decays, or \(\Sigma^+ - n + e^+ + \nu\) in which \(\Delta S = -\Delta Q\) currents play a role. For the other processes we make the hypothesis that the main contributions come from that part of \(J_\mu\) which is in the eightfold representation.

2. The vector part of \(J_\mu\) is in the same octet as the electromagnetic current. The vector contribution can then be deduced from the electromagnetic properties of strong interacting particles. For \(\Delta S = 0\), this assumption is equivalent to vector-
Should 10% tests be good enough?

Vital Lessons from our past

• **LESSON # 1: Remember $\varepsilon_K$**

• It's extremely important to reflect on the severe and tragic consequences if Cronin et al had decided in 1963 that $O(10\%)$ searches for $\varepsilon$ were good enough!

Imagine what an utter disaster for our field that would have been.

Note also even though CKM-CP-odd phase is $O(1)$ (as we now know) in the SM due to this $O(1)$ phase only in B-physics we saw large effects… in K (miniscule), D(very small), t(utterly negligible).

*Understanding the fundamental SM parameters to accuracy only of $O(10\%)$ would leave us extremely vulnerable …..Improvement of our understanding should be our crucial HOLY GRAIL!*
Lesson #2

Remember $m_\nu$

Just as there was never any good reason for $m_\nu = 0$
there is none for BSM-CP-odd phase not to exist
$\Delta m^2 \sim 1 \text{eV}^2 \sim 1980 \rightarrow \Delta m^2 \sim 10^{-4} \text{eV}^2 \ldots \text{’97}$

Osc. Discovered….

Similarly for BSM-CP-odd phase, we may need to look for much smaller deviations than the current $O(10\%)$
demanding precision from expt. & theory
Tantalizing (possible) signs of a BSM-CP phase
$\Delta S = S_{\text{penguin}} - S_{4K}\varphi = 0(n^2)$

Decay $S_{\text{penguin}} \approx 0(n^2)$ few/

Grossman & Worah PLB’97; London and A.S. PLB’97
Testing the SM with penguin dominated modes

- $\Delta S = C_{MD} \mathcal{O}(\lambda^2)$, expect $C_{MD} \sim \mathcal{O}(1)$

- Significant deviation from this expectation is a sign of BSM-CP-odd phase!

- Unfortunately $C_{MD}$ is a (QCD) model dependent coefficient
TABLE I: Some expectations for ΔS in the cleanest modes.

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta'K^0$</td>
<td>0.00$^{+0.00}_{-0.04}$</td>
<td>0.01 ± 0.01</td>
<td>0.01 ± 0.02</td>
<td>$-0.019 ± 0.009$</td>
</tr>
<tr>
<td>$\phi K^0$</td>
<td>0.03$^{+0.01}_{-0.04}$</td>
<td>0.02 ± 0.01</td>
<td>0.02 ± 0.01</td>
<td>$-0.010 ± 0.001$</td>
</tr>
<tr>
<td>$K_SK_SK^0$</td>
<td>0.02$^{+0.00}_{-0.04}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Comparison to $b \rightarrow c\bar{c}s$

$$\sin(2\beta_{\text{eff}}) = \sin(2\phi_{1\text{eff}})$$

<table>
<thead>
<tr>
<th></th>
<th>World Average</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \rightarrow c\bar{c}s$</td>
<td>$0.68 \pm 0.03$</td>
<td></td>
</tr>
<tr>
<td>$\phi K^0$</td>
<td>$0.39 \pm 0.13$</td>
<td></td>
</tr>
<tr>
<td>$\eta^* K^0$</td>
<td>$0.61 \pm 0.07$</td>
<td></td>
</tr>
<tr>
<td>$K_S K_S K_S$</td>
<td>$0.51 \pm 0.21$</td>
<td></td>
</tr>
<tr>
<td>$\pi^0 K_S$</td>
<td>$0.33 \pm 0.21$</td>
<td></td>
</tr>
<tr>
<td>$\rho^0 K_S$</td>
<td>$0.20 \pm 0.57$</td>
<td></td>
</tr>
<tr>
<td>$\omega K_S$</td>
<td>$0.48 \pm 0.24$</td>
<td></td>
</tr>
<tr>
<td>$f_0 K^0$</td>
<td>$0.42 \pm 0.17$</td>
<td></td>
</tr>
<tr>
<td>$\pi^0 \pi^0 K_S$</td>
<td>$-0.84 \pm 0.71$</td>
<td></td>
</tr>
<tr>
<td>$K^* K K^0$</td>
<td>$0.58 \pm 0.13$</td>
<td></td>
</tr>
</tbody>
</table>

NP? More data needed!

Sign of $\Delta S = 1$ is systematically opposite to theory.
Current situation

- Reference value reduced to 0.68 ± 0.03
- Average value from penguin modes increased to 0.52 ± 0.05
- Deviation reduced to 2.8σ 😞

New Physics in penguin processes?

Matthias Neubert
On the issue of adding many modes

EXTRACT from David London+ A.S PLB407, 61 (1997)

where η′KS and many penguin dominated modes were first discussed.

To sum up this point, CP asymmetries in b → s penguins do indeed measure the CP angle β. The tree contributions to these decays are quite small, at most a few percent. It is therefore possible to add up the measured CP asymmetries in all these modes to obtain a larger signal. If the value of β extracted in this way differs by more than about 10% from that found in ΨKs, then it is a clear signal of new physics, with new phases, in the b → s FCNC. If the difference is less than about 10%, it could in principle be due to the tree contamination. However, this can be checked by using only the final states φKs and η′KS (to a very good approximation).

However, call from Stockholm will demand conclusive evidence for ΔS>0.10 in several separate modes
Although, at the moment it is not a conclusive effect, it may well become a serious blunder on the part of experimentalists to ignore it! We can try learn some lessons from history.

It is extremely important to understand that basically it is a very good test of the SM.
FIG. 15. Experimental cross sections at two energies compared with a simple $1/m^6$ continuum.
mass range of 3–5 GeV/c², there is a distinct excess of the observed cross section over the reference curve. If this excess is assumed (certainly not required) to be the production of a resolution-broadened resonance, the cross-section-branching-ratio production $\sigma B$ would be approximately $6 \times 10^{-35}$ cm², subject to the cross-section uncertainties discussed above. Alternatively the excess may be interpreted as merely a departure from the overly simplistic (and arbitrarily normalized) $1/m^5$ dependence. In this regard, we should remark that there may be two entirely different processes represented here: a low-$Q^2$ part which has to do with vector mesons, tail of the $\rho$, bremsstrahlung, etc., and a core yield with a slower mass dependence, which may be relevant to the scaling argument discussed below.

The "heavy photon" pole that has been postulated to remove divergence difficulties in quan-

icles produced in the initial proton-uranium collision. In principle, these secondary particles could also create muon pairs. In this case, the observed spectrum would represent the inseparable product of the spectrum of the secondary particle and its own yield of muon pairs. In exploratory research of this kind this disadvantage is largely offset by the fact that the variety of initial states provides a more complete exploration of dimuon production in hadron collisions.

2. Real Photons

Real photons produced in the target (presumably from the decay of neutral pions) yield muon pairs by Bethe-Heitler or Compton processes. Estimates were made for the photon flux on the basis of pion-production models, and this method of calculating the flux was checked against the experimental data of Fidecaro et al. The argument
Sensitivity to new CP phases

Estimated error in the measurement of time dependent CP violation

Discovery region with 50 ab$^{-1}$

Masa Yamauchi
Proposed schedule

Integrated luminosity (ab⁻¹)

Calendar year

Belle is here. 0.58ab⁻¹
Crab cavity installation
2 yr shutdown for upgrade
L_{peak} \sim 1.5 \times 10^{34}
1.5 - 3 \times 10^{34}
\sim 8 \times 10^{35}

SuperKEKB

~10B BB and τ⁺τ⁻ every year

Masa Yamauchi
$B \rightarrow X_s \gamma$ branching fraction

Average branching fraction for $E_\gamma > 1.6$ GeV
(Heavy Flavor Averaging Group (HFAG), hep-ex/0603003)

\[ \mathcal{B}(B \rightarrow X_s \gamma; E_\gamma > 1.6 \text{ GeV}) = (355 \pm 24_{\text{stat+sys}}^{+9}_{-10}(\text{shape}) \pm 3_{(d\gamma)}) \times 10^{-6} \]

- CLEO: PRL87,251897(2001) [8.1 fb$^{-1}$]
- BaBar: PRD72,032004(2005) [81.5 fb$^{-1}$]
- BaBar: hep-ex/0507001 [81.5 fb$^{-1}$]
- Belle: PLB511,151(2001) [5.8 fb$^{-1}$]
- Belle: PRL93,061803(2004) [140 fb$^{-1}$]
- Average: HFAG hep-ex/0603003

- NLO

\[ \mathcal{B}(B \rightarrow X_s \gamma) \times 10^{-4} \]

- CLEO: (3.29$^{+0.53}_{-0.43}) \times 10^{-4}$
- BaBar: (3.35$^{+0.82}_{-0.71}) \times 10^{-4}$
- BaBar: (3.92$^{+0.57}_{-0.51}) \times 10^{-4}$
- Belle: (3.69$^{+0.95}_{-0.87}) \times 10^{-4}$
- Belle: (3.50$^{+0.44}_{-0.41}) \times 10^{-4}$
- Average: (3.55$^{+0.26}_{-0.23}) \times 10^{-4}$

- Very consistent with NLO SM, e.g., $(357 \pm 30) \times 10^{-6}$
- Many NLO SM calculations — theory error?

Mikihiro Nakao @ CKM06; c also Matthias Neubert
\( B \rightarrow X_s \gamma \) branching fraction

Average branching fraction for \( E_\gamma > 1.6 \text{ GeV} \)
(Heavy Flavor Averaging Group (HFAG), hep-ex/0603003)

\[
\mathcal{B}(B \rightarrow X_s \gamma; E_\gamma > 1.6 \text{ GeV}) = (355 \pm 24_{\text{stat+sys}}^{+9}_{-10(\text{shape})} \pm 3_{(d_\gamma)}) \times 10^{-6}
\]

**NNLO**
- CLEO
  - PRL87, 251801(2001) [9.1 fb\(^{-1}\)]
- BaBar
  - PRD72, 052004(2005) [81.5 fb\(^{-1}\)]
  - hep-ex/0507091 [81.5 fb\(^{-1}\)]
- Belle
  - PLB511, 151(2001) [5.8 fb\(^{-1}\)]
  - PRL93, 061803(2004) [140 fb\(^{-1}\)]

**Average**
- HFAG hep-ex/0603003

- Kocher Neubert (hep-ph/0610067)

- \((3.29 \pm 0.53) \times 10^{-4}\)
- \((3.35 \pm 0.62) \times 10^{-4}\)
- \((3.92 \pm 0.57) \times 10^{-4}\)
- \((3.69 \pm 0.95) \times 10^{-4}\)
- \((3.50 \pm 0.44) \times 10^{-4}\)
- \((3.55 \pm 0.26) \times 10^{-4}\)

- Very consistent with NLO SM, e.g., \((357 \pm 30) \times 10^{-6}\)
- Many NLO SM calculations — theory error?
- Or slightly higher than first NNLO SM estimates?

Mikihiko Nakao @ CKM06 ; c also Matthias Neubert
**Direct CP asymmetry**

\[ A_{CP} = \frac{\Gamma(b \rightarrow s\gamma) - \Gamma(b \rightarrow \bar{s}\gamma)}{\Gamma(b \rightarrow s\gamma) + \Gamma(b \rightarrow \bar{s}\gamma)} \]

- Precisely measured: HFAG \( A_{CP}(B \rightarrow X_s\gamma) = (5 \pm 36) \times 10^{-3} \)
  - Belle 140 fb\(^{-1}\): \((2 \pm 50 \pm 30) \times 10^{-3}\)
  - BaBar 82 fb\(^{-1}\): \((25 \pm 50 \pm 15) \times 10^{-3}\)
- but extremely small in SM: e.g., \( A_{CP} = (4.2^{+1.7}_{-1.2}) \times 10^{-3} \) (I.Hurth et al)
  - Only up to a few percent even in SUSY (with EDM constraints)

- BaBar 82 fb\(^{-1}\): \( A_{CP}(B \rightarrow X_{(s+d)}\gamma) = (-110 \pm 115 \pm 17) \times 10^{-3} \)
  - \( b \rightarrow s\gamma \) and \( b \rightarrow d\gamma \) are not separated — even smaller SM CPV (canceling)

Better \( A_{CP} \) highly desirable due to indications of 2HD

Mikihiho Nakao @ CKM06
B-Factory Signals for a WED

(Agashe,Perez,Soni,hep-ph/0406101(PRL);0408134)

- RS1 with a WARPED EXTRA DIMENSION (WED) provides an elegant solution to the HP
- In this framework, due to warped higher-dimensional spacetime, the mass scales (i.e. flavors) in an effective 4D description depend on location in ED. Thus, e.g. the light fermions are localized near the Plank brane where the effective cut-off is much higher than TeV so that FCNC’s from HDO are greatly suppressed. The top quark, on the other hand is localized on the TeV brane so that it gets a large 4D top Yukawa coupling.
Key features of WED

• **Amielorating the Flavor Problem.** This provides an understanding of hierarchy of fermion masses w/o hierarchies in fundamental 5D params. Thus “solving” the SM flavor problem.

**Flavor violations** Most flavor-violating effects arise due to the violation of RS-GIM mechanism by the large top mass. This originates from the fact that $(t,b)_L$ is localized on the TeV brane.
Basics of the framework

between the relevant models considered below. The basic set-up of our models is the RS1 framework [1]. The space time of the model is described by a slice of $\text{ADS}_5$ with curvature scale, $k \sim M_{\text{Pl}}$, the 4D Planck mass. The Planck brane is located at $\theta = 0$, where $\theta$ is the compact extra dimension coordinate. The TeV brane is located at $\theta = \pi$. The metric of RS1 can be written as:

$$(ds)^2 = \frac{1}{(kz)^2} \left[ \eta_{\mu \nu} dx^\mu dx^\nu - (dz)^2 \right],$$

where $kz = e^{kr_c \theta}$. We assume that $k \pi r_c \sim \log(M_{\text{Pl}}/\text{TeV})$ to solve the hierarchy problem,

$$\left( z_h \equiv \frac{1}{k} \right) \leq z \leq \left( z_v \equiv \frac{e^{k \pi r_c}}{k} \right),$$

where $z_v \sim \text{TeV}^{-1}$.

The gauge group of the models under study is given by [9, 10] $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. The gauge symmetry is broken on the Planck brane down to the SM gauge group and in the TeV brane it is broken down to $SU(3)_c \times SU(2)_D \times U(1)_{B-L}$. $SU(2)_D$ is the diagonal subgroup of the two $SU(2)'s$ present in the bulk.
There are essentially 3 types of top quark dominated FCNC contributions:

i) Contributions to FCNC processes arise from a relatively large dispersion in the doublets 5D masses, specifically large coupling of $(t, b)_L$ to gauge modes due to heaviness of the $t$. 
ii) Contributions to FCNC processes (mostly semi-leptonic)

These arise from contribution of i) and mixing between the zero and KK states of the Z due to EWSB.

iii) Contribution to radiative B-decays via dipole operators arise from large 5D Yukawa required to obtain $m_t$
<table>
<thead>
<tr>
<th>Flavor</th>
<th>$f_Q^{-1}$</th>
<th>$f_u^{-1}$</th>
<th>$f_d^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$\frac{\lambda^3}{f_Q^3} \sim 0.4 \times 10^{-2}$</td>
<td>$\frac{m_u}{m_t} \frac{f_u^{-1}}{\lambda^3} \sim 10^{-3}$</td>
<td>$\frac{m_d}{m_b} \frac{f_d^{-1}}{\lambda^3} \sim 10^{-3}$</td>
</tr>
<tr>
<td>II</td>
<td>$\frac{\lambda^2}{f_Q^3} \sim 2 \times 10^{-2}$</td>
<td>$\frac{m_c}{m_t} \frac{f_u^{-1}}{\lambda^2} \sim 10^{-1}$</td>
<td>$\frac{m_s}{m_b} \frac{f_d^{-1}}{\lambda^2} \sim 0.3 \times 10^{-2}$</td>
</tr>
<tr>
<td>III</td>
<td>$\frac{f_u^{-1} m_t}{v \lambda_{5D}} \sim \frac{1}{3}$</td>
<td>$O\left(\frac{5}{6}\right)$</td>
<td>$\frac{m_b}{m_t} f_u^{-1} \sim 0.6 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Table 3: The known quark masses and CKM mixing implies relation between the model flavor parameters, $f_{x^i}$, (11,12). The value of $f_{u^3}, \lambda_{5D}$ is determined by requiring the theory is perturbative (13,14).
Notable FCNC characteristic
(see table)

$f_{x_i}^{-1}$ apart from the ones related to the top mass are small. This implies that the model has a built-in approximate flavor symmetry for the light quarks. This is indeed the reason why the framework may avoid the severe constraint from FCNC processes with such a low KK masses. We can compare this with the flat extra dimension models which require KK masses of $O(1000 \text{ TeV})$. 
Fig. 1: Contributions to $\Delta F = 2$ processes from KK gluon exchange.
Contrasting B-Factory Signals from WED with those from the SM

<table>
<thead>
<tr>
<th></th>
<th>$\Delta m_{B_s}$</th>
<th>$S_{B_s} - \psi_\phi$</th>
<th>$S_{B_d} - \phi_{K_s}$</th>
<th>$Br[b \rightarrow s l^+ l^-]$</th>
<th>$S_{B_{d,s}} - K^* \phi_{\gamma}$</th>
<th>$S_{B_{d,s}} - \rho_{K^* \gamma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS1</td>
<td>$\Delta m_{B_s}^{SM} [1 + O(1)]$</td>
<td>$O(1)$</td>
<td>$\sin 2\beta \pm O(2)$</td>
<td>$Br_{SM}[1 + O(1)]$</td>
<td>$O(1)$</td>
<td>$O(1)$</td>
</tr>
<tr>
<td>SM</td>
<td>$\Delta m_{B_s}^{SM}$</td>
<td>$\lambda_c^2$</td>
<td>$\sin 2\beta$</td>
<td>$Br_{SM}$</td>
<td>$\frac{m_s}{m_b} (\sin 2\beta, \lambda_c^2)$</td>
<td>$\frac{m_d}{m_b} (\lambda_c^2, \sin 2\beta)$</td>
</tr>
</tbody>
</table>

MODELS ARE NOT YET DEVELOPED TO BE PRECISE.
Two Higgs Doublet Models with Natural Flavor Conservation

The charged Higgs boson interactions with the quark sector are governed by the Lagrangian

\[ \mathcal{L} = \frac{g}{2\sqrt{2}M_W} H^\pm \left[ V_{ij} m_u A_u \bar{u}_i (1 - \gamma_5) d_j + V_{ij} m_d A_d \bar{d}_i (1 + \gamma_5) d_j \right] + \text{h.c.}, \]

where \( g \) is the usual SU(2) coupling constant and \( V_{ij} \) represents the appropriate CKM element. In model I, \( A_u = \cot \beta \) and \( A_d = -\cot \beta \), while in model II, \( A_u = \cot \beta \) and \( A_d = \tan \beta \), where \( \tan \beta \equiv v_2/v_1 \) is the ratio of vev
Two Higgs Doublet Model For the top quark.....(Das and Kao ’96)

Huge $m_{top}$ is accommodated naturally by postulating that the second Higgs doublet, with a much larger VEV compared to the 1st, couples only to the top quark $\rightarrow \tan \beta >> 1$. 
This is accomplished via:

\[ L_{\text{yukawa}} = -\bar{L}_L \phi_1 E_l R - \bar{Q}_L \phi_1 F d_R - \bar{Q}_L \phi_1 G I^{(1)} u_R - \bar{Q}_L \phi_2 G I^{(2)} u_R. \]

\[ H.c.; \]

Here \( \phi_1 \) are the two Higgs doublets; \( E, F \) and \( G \) are 3 \( \times \) 3 Yukawa matrices giving masses respectively to the charged leptons, the down and up type quarks; \( I^{(1)} \equiv \text{diag}(1, 1, 0) \) and \( I^{(2)} \equiv \text{diag}(0, 0, 1) \) are the two orthogonal projectors onto the 1st two and third family respectively. \( Q_L \) and \( L_L \) are the usual left-handed quark and lepton doublets.

(b) T2HDM should be viewed as LEET that parametrizes through the Yukawa interactions some high energy dynamics which generates the top quark mass as well as the weak scale...

(c) In addition to large \( \tan \beta \) the model has restrictive FCNC (since it belongs to type III) amongst only the up-type
Direct CP violation in Radiative B decays in and beyond the SM

Kiers, Soni and Wu hep-ph/0006280 (some input from refs. below)

<table>
<thead>
<tr>
<th>Model</th>
<th>$A_{CP}^{B \rightarrow X_d \gamma}(%)$</th>
<th>$A_{CP}^{B \rightarrow X_s \gamma}(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>0.6</td>
<td>-16</td>
</tr>
<tr>
<td>2HDM (Model II)</td>
<td>$\approx 0.6$</td>
<td>$\approx -16$</td>
</tr>
<tr>
<td>3HDM</td>
<td>-3 to +3</td>
<td>-20 to +20</td>
</tr>
<tr>
<td>T2HDM</td>
<td>$\approx 0$ to +0.6</td>
<td>$\approx -16$ to +4</td>
</tr>
<tr>
<td>Supergravity[*]</td>
<td>$\approx -10$ to +10</td>
<td>($5$ - 45) and (2)</td>
</tr>
<tr>
<td>SUSY with squark mixing[+]</td>
<td>$\approx -15$ to +15</td>
<td></td>
</tr>
<tr>
<td>SUSY with R-parity violation[+*]</td>
<td>$\approx -17$ to +17</td>
<td></td>
</tr>
</tbody>
</table>

Soni's RECENT Obsession

- Post-Bfactory confirmation that CKM phase is the dominant source in $a_{CP}$ ($B \to \psi K_s$) suggests that even if $X_{BSM}$ exists and is $O(1)$ its effects in B-physics may well be small.

- While difficult to reliably say, how small; in planning B-expts, it may be best to target $a_{CP}[X_{BSM}]$ very small, say $O(10^{-3}) \approx \epsilon_K$.

Our enlightened understanding of the CKM-phase (post B-factory results) is that it is $O(1)$ and while it causes large asymmetry in B-physics, in K-decays its effects are miniscule.

- In suggesting the target, $a_{CP}[X_{BSM}] \approx 10^{-3}$, we are taking cue from this SM example. Thus even isospin symmetry (widely used) can cause problems. So:
  - Need lots and lots of CLEAN B's (i.e. $O(10^{10})$ or more).
  - Intensive study of $B_s$ mesons (in addition to B's) becomes very important.
  - Need extremely clean predictions from theory.
Indirect Searches w/o theory input: Elements of a Superclean UT

This is a gold plated method for searching for NP in B-decays.

- TDCPA in $B^0 \rightarrow \psi K^0$; gives $\beta$
- DIRCP in $B^{\pm} \rightarrow "K^{\pm}\" D^0, \bar{D}^0$; gives $\gamma$
- TDCPA in $B^0 \rightarrow "K^{0}\" D^0, \bar{D}^0$; gives $\gamma$ OR $\alpha$ AND $\beta$

Also, incidentally

- TDCPA in $B_s \rightarrow KD_s$; gives $\gamma$.
- AND DIRCP in $K_L \rightarrow \pi^0 \nu \bar{\nu}$ gives $\eta$

Note that the irreducible theory error (ITE) in each of these methods is expected to be $< 1\%$

- Using TDCPA studies in all three final states $B \rightarrow \pi \pi, \rho \pi$ and $\rho \rho$ should give a very good determination of $\alpha$ (may be with $ITE \approx 1\%$?) although each final state by itself is likely to
have (at least) several percent theory error, with our present level of understanding.

It is extremely important that we make use of the opportunity afforded to us by as many of these very clean redundant measurements as possible.

In order to exploit these methods to their fullest potential and get the angles with errors of order ITE will, for sure, require a SUPER-B Factory.

This end in itself constitutes a strong enough reason for a SBF, as it represents a great opportunity to precisely nail down the important parameters of the CKM paradigm, therefore not going in that direction is a serious mistake.
SUMMARY on UTA

Angle NOW(1/au) 09(2/au)

β(ψ₁) 4° 3.5°

α(ψ₂) ~12° ~9°

γ(ψ₃) ~50° ~25°

<Exp. ERROR →

SBF IS ESSENTIAL
K-Unitarity Triangle

- There is considerable interest in constructing the UT purely from K-decays...relevant reactions being pursued:
- Indirect CP violation parameter $\varepsilon$ with $B_K$ from lattice
- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ can give clean $V_{td}$
- $K_L \rightarrow \pi^0 \nu \bar{\nu}$ can give super-clean $\eta$ (expt. very challenging)
- Direct CP $\varepsilon'$ with lattice matrix elements (theo. Very Challenging)

EDM@INT.....A.Soni

47
J-PARC has a very ambitious menu:

$K_L \to \pi^0 \nu \bar{\nu}$; T2K pol in $K_L \to \pi^+ \mu^+ \nu$; T2K 20Sc
**$K_L \rightarrow \pi^0 \nu \bar{\nu}$ experiments**

- **extremely challenging**
  - small branching fraction
  - many background sources
  - 3 body decay
  - weak kinematical constraint
  - all particles neutral
- Current upper limit
  - $\text{Br} < 2.1 \times 10^{-7}$ (90% C.L.)
  - E391a, PRD 74:051105, 2006
- Step by Step approach
  - E391a
    - The first dedicated experiment to establish experimental method measurement at $O(10^{-9})$
  - J-Parc K
    - Step-1: $8 \times 10^{-12}$, event observation
    - Step-2: $\sim 10^{-13}$, precise measurement
Setting the bar for future Kaon experiments

- Present (E787/949): \( \text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10} \)

100 events
Mean: E787/949

Current constraint on \( \rho, \eta \) plane

M. Piccini
Rare Kaon Decays and CKM matrix

- $K \to \pi \nu \bar{\nu}$ decay is sensitive to $V_{td}$
- $|V_{td}|$ determination independent on $B^0 - \bar{B}^0$ mixing
- Theoretically the **cleanest** processes in K and B physics

- **Standard Model predictions**
  - $\text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) \approx (1.6 \times 10^{-5}) |V_{cb}|^4 [\sigma \eta^2 + (\rho_c - \rho)^2] \to (8.0 \pm 1.1) \times 10^{-11}$
  - $\text{BR}(K_L \to \pi^0 \nu \bar{\nu}) \approx (7.6 \times 10^{-5}) |V_{cb}|^4 \eta^2 \to (3.0 \pm 0.6) \times 10^{-11}$

Piccini NA48/3 (Expt P326) @ CERN
$B_K$ is the low energy matrix element relevant to indirect CP-violation in the $K^0-\bar{K}^0$ system

$$|\epsilon_K| = C_\epsilon A^2 \lambda^6 \eta \left[ -\eta_1 S(x_c) + \eta_2 S(x_t) (A^2 \lambda^4 (1 - \bar{\rho}) + \eta_3 S(x_c, x_t) \right] \hat{B}_K$$

- This is the CKMfitter group's plot from ICHEP 2004. The input used was

$$\hat{B}_K = 0.86 \pm 0.06 \pm 0.14$$

- PDG: $\hat{B}_K = 0.68 - 1.06$

For past ~decade error has stood at ~17%

- For both these results, the value quoted is the result of lattice calculations; the main error is from the use of the quenched approximation.
OVER 20 years of $B_K$

C. Bernard, A. Soni / Weak matrix elements on the lattice

\[ \langle \bar{K}^0|\langle \Delta s = 2 \rangle_{LL}|K^0 \rangle \text{ with Wilson fermions has been proposed in Ref. 32. One starts by writing the CPTh form for the matrix elements of the continuum (physical) operator and for its Wilson lattice counterpart:} \]

\[ \langle \bar{K}^0|\langle \Delta s = 2 \rangle_{LL}|K^0 \rangle_{\text{cont}} = \gamma(p_K \cdot p_{\bar{K}}) + \cdots \]

\[ \langle \bar{K}^0|\langle \Delta s = 2 \rangle_{LL}|K^0 \rangle_{\text{latt}} = \alpha + \beta m^2 + \gamma'(p_K \cdot p_{\bar{K}}) + \cdots, \quad (8) \]

where the $\alpha$ and $\beta$ terms in the lattice amplitude (and the change from $\gamma$ to $\gamma'$) are due to "bad" chirality operators such as $O_\perp$ which have not been correctly removed by perturbation theory. Note that for $K$, $\bar{K}$ at rest, $p_K \cdot p_{\bar{K}} = m^2$; while for the crossed amplitude $\langle \bar{K}^0 K^0|\langle \Delta s = 2 \rangle_{LL}|0 \rangle$, $p_K \cdot p_{\bar{K}} = -m^2$. Both the original $K^0 - \bar{K}^0$ amplitude and the crossed amplitude are then computed at rest on the lattice for various values of $m$, and the $\gamma'$ term is extracted by a fit to the data. Finally, with the assumption $\gamma \equiv \gamma'$ (see below for a critique), the order $m^2$ term in the continuum ampli-

FIGURE 4
The amplitude $\langle \bar{K}^0|\langle \Delta s = 2 \rangle_{LL}|K^0 \rangle \times 10^2$ vs. $m^2$. The solid line is a naive (uncorrelated) fit to the data.
Operator Mixing and $B_K$ ...

- If chiral symmetry is broken, four other operators can mix (the four other possible gamma matrix structures)

$$\langle \overline{K}^0 | O_{VV+AA} | K^0 \rangle_{\text{latt}} \propto \langle \overline{K}^0 | O_{VV+AA} | K^0 \rangle_{\text{ren}} + \sum_{i \geq 2} c_i \langle \overline{K}^0 | O_{MIX,i} | K^0 \rangle_{\text{ren}}$$

These operators, of course, have a different chiral structure.

Mixing is hard to control using perturbation theory; First order chiral perturbation theory predicts that

$$\langle \overline{K}^0 | O_{VV+AA} | K^0 \rangle \propto M_\pi^2$$

and,

$$\langle \overline{K}^0 | O_{\text{THE REST}} | K^0 \rangle \propto \text{constant}$$

small enough mass, wrong chirality operators will dominate.

Lack of chiral symmetry becomes a fine-tuning problem!
EXACT CHIRAL SYMMETRY ON THE LATTICE

Conventional fermions do not preserve chiral-flavor symmetry on the lattice (Nielsen - Ninomiya Theorem) \( \Rightarrow \Delta S = 1, \Delta I = 1/2 \) case mixing with lower dim. (power-divergent) operators & or mixing of 4-quark operators with wrong chirality ones makes lattice study of \( K - \pi \) physics virtually impossible.

**Domain Wall Fermions**  (Kaplan, Shamir, Narayanan and Neuberger)

![Domain Wall Fermions Diagram](diagram.png)

Practical viability of DWF for QCD demonstrated (96-97) Tom Blum & A. S.
Chiral symmetry on the lattice, \( a \neq 0 \)! Huge improvement
\( \Rightarrow \) Now widespread use at BNL and elsewhere
$B_K$ with DWF’s confronts staggered fermion results

Indications are that DWQ answer is 10-15% below the old (staggered) result ⇒ tends to correspondingly increase the CP violating phase $\tilde{\eta}$ of the SM.
Expectations from the lattice for $B_K$

- Iwasaki + DWF 2+1f
- DBW2 + DWF 2f
- DBW2 + DWF 0f
- AsqTad staggered 2+1 f
- Iwasaki + DWF 0f

RBC-UKQCD
$B_K$ with DWF

$0.557 \pm 0.012 \pm 0.029$

$a^2 (\text{fm})^2$

Look forward in near future

$B_K, S_B, \xi \leq 5\%$

(IMPORTANCE OF SYMMETRIES)
Continuing Quest for $\frac{\epsilon}{\epsilon}$ for ~quarter century

Current Status & Outlook
### Final Results

<table>
<thead>
<tr>
<th>QUANTITY</th>
<th>Experiment</th>
<th>This calculation (statistical errors only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re $A_0$(GeV)</td>
<td>$3.33 \times 10^{-7}$</td>
<td>$2.96 \pm 0.17 \times 10^{-7}$</td>
</tr>
<tr>
<td>Re $A_2$(GeV)</td>
<td>$1.50 \times 10^{-8}$</td>
<td>$1.17 \pm 0.05 \times 10^{-8}$</td>
</tr>
<tr>
<td>Re $A_0/Re A_2$</td>
<td>22.2</td>
<td>25.3 $\pm$ 1.8</td>
</tr>
<tr>
<td>Re $(\epsilon'/\epsilon)$</td>
<td>$17 \pm 2 \times 10^{-4}$ (WA)</td>
<td>$-4.0 \pm 2.3 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

($\mu = 2.13$ GeV, One-loop chiral logs)

- Results show clear $\Delta I = 1/2$ enhancement!
  - (Although further scrutiny and confirmation is desirable and will be coming shortly) it certainly seems that we are very very close to putting a complete end to some 4-decades of speculation on the origin of this enhancement.
- Much more work is needed to improve our calculation of $\epsilon'/\epsilon$; discrepancy with experiment due to uncontrollable systematic
Two Key Steps

I. The $\Delta S = 1$ Effective Hamiltonian in terms of effective local four-quark operators $Q_i(\mu)$ with generic Wilson coefficients $c_i(\mu)$ including CKM factors.

$$\mathcal{H}(\Delta S=1) = \frac{G_F}{\sqrt{2}} \left\{ \sum_{i=1}^{10} c_i(\mu)Q_i(\mu) \right\}$$

II. Chiral Perturbation theory ($\chi PT$)

Significant technical difficulties associated with $|\pi\pi\rangle$, so use LO $\chi PT$ to relate physical $K \to \pi\pi$ amplitudes to unphysical $K \to \pi$ and $K \to 0$; for example:

$$\langle \pi^+\pi^-|\Theta^{(8,1)}_i|K^0\rangle = \frac{4i}{f^3} \left( m_{K^0}^2 - m_{\pi^+}^2 \right) \alpha^{(8,1)}_i$$

Here $\alpha$’s are LOW ENERGY CONSTANTS calculable on the lattice via $<\pi|\Theta|K>$, which through above eqns. give all $K \to \pi\pi$ amplitudes to leading order (LO) in $\chi PT$. 
Final values for low energy constants

<table>
<thead>
<tr>
<th>$i$</th>
<th>$\alpha_{\text{idlat}}^{(1/2)} \times 10^{-5}$</th>
<th>$\alpha_{\text{idlat}}^{(3/2)} \times 10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$-1.19(31)$</td>
<td>$-1.38(6)$</td>
</tr>
<tr>
<td>2</td>
<td>$2.22(16)$</td>
<td>$-1.38(6)$</td>
</tr>
<tr>
<td>3</td>
<td>$0.15(113)$</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>$3.55(96)$</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>$-2.97(100)$</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>$-8.12(98)$</td>
<td>0.0</td>
</tr>
<tr>
<td>7</td>
<td>$-3.22(16)$</td>
<td>$-1.61(8)$</td>
</tr>
<tr>
<td>8</td>
<td>$-9.92(54)$</td>
<td>$-4.96(27)$</td>
</tr>
<tr>
<td>9</td>
<td>$-1.85(16)$</td>
<td>$-2.07(9)$</td>
</tr>
<tr>
<td>10</td>
<td>$1.55(31)$</td>
<td>$-2.07(9)$</td>
</tr>
</tbody>
</table>

Statistical errors only, for now; work in progress to quantify systematic error.
Regarding the $\Delta I = 1/2$ Rule

<table>
<thead>
<tr>
<th>$Q_1$</th>
<th>$(3.48 \pm .77) \times 10^{-8}$</th>
<th>$(.363 \pm .016) \times 10^{-8}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_2$</td>
<td>$(24.5 \pm 1.6) \times 10^{-8}$</td>
<td>$(1.520 \pm .068) \times 10^{-8}$</td>
</tr>
<tr>
<td>$Q_6$</td>
<td>$(0.050 \pm .006) \times 10^{-8}$</td>
<td></td>
</tr>
</tbody>
</table>

$\Rightarrow Q_1/Q_2 \sim .14$

$\Rightarrow Q_6/Q_2 \leq .01$

$\Rightarrow$ For the $\Delta I = 1/2$ rule $Q_2$ [the aboriginal 4-Fermi operator] is the most important; in particular, $Q_6$ is completely negligible

$\Rightarrow$ CLEARLY Rules out SVZ conjecture at least at $\mu \approx 2$ GeV

$\Rightarrow$ Repercussions for phenomenological model calculations of $\varepsilon'/\varepsilon$. For instance, Bertolini et al “chiral quark model” use $Q_6/Q_2 \approx 20 - 30\%$. 
Results show clear $\Delta I = 1/2$ enhancement!

⇒ (Although further scrutiny and confirmation is desirable and will be coming shortly) it certainly seems that we are very very close to putting a complete end to some 4-decades of speculation on the origin of this enhancement.

• Much more work is needed to improve our calculation of $\varepsilon'/\varepsilon$. 
Source of significant quench pathology

• Quench Approx by definition ignores vac. Loops

\[ Q_6 = \bar{\psi} \gamma^m \gamma_5 \partial_\mu \gamma_5 \partial_\nu \psi \]

• \( Q_6 \sim (8,1) \) has quark loops

\[ Q_8 = \bar{\psi} \gamma^m \gamma_5 \partial_\mu \gamma_5 \partial_\nu \psi \]

• Recall \( Q_8 \sim (8,8) \)

• Even a slight mistreatment messes up the crucial (8,1) since as \( m_q \to 0 \), \( Q_6 \) should \(-\to0\) but \( Q_8 \to \) constant

Proper treatment of \( Q_6 \) demands dynamical Lattice simulations EVEN for DWQ!!
$\Delta I = 1/2$ Plateau - unsubtracted $Q_6$

Mawhinney @DWF after 10 years, March '07
ΔI = 3/2 Plateau

Mawhinney at DWF after 10 years
RBC - UKQCD DYN DWQ

Subtracting $Q_6$

Mawhinney at DWF after 10 years
Subtracted $Q_6$ Comparison

$$\langle \pi^+ | Q_i^{(1/2)} | K^+ \rangle + \eta_{1,i} (m_s + m_d) \langle \pi^+ | (\bar{s}d)_{\text{lat}} | K^+ \rangle$$

Previous Quenched  

New 2+1 Flavor

Mawhinney at DWF after 10 years
BSM implications for edm’s
Neutron EDM: a classic “null” test

- In the SM NEDM cannot arise at least to two
- loops in EW……..expect $< 10^{-31}$ ecm
- Long series of experiments now place
- a 90% CL bound, $<6.3 \times 10^{-26}$ ecm (Harris et al, ’99)
- In numerous BSM, including SUSY, Warped
- extra-dimensions, ….. neutron edm close
- to current bound is expected

SHOULD BE PURSUED with very high priority!
Top quark EDM: a clean “null” test

- Top is so heavy compared to other quarks that
- GIM mechanism is super-effective -> all SM
- CP violation effects are vanishingly small.
- As one concrete illustration is the top quark
- Electric dipole moment….In the SM you need to
- Go to 2 loops in EW
<table>
<thead>
<tr>
<th>type of moment $(e - cm)$</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>Standard Model</th>
<th>neutral Higgs $m_h = 100 - 300$</th>
<th>charged Higgs $m_{H^+} = 200 - 500$</th>
<th>Supersymmetry $m_{\tilde{g}} = 200 - 500$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\Im m(d_r^Z)</td>
<td>$</td>
<td>500</td>
<td>$&lt; 10^{-30}$</td>
<td>$(4.1 - 2.0) \times 10^{-19}$</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td></td>
<td>$(0.9 - 0.8) \times 10^{-19}$</td>
<td>$(15.7 - 1.0) \times 10^{-22}$</td>
<td>$(1.2 - 0.8) \times 10^{-19}$</td>
</tr>
<tr>
<td>$</td>
<td>\Re (d_r)</td>
<td>$</td>
<td>500</td>
<td>$&lt; 10^{-30}$</td>
<td>$(0.3 - 0.8) \times 10^{-19}$</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td></td>
<td>$(0.7 - 0.2) \times 10^{-19}$</td>
<td>$(0.3 - 2.7) \times 10^{-22}$</td>
<td>$(1.1 - 0.3) \times 10^{-19}$</td>
</tr>
<tr>
<td>$</td>
<td>\Im m(d_t^Z)</td>
<td>$</td>
<td>500</td>
<td>$&lt; 10^{-30}$</td>
<td>$(1.1 - 0.2) \times 10^{-19}$</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td></td>
<td>$(0.2 - 0.2) \times 10^{-19}$</td>
<td>$(9.2 - 1.2) \times 10^{-22}$</td>
<td>$(0.4 - 0.3) \times 10^{-19}$</td>
</tr>
<tr>
<td>$</td>
<td>\Re (d_t^Z)</td>
<td>$</td>
<td>500</td>
<td>$&lt; 10^{-30}$</td>
<td>$(1.6 - 0.2) \times 10^{-19}$</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td></td>
<td>$(0.2 - 1.4) \times 10^{-19}$</td>
<td>$(0.6 - 1.9) \times 10^{-22}$</td>
<td>$(0.4 - 0.1) \times 10^{-19}$</td>
</tr>
</tbody>
</table>
Table 5: Attainable 1-σ sensitivities to the CP-violating dipole moment form factors in units of $10^{-18}$ e-cm, with ($P_e = \pm 1$) and without ($P_e = 0$) beam polarization. $m_t = 180$ GeV. Table taken from [175].

<table>
<thead>
<tr>
<th></th>
<th>$20 \text{ fb}^{-1}, \sqrt{s} = 500$ GeV</th>
<th>$50 \text{ fb}^{-1}, \sqrt{s} = 800$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_e = 0$</td>
<td>$P_e = +1$</td>
</tr>
<tr>
<td>$\delta(\text{Re}d_{t}^f)$</td>
<td>4.6</td>
<td>0.86</td>
</tr>
<tr>
<td>$\delta(\text{Re}d_{t}^{Z})$</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>$\delta(\Im d_{t}^f)$</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>$\delta(\Im d_{t}^{Z})$</td>
<td>7.3</td>
<td>2.0</td>
</tr>
</tbody>
</table>

PHY. Rep. "CPV in top-quark Physics"
Atwood, Barshalom, Eilam + A.S.
Summary & Outlook

• Asym. B factories + Lattice -> KM phase is the dominant contributor to observed CP

• Search for BSM-CP-odd phase imposes greater demands of precision on expt. & on theory

• $\Delta S$ test of the CKM-paradigm extremely tantalizing with $\sim 2.5 \sigma$ deviations.

• Given that such effects occur quite naturally in most BSMs the expt. situation needs to be clarified at the highest priority.

• Most of the BSMs also exhibit nedm $\sim 10^{-26}$ ecm & tedm $\sim 10^{-19}$ ecm; should pursue both vigorously.