CP Violation: SM & Beyond

Amarjit Soni
HET,BNL
(soni@bnl.gov)

YITP@40

*Outline**

- I. (since ~’01) B-factories +lattice (WME) help us attain an important milestone
- II. (since ~’05) improved BF tests

  are revealing interesting hints of BSM-CP-odd phase(s) *
- III..**Whodunit ?** $\cancel{\theta}$

I. A tale of two numbers

I. $S_{BF}(t)\,[B^0 \to \text{"}\psi\text{"}\,K_s] \Rightarrow \sin 2\beta|_{BF} = .674 \pm .026$

$$\text{II.}\ \left.\begin{array}{l} \text{a)}\ \epsilon_K + B_K \\ \text{2)}\ \text{"}f_B\text{"} + B_d\text{-}\bar{B}_d\ (\text{also } B_s) \\ \text{3)}\ \dfrac{b \to u e \nu}{b \to c e \nu} \\ \text{- - - - - -} \end{array}\right\} \sin 2\beta|_{SM} = .79 \pm .10$$

Lightning recap to SM-CKM paradigm of CPV

~1% $\lambda = .2257 \pm .0021$

~2% $A = .818^{+.007}_{-.017}$

CKM unitary matrix

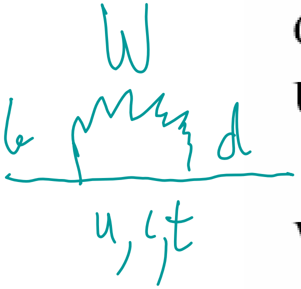
CKM matrix relates weak and mass eigenstates of quarks

Four physical parameters; fundamental constants of the SM

Complex elements allow (only source of) CP violation in SM

25% $\rho \sim .22$

20% $\eta \sim .34$

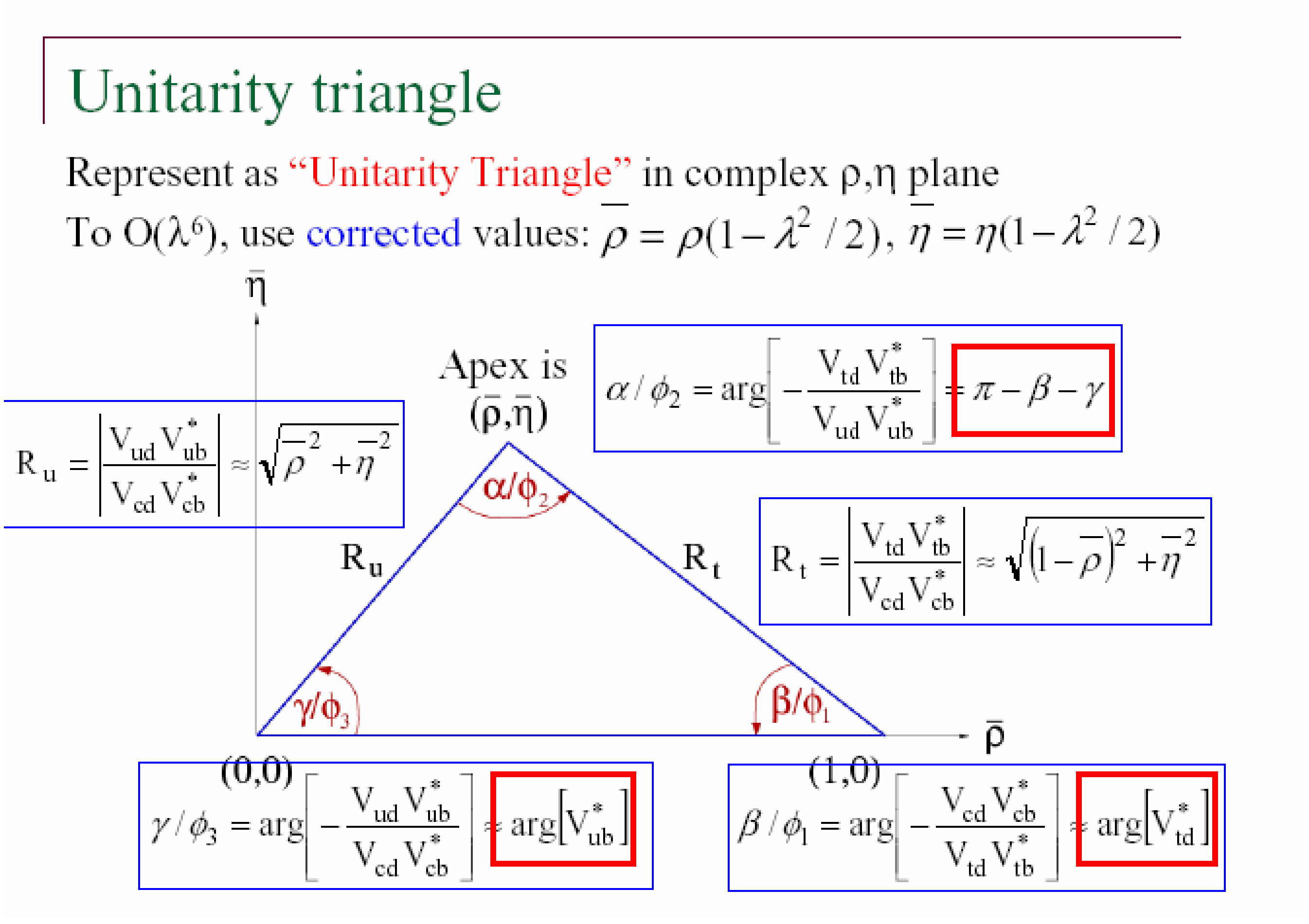


$\Rightarrow$ Unitary means $V_{ud}\boxed{V_{ub}^{*}} + V_{cd}V_{cb}^{*} + \boxed{V_{td}}V_{tb}^{*} = 0$

Wolfenstein expansion (A~0.82, λ~0.23, ρ, η) in powers of λ:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & \boxed{A\lambda^3(\rho - i\eta)} \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ \boxed{A\lambda^3(1-\rho-i\eta)} & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Only two complex elements to this order; both small ~λ^3



Unitarity triangle

Represent as “Unitarity Triangle” in complex ρ,η plane

To O(λ^6), use corrected values: $\overline{\rho} = \rho(1-\lambda^2/2)$, $\overline{\eta} = \eta(1-\lambda^2/2)$

$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| \approx \sqrt{\overline{\rho}^2 + \overline{\eta}^2}$$

$$\alpha/\phi_2 = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] = \boxed{\pi - \beta - \gamma}$$

$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| \approx \sqrt{(1-\overline{\rho})^2 + \overline{\eta}^2}$$

$$\gamma/\phi_3 = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right] \boxed{\approx \arg\left[V_{ub}^*\right]}$$

$$\beta/\phi_1 = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \boxed{\approx \arg\left[V_{td}^*\right]}$$

Youngjoon Kwon

Why Lattice is Needed

Due to the non-perturbative nature of low energy QCD, many experimental results, often attained at enormous cost cannot be used effectively to test the Standard Model unless accurate values of hadronic matrix elements are known; lattice is the only reliable tool for such calculations

$\langle K | [\bar{s} \gamma_\mu (1-\gamma_5) d]^2 | \bar{K} \rangle / \frac{8}{3} f_K^2 m_K^2$

$|\varepsilon_K|$ (BNL '64; Christenson et al), provides a CLASSIC EXAMPLE.

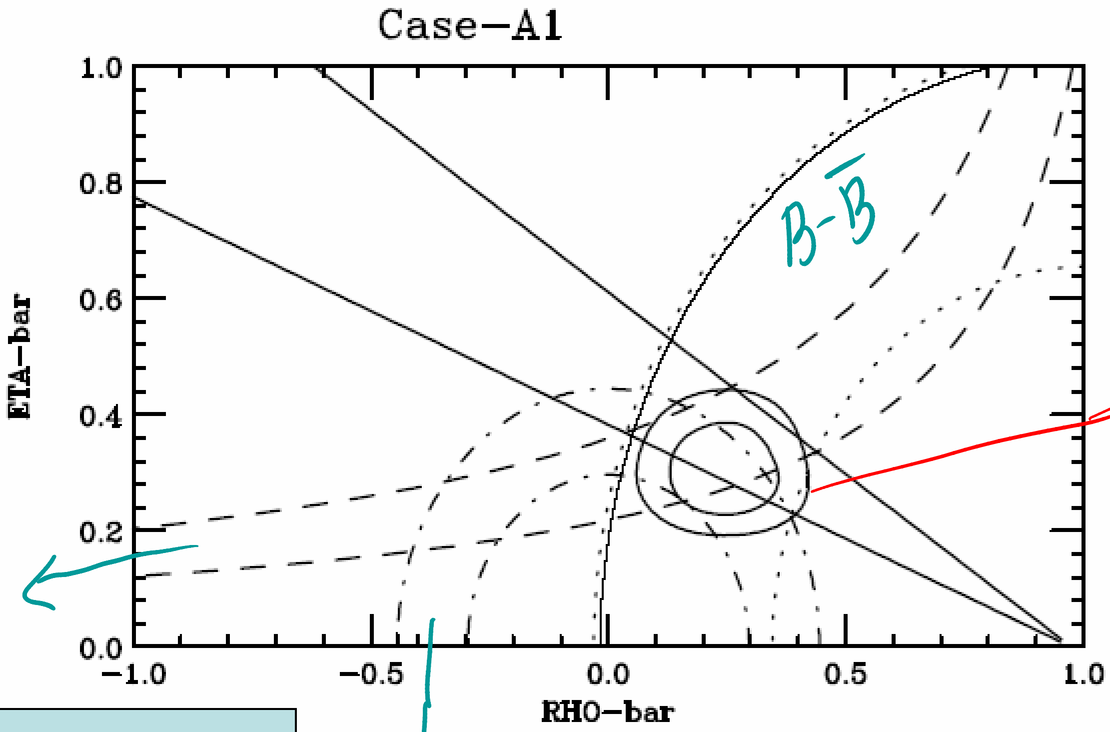
$$|\varepsilon_K| = \hat{B}_K C_K \lambda^6 A^2 \bar{\eta} \{ \eta_1 S(x_c) + \eta_2 S(x_t) [A^2 \lambda^4 (1-\bar{\rho})] + \eta_3 S(x_c, x_t) \} \qquad C_K = \frac{G_F^2 f_K^2 m_K m_W^2}{6\sqrt{2}\pi^2 \Delta m_K}$$

$\varepsilon_K = \# \, \eta \, B_K$

The experimentally known value $|\varepsilon_K| = 2.27 \times 10^{-3}$ can be used to extract information on the poorly known SM parameters $\bar{\rho}$ and $\bar{\eta}$, once the non-perurbative quantity, B_K becomes known, as everything else on the RHS is known quite well.

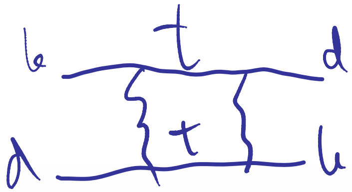
1^{st} Hints of confirmation Of CKM-CP violation

Atwood&A.S,
hep-ph/0103197



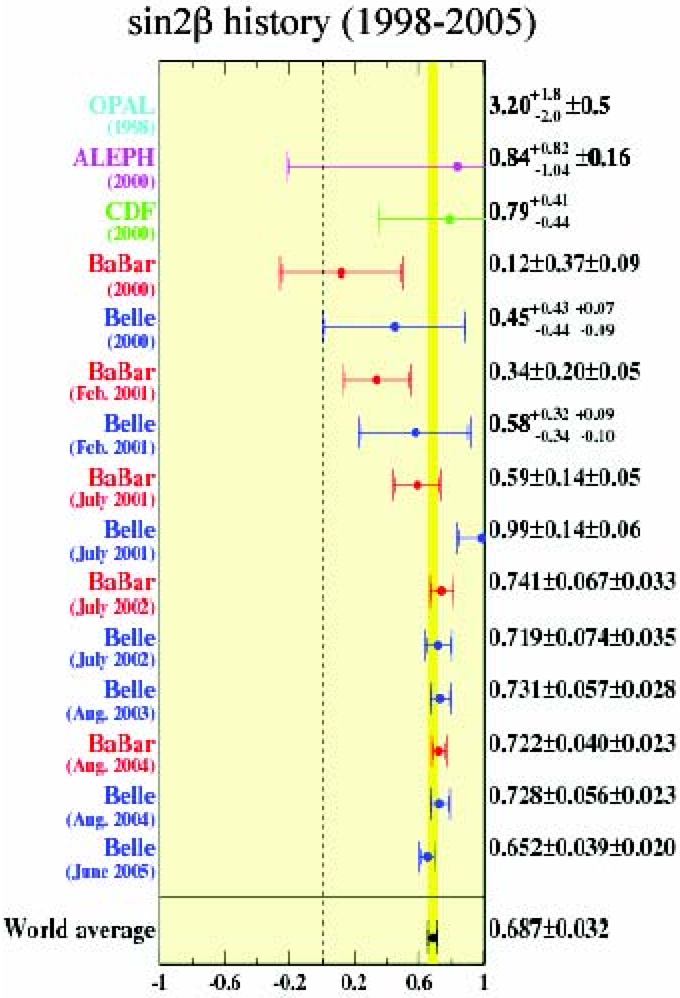
Most bands due
To theory errors

MEASUREMENT of $\beta(\phi_1)$

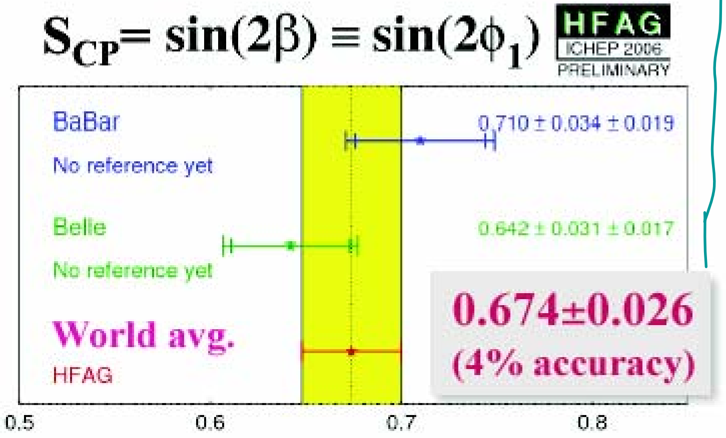


$10+5K

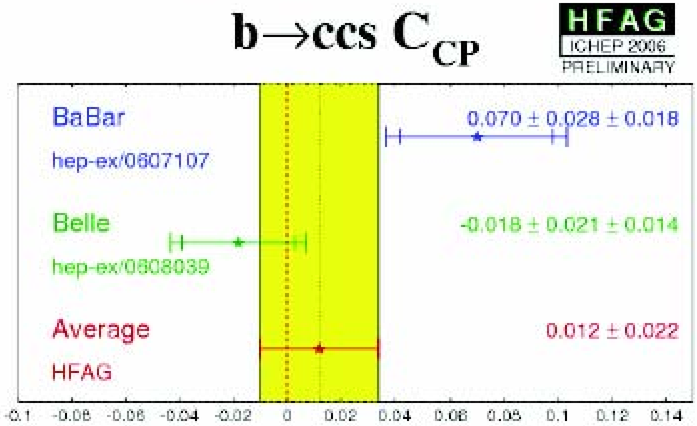
M-y


sin2β history (1998-2005)

2006 BaBar + Belle


$S_{CP} = \sin(2\beta) \equiv \sin(2\phi_1)$

0.674±0.026 (4% accuracy)


$b \to c\bar{c}s$ C_{CP}

SM $\sin 2\beta = .79 \pm .10$

Youngjoon Kwon

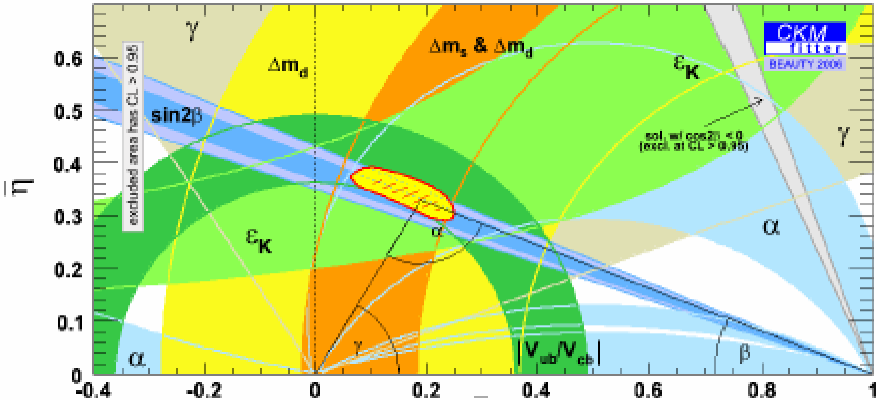
Overall CKM agreement

$S(t)(B^0 \to \psi K_S) \sim 70\%$

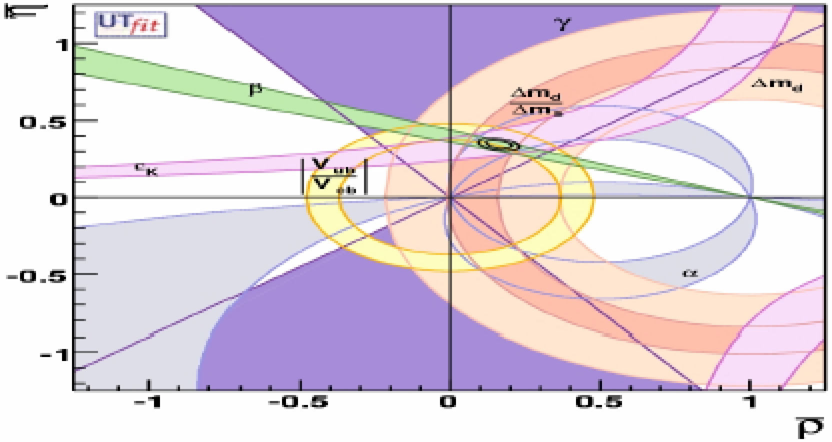
Frequentist

$\epsilon_K (K_L \to \pi\pi) \sim 10^{-3}$

BOTH Accounted by the KM phase!!



Bayesian

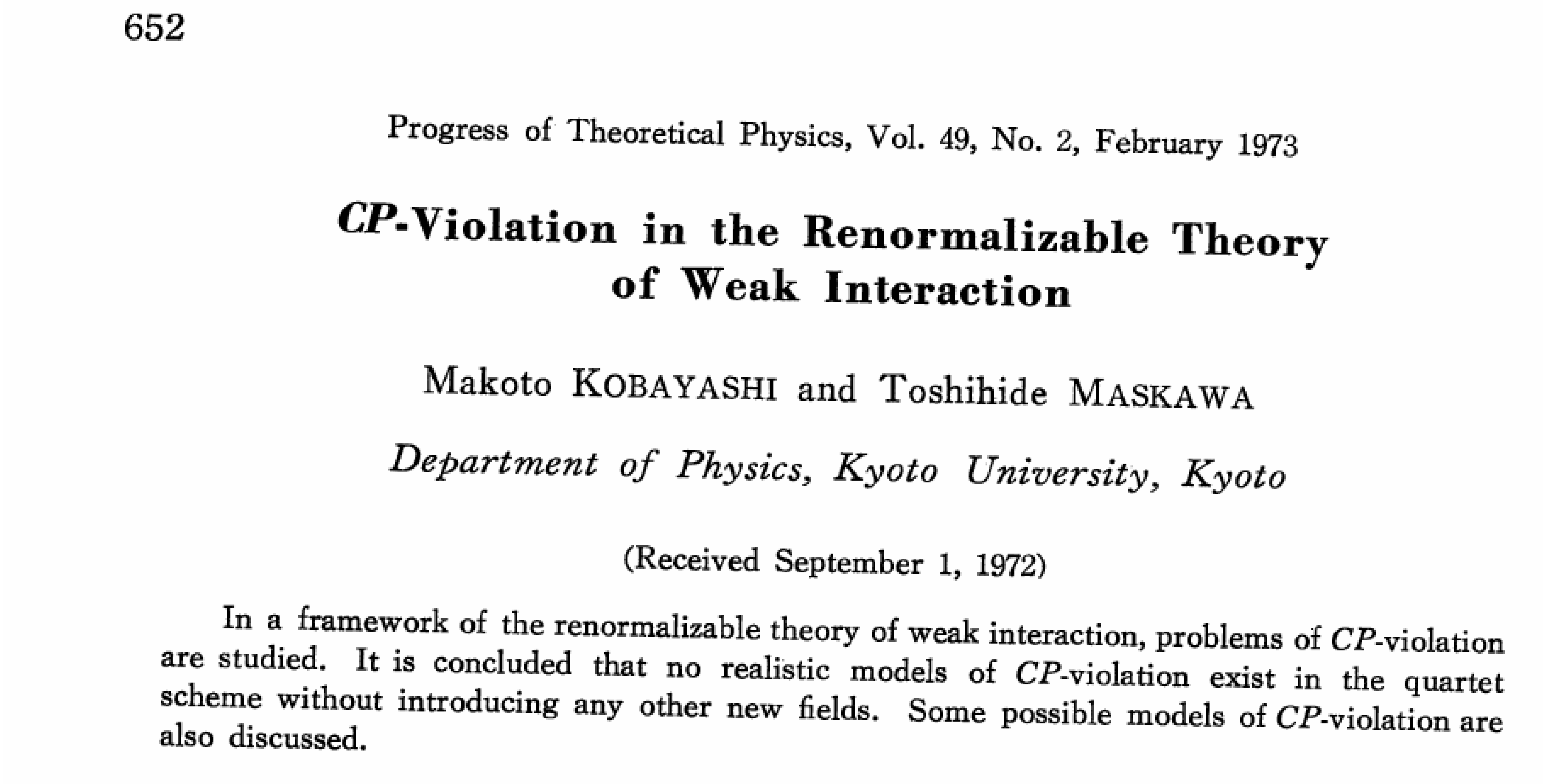


Conclusion is the same:

All measurements agree with SM picture of CKM matrix within errors

Youngjoon Kwon

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!!



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

CP-Violation in the Renormalizable Theory of Weak Interaction

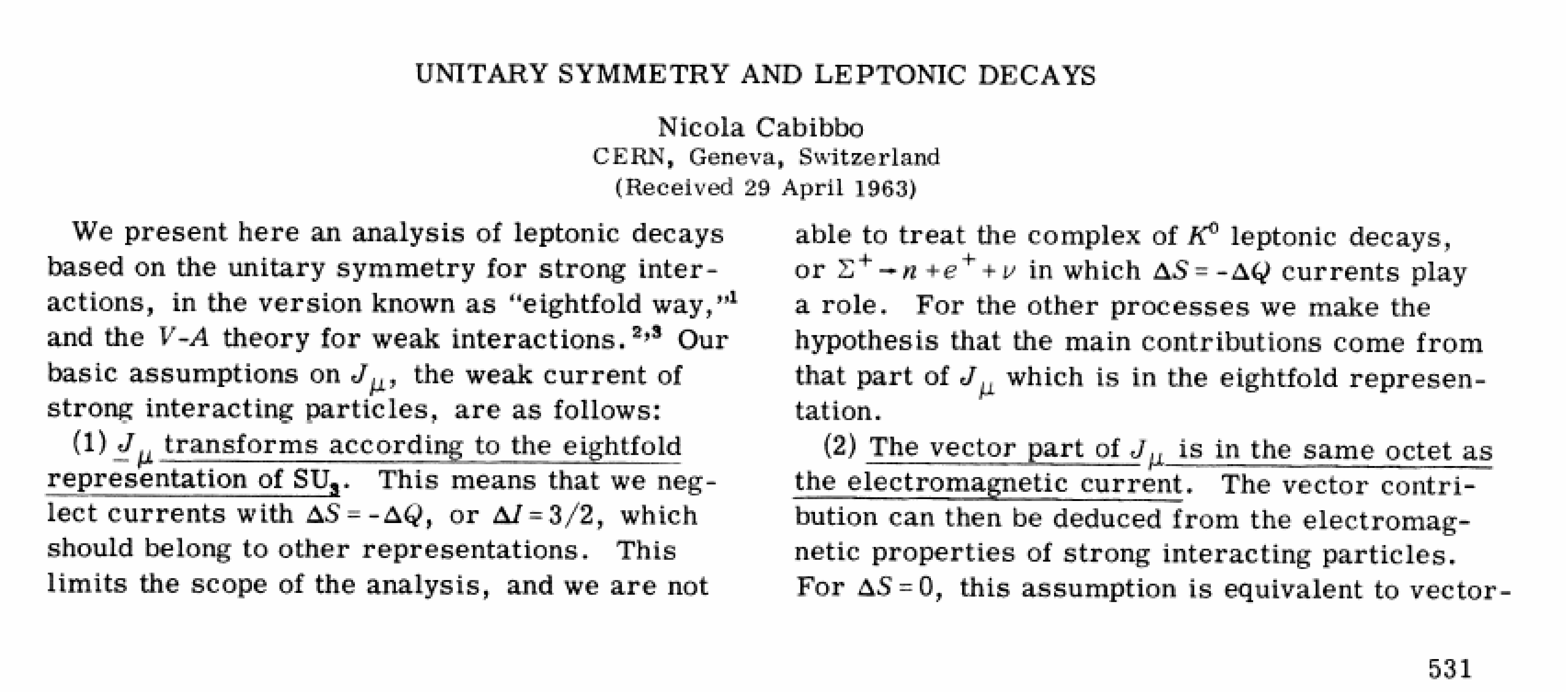
Makoto KOBAYASHI and Toshihide MASKAWA

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.

And of course we must not forget the C!



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 "eightfold way,"[1] and the V-A theory for weak interactions.[2,3] Our basic assumptions on J_μ, the weak current of strong interacting particles, are as follows:

(1) J_μ 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 $\Sigma^+ \to n + e^+ + \nu$ 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_μ which is in the eightfold representation.

(2) The vector part of J_μ 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 ε_K***
- Its extremely important to reflect on the severe and tragic consequences if

Cronin et al had decided in 1963 that O(10%) searches for ε 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_ν

Just as there was never any good reason for $m_\nu = 0$ there is none for BSM-CP-odd phase not to exist

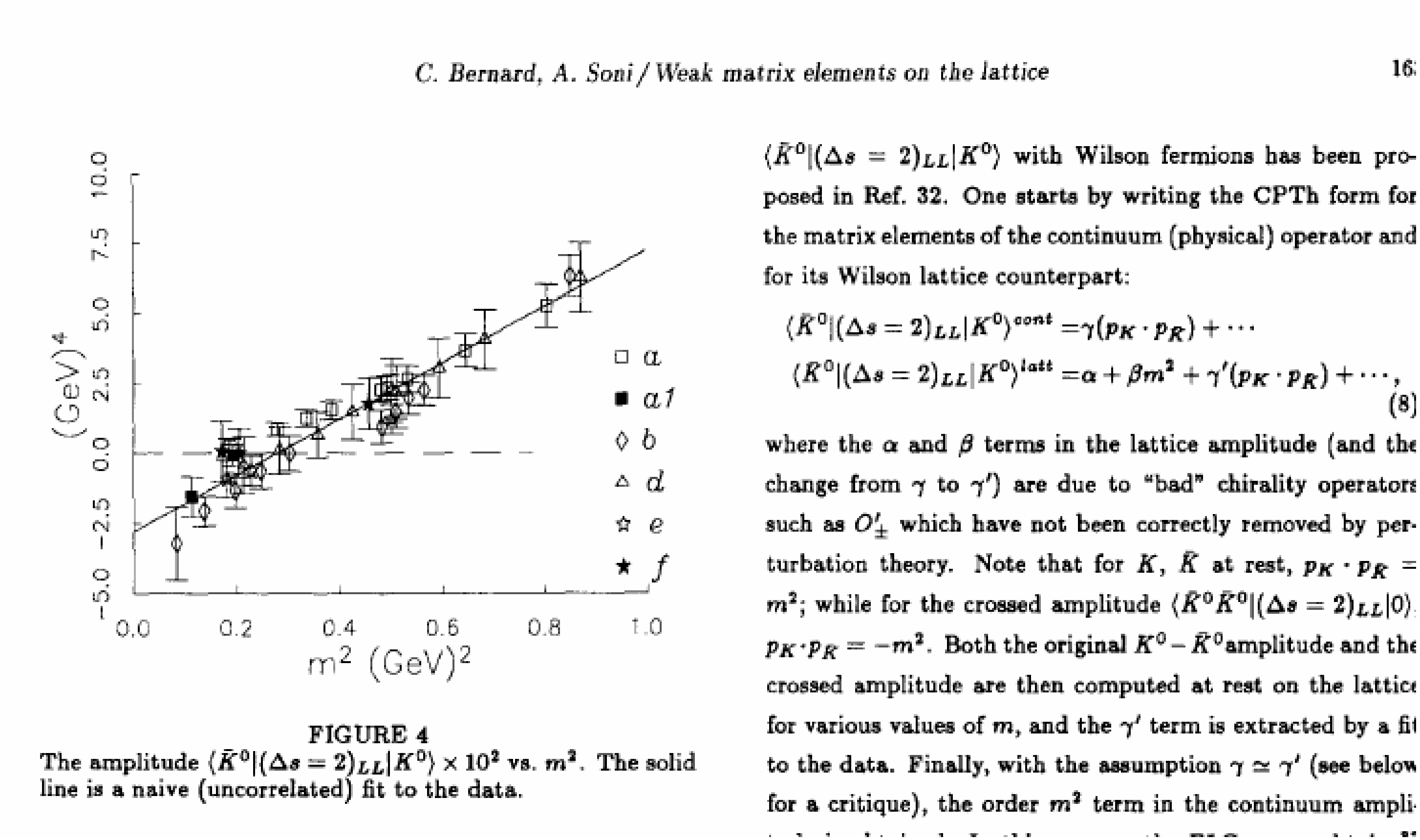
$\Delta m^2 \sim 1\,\mathrm{eV}^2$ ~ 1980 -> $\Delta m^2 \sim 10^{-4}\,\mathrm{eV}^2$ …'97

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

~25 years of B_K



C. Bernard, A. Soni / Weak matrix elements on the lattice 16

FIGURE 4

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

$\langle \bar K^0|(\Delta s = 2)_{LL}|K^0\rangle$ 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:

$$\langle \bar K^0|(\Delta s=2)_{LL}|K^0\rangle^{cont} = \gamma(p_K\cdot p_{\bar K}) + \cdots$$
$$\langle \bar K^0|(\Delta s=2)_{LL}|K^0\rangle^{latt} = \alpha + \beta m^2 + \gamma'(p_K\cdot p_{\bar K}) + \cdots, \quad (8)$$

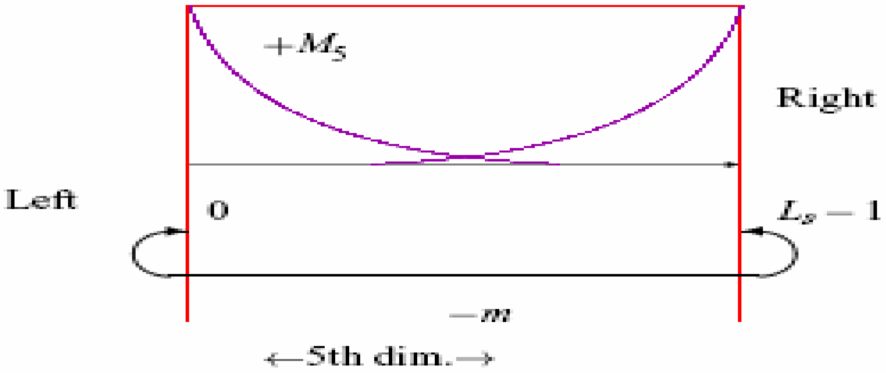
where the α and β terms in the lattice amplitude (and the change from γ to γ') are due to "bad" chirality operators such as $O'_\pm$ which have not been correctly removed by perturbation theory. Note that for K, $\bar K$ at rest, $p_K\cdot p_{\bar K} = m^2$; while for the crossed amplitude $\langle \bar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

Bernard & A.S.
Lattice ‘88

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)

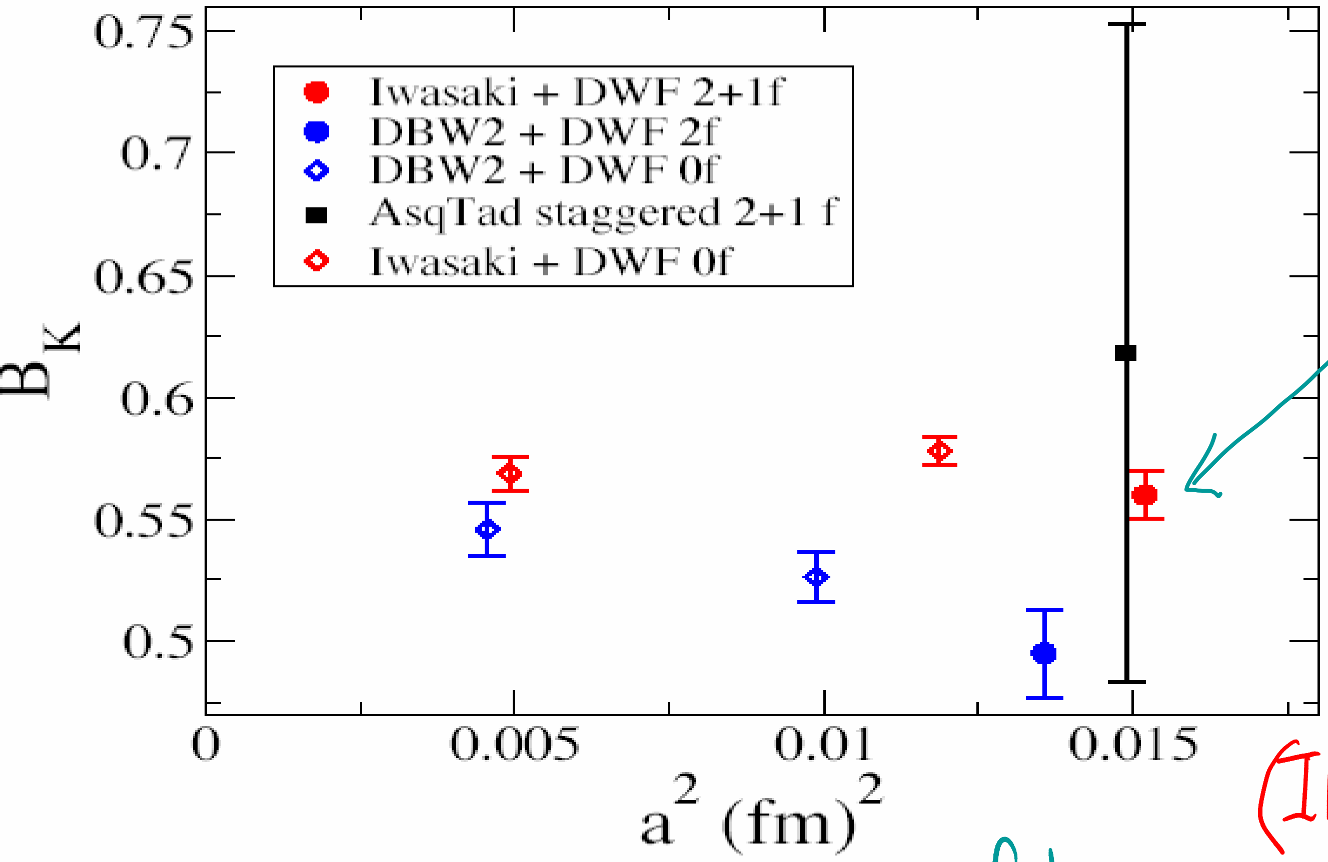


Practical viability of DWF for QCD demonstrated (96-97) Tom Blum & A. S.

Chiral symmetry on the lattice, $a \neq 0$! Huge improvement

$\Rightarrow$ Now widespread use at BNL and elsewhere

Expectations from the lattice for B_K



RBC-UKQCD

B_K with DWQ

hep-ph/0702042

$.557 \pm .012 \pm .029$

2%

5%

(IMPORTANCE of SYMMETRIES)

LOOK forward in Near future

$B_K, f_B, \xi, \ldots < 5\%$

Brief (~25 years) History of B_K

, ~’83 DGH use K^+ lifetime + LOChPT + SU(3)->
B_K ~0.33… no error estimate, no scale dependence… UNCONTROLLABLE APPROXIMATION

~’84 Lattice method for WME born…many attempts & improvements for B_K evaluations

~’98 JLQCDstaggered B_K (2GeV)= 0.628(42)quenched(~110).

~’97 1st B_K with DWQ(T.Blum&A.S),0.628(47) quenched.

~’01 RBC B_K with DWQ, quenched=0.532(11) quenched

~’05 RBC , nf=2, dyn. DWQ, B_K =0.563(21)(39)(30)

~’06 Gimnez et al (HPQCD; stagg.) 2+1, B_K =0.618(18)(19)(30)(130)

~07,RBC-UKQCD DWQ 2+1 …..0.557(12)(29)

DWQ lower B_K -> requiring larger CKM-phase

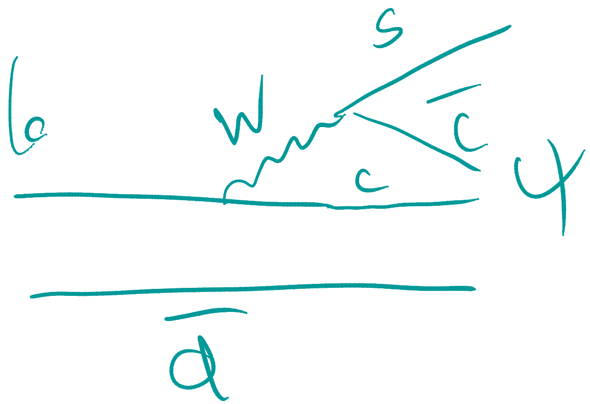
~’08 Target 2+1 dyn. DWQ, B_K with total error 5%

II. A tale of four numbers

- **Tantalizing (possible) signs of a BSM-CP-odd phase**

$$\Delta S \equiv S_{penguin} - S_{\psi K_S} = O(\lambda^2)$$

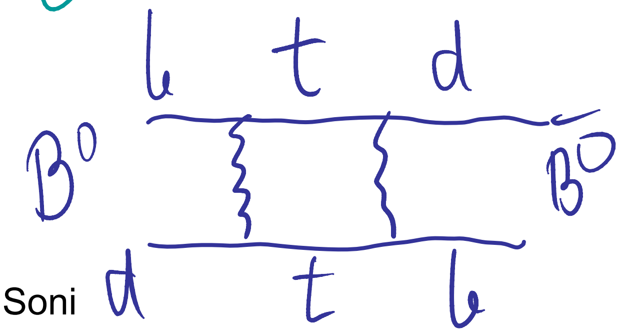
$$S^{Decay}_{peng} \simeq O(\lambda^2) \sim few\%$$



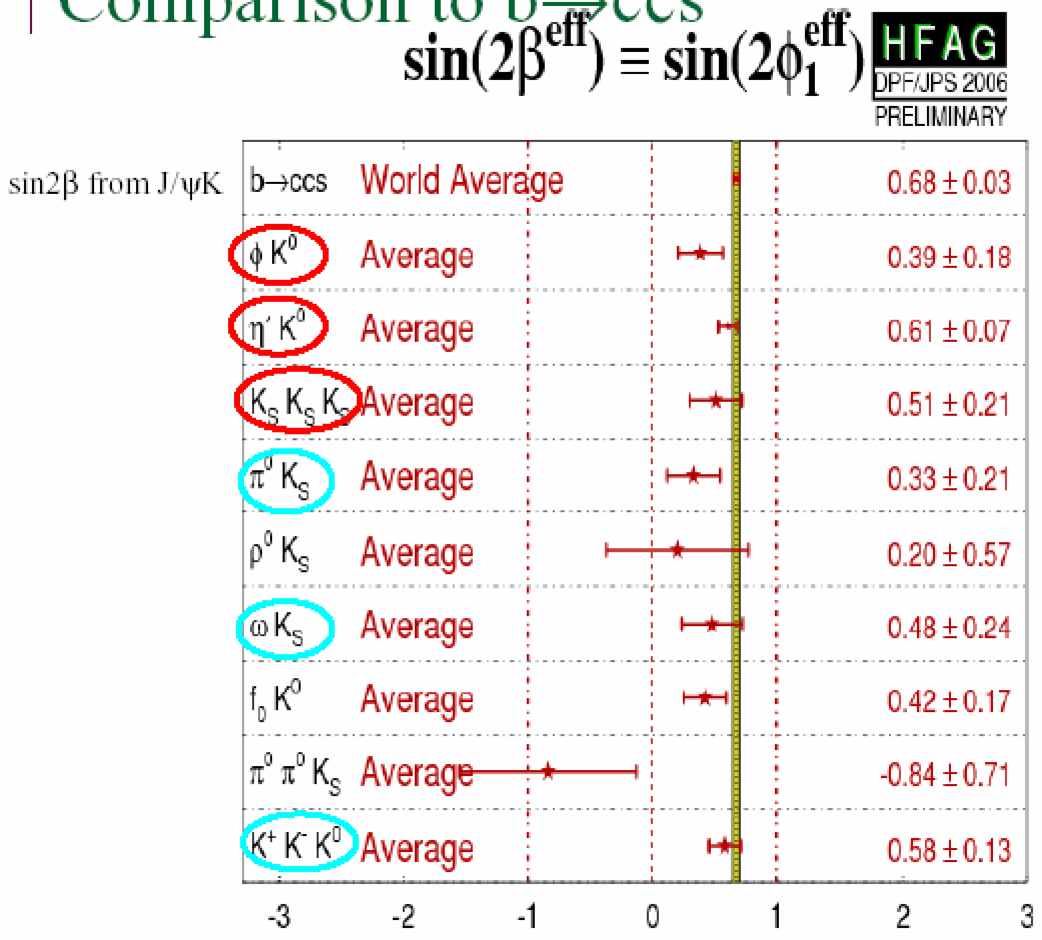
$$S^{Decay}_{\psi K_S} = 0$$

Grossman & Worah PLB'97;
London and A.S. PLB'97

OSC is
COMMON



Comparison to b→$c\bar{c}s$



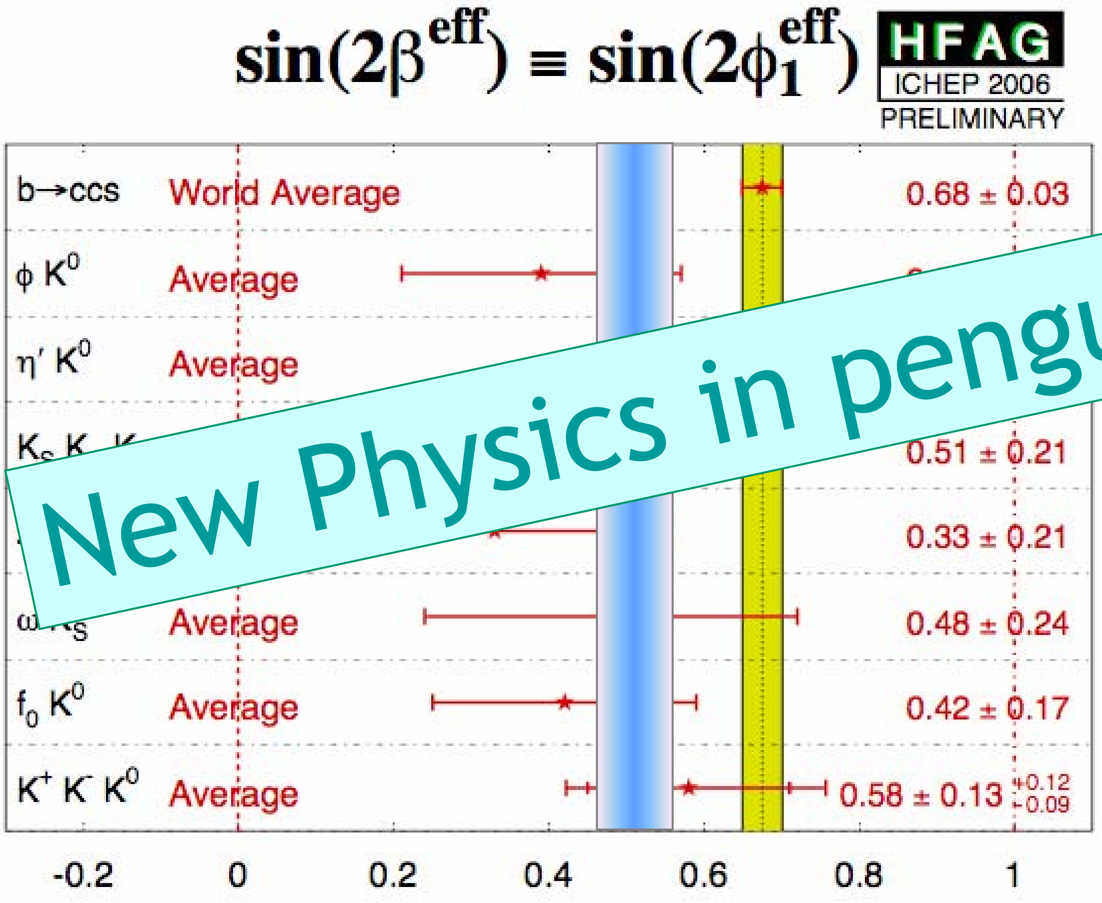
INTRIGUING!

NP?
More
data
needed!

ALL Penguin Measurements are < ψKs Measurement

Youngjoon Kwon; c also
Matthias Neubert

Current situation



New Physics in penguin processes?

- Reference value reduced to 0.68
- A odes increased to

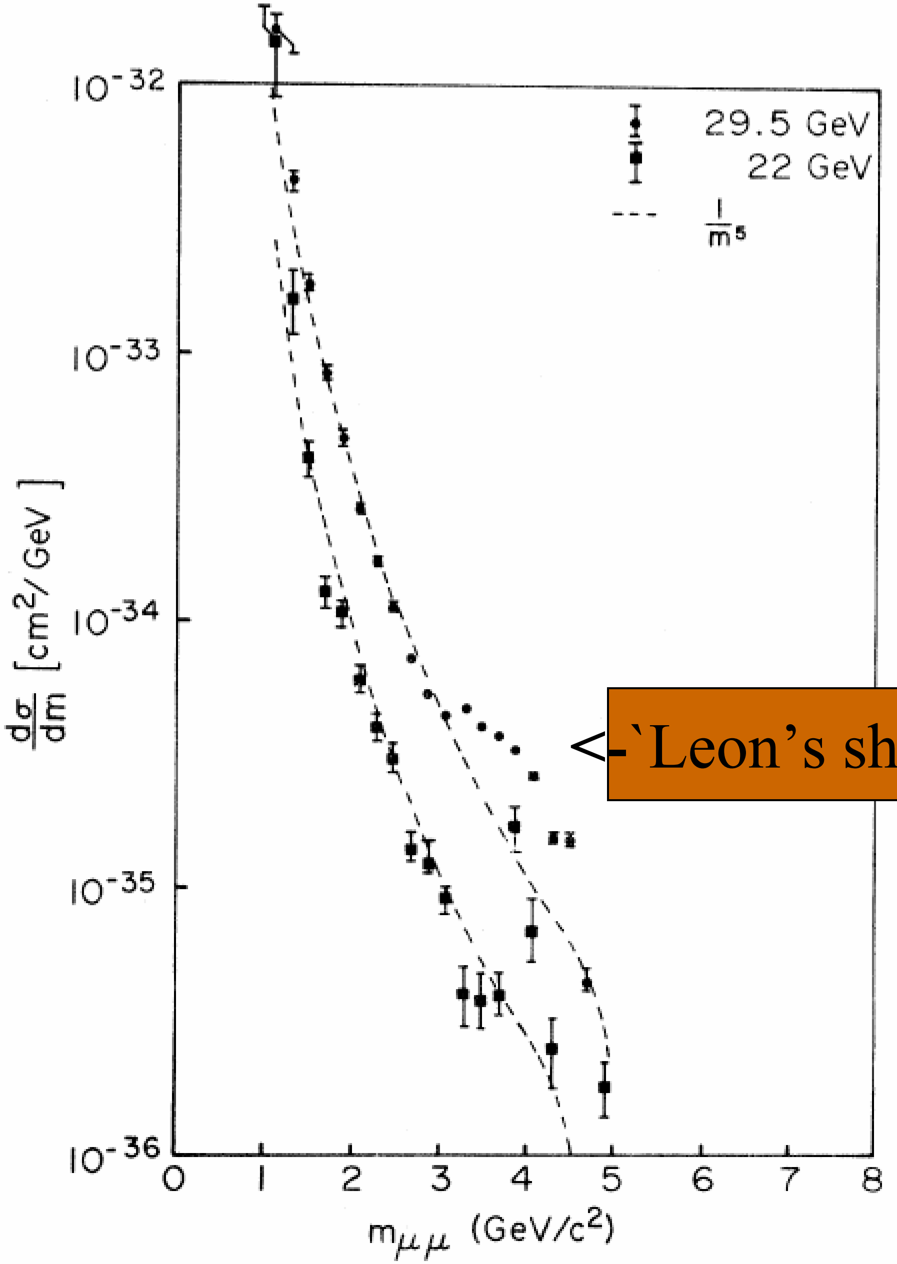
0.52±0.05

- Deviation reduced to 2.8σ ☹

Matthias Neubert

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.

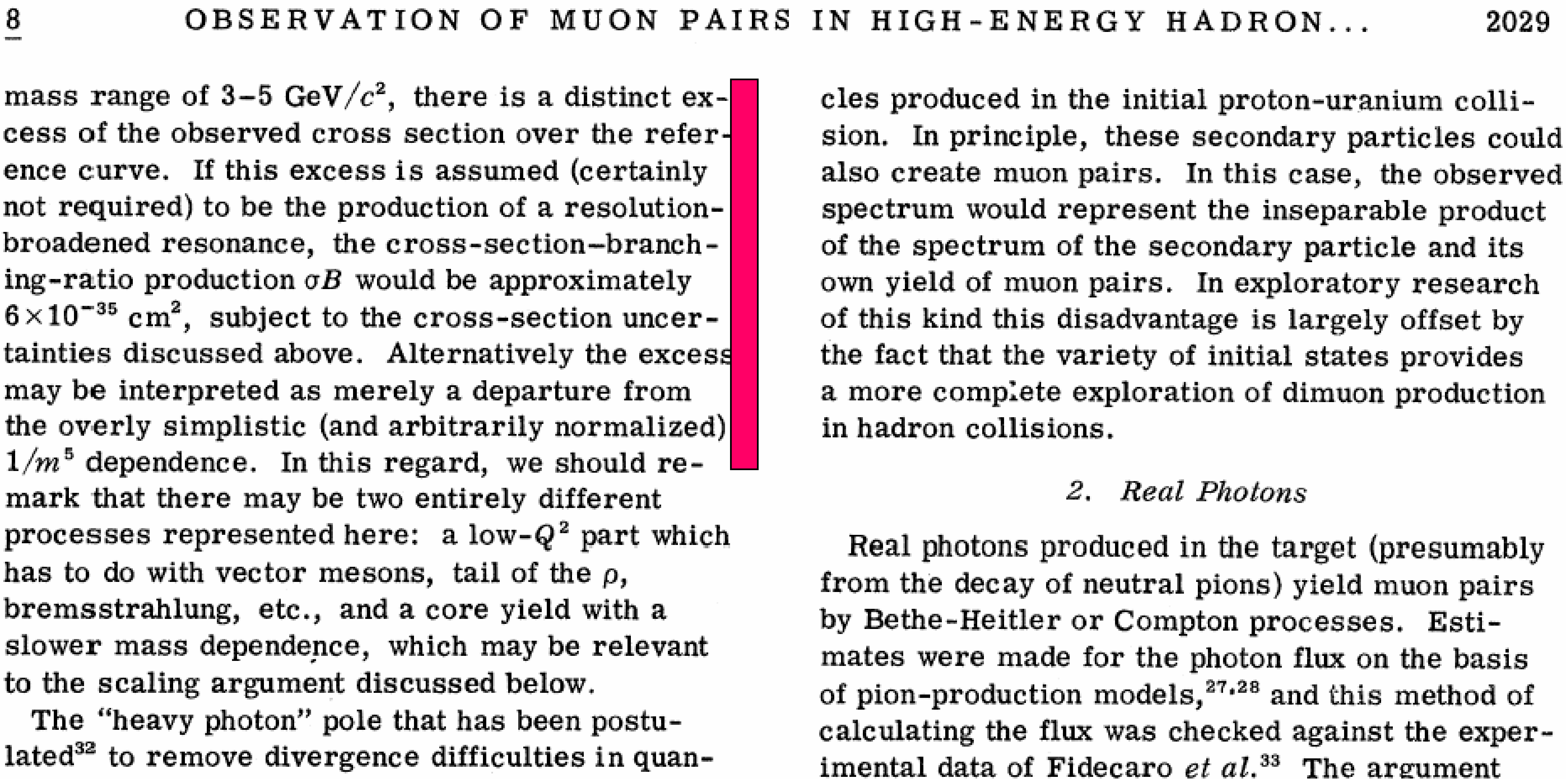
It is extremely important to understand that basically it is a very good test of the SM.



<-`Leon’s shoulder

FIG. 15. Experimental cross sections at two energies compared with a simple $1/m^5$ continuum.

Christenson,Hicks,Lederman,Limon,Pope & Zavattini
PRD 8,2016 ‘72



mass range of 3–5 GeV/c^2, 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 σB would be approximately 6×10^{-35} cm^2, 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 ρ, 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[32] to remove divergence difficulties in quan-

cles 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,[27,28] and this method of calculating the flux was checked against the experimental data of Fidecaro *et al.*[33] The argument

So far 3 numbers

- Expt [ε_K , B-mixing, b->uev…] + Lattice WME -> $\sin 2\beta_{SM}$ =0.79+-0.10
- BF measurements [B -> “ψ” K_S]=0.674+-0.026
- BF measurements [B-> (φ, η’…) K_S]=0.52+-.05

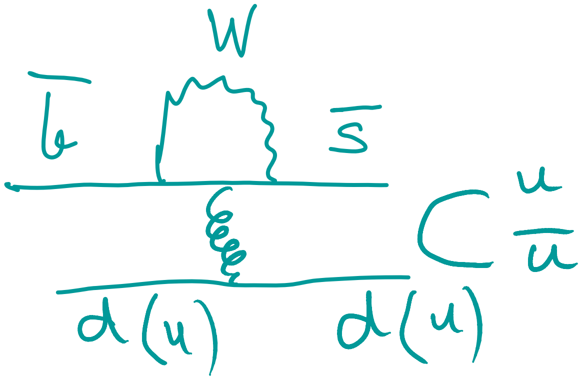
- ***-> Deviations 2.8 -3.5 sigmas***

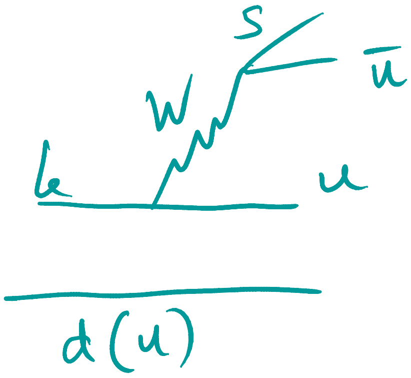
Last but quite significant

$$A_{CP}(B^0 \to K^+\pi^-) = -9.7 \pm 1.2\,\%$$

$$A_{CP}(B^+ \to K^+\pi^0) = 4.7 \pm 2.6\,\%$$

$$\Delta A_{CP} = (14.4 \pm 2.9)\,\% \quad !!!$$





4th Imp. #

WHODUNIT?

Honest answer &

- Don’t really know (too many possibilities…)
- But theoretically the most interesting possibility is that we may be witnessing

  Dawning of the age of

“Warped Quantum Flavordynamics”

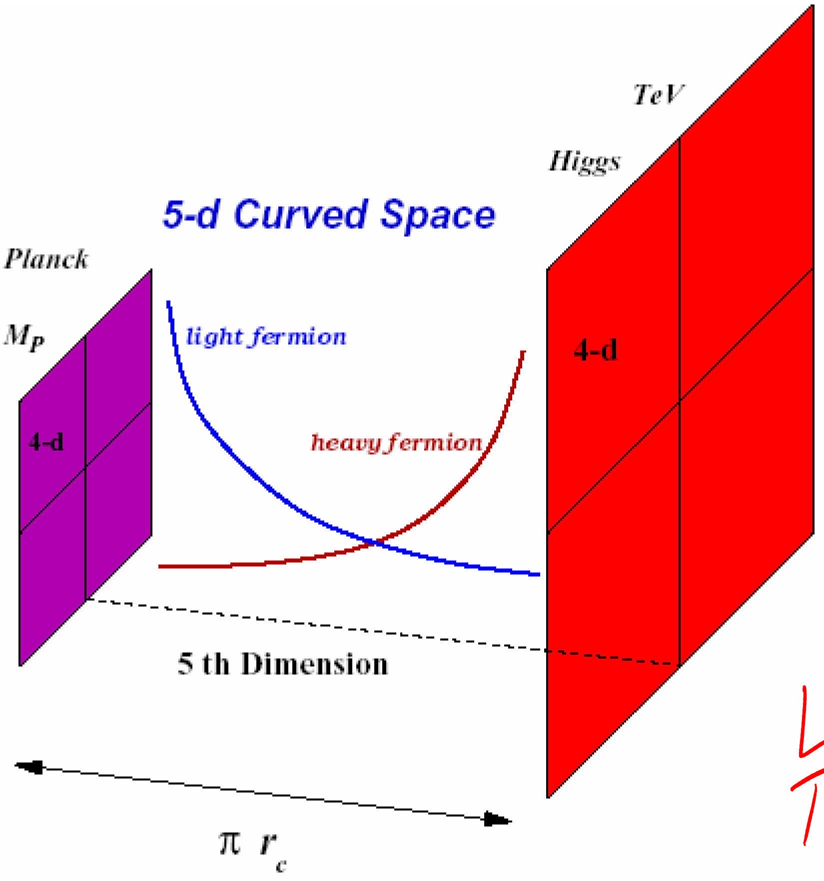
B-Factory Signals for a WED

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

- RS 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.

G+N;
G+P

[FIG BY H DAVOUDIASL]



$$ds^2 = e^{-2\sigma} \eta_{\mu\nu} dx^\mu dx^\nu - r_c^2 d\phi^2$$

$$\langle H_4 \rangle = e^{-\sigma} \langle H_5 \rangle$$

$$\sigma = \underbrace{k r_c}_{\sim 12} \pi$$

TeV

M_P

Figure 1: Warped geometry with flavor from fermion localization. The Higgs field resides on the TeV-brane. The size of the extra dimension is $\pi r_c \sim M_P^{-1}$.

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.

NP Contributions due WED

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.

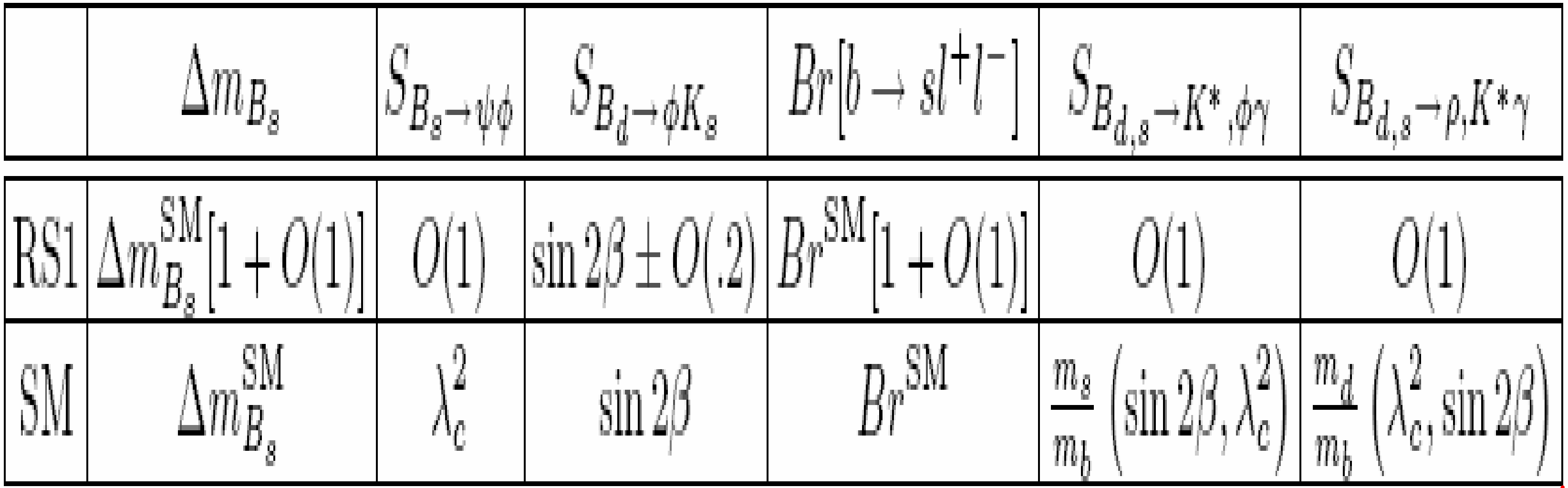
ii) Contributions to FCNC processs (mostly semi-leptonic)

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

Contrasting B-Factory Signals from WED with those from SM

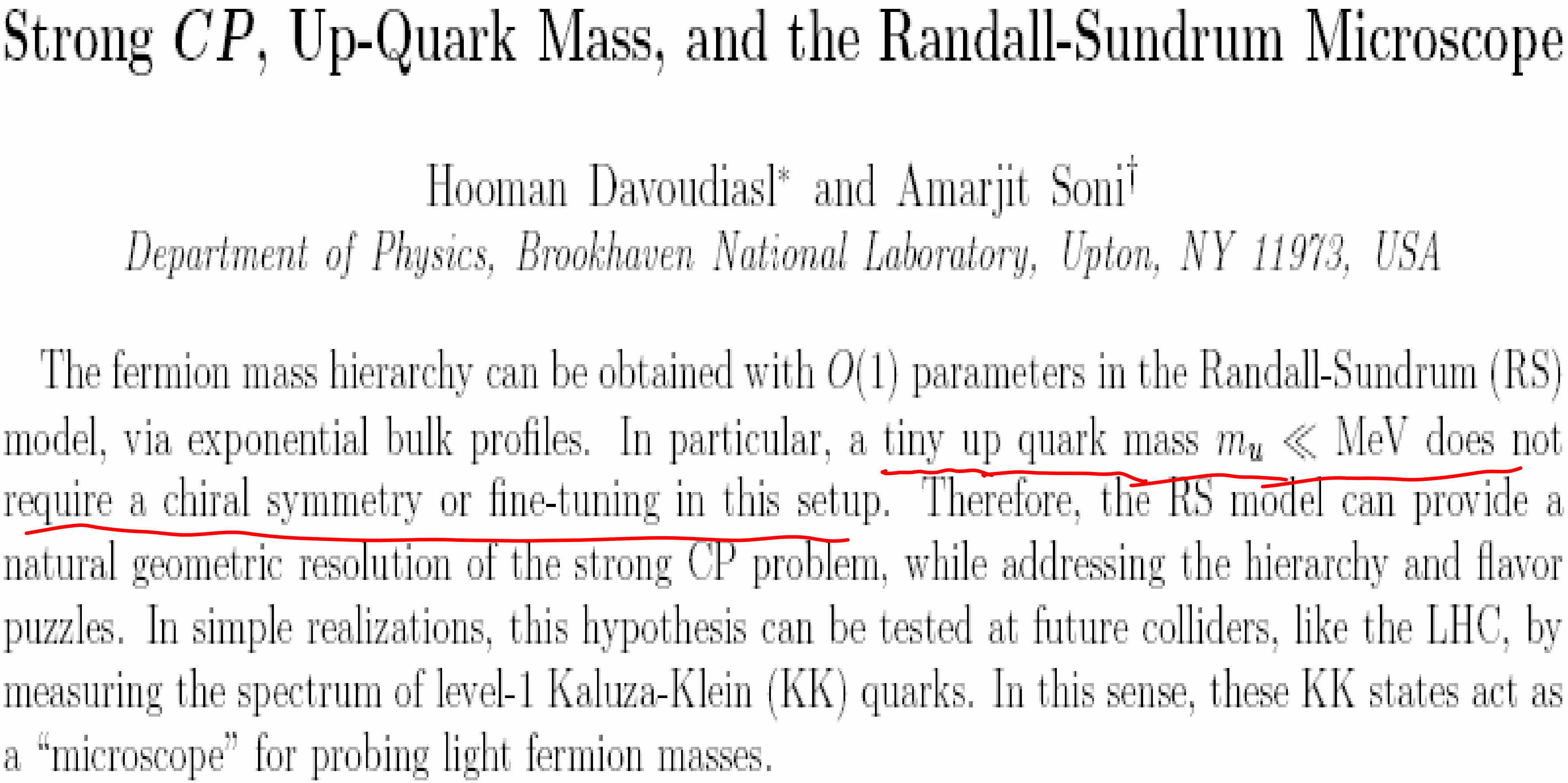


	Δm_{B_s}	$S_{B_s\to\psi\phi}$	$S_{B_d\to\phi K_s}$	$Br[b\to s l^+ l^-]$	$S_{B_{d,s}\to K^*,\phi\gamma}$	$S_{B_{d,s}\to\rho,K^*\gamma}$
RS1	$\Delta m_{B_s}^{SM}[1+O(1)]$	$O(1)$	$\sin 2\beta \pm O(.2)$	$Br^{SM}[1+O(1)]$	$O(1)$	$O(1)$
SM	$\Delta m_{B_s}^{SM}$	λ_c^2	$\sin 2\beta$	Br^{SM}	$\frac{m_s}{m_b}\left(\sin 2\beta, \lambda_c^2\right)$	$\frac{m_d}{m_b}\left(\lambda_c^2, \sin 2\beta\right)$

MODELS ARE NOT YET Developed to be precise.

$[\theta G_{\mu\nu} \tilde{G}^{\mu\nu}]$

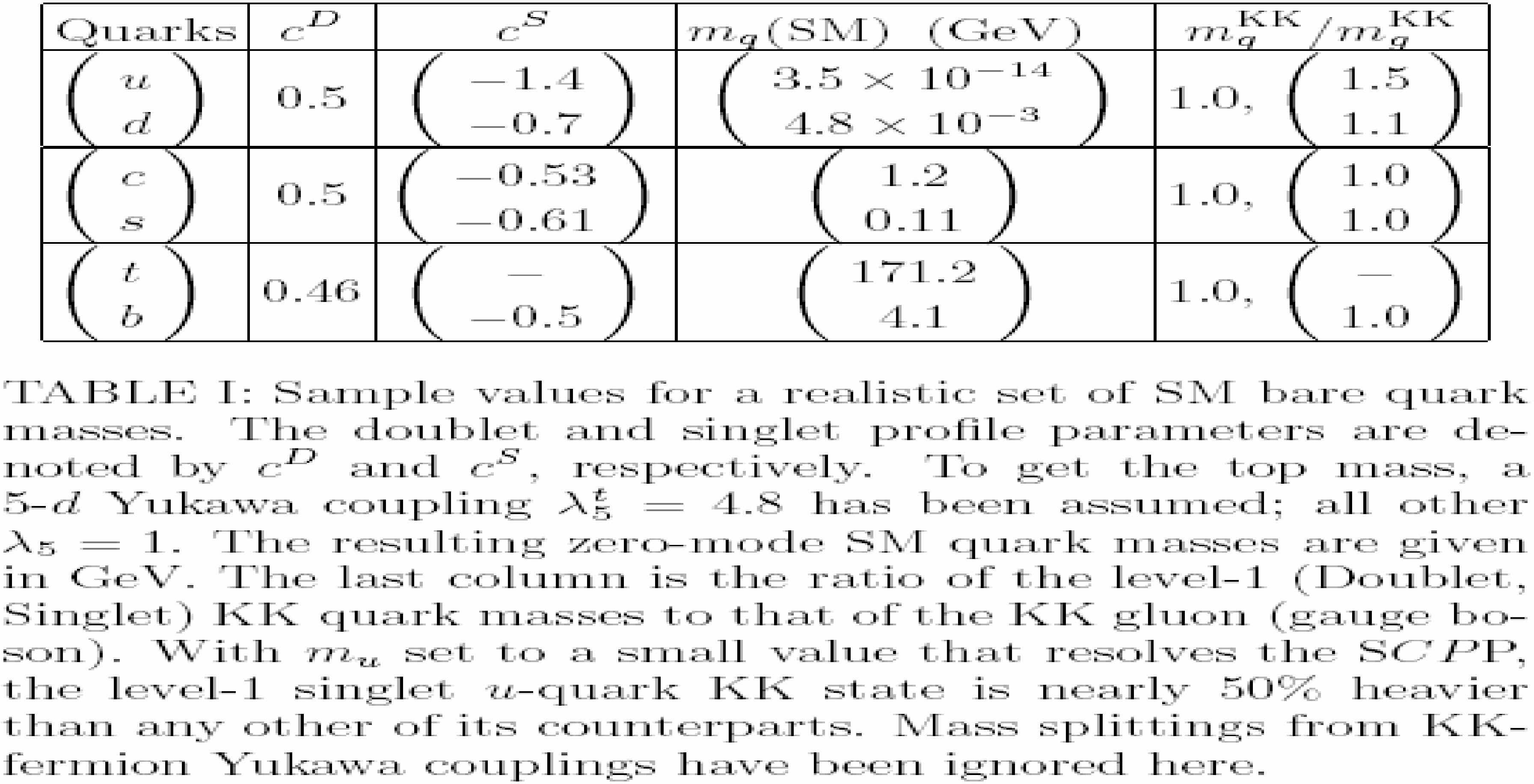
hep-ph07050151



Strong *CP*, Up-Quark Mass, and the Randall-Sundrum Microscope

Hooman Davoudiasl* and Amarjit Soni†
Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA

The fermion mass hierarchy can be obtained with $O(1)$ parameters in the Randall-Sundrum (RS) model, via exponential bulk profiles. In particular, a tiny up quark mass $m_u \ll$ MeV does not require a chiral symmetry or fine-tuning in this setup. Therefore, the RS model can provide a natural geometric resolution of the strong CP problem, while addressing the hierarchy and flavor puzzles. In simple realizations, this hypothesis can be tested at future colliders, like the LHC, by measuring the spectrum of level-1 Kaluza-Klein (KK) quarks. In this sense, these KK states act as a "microscope" for probing light fermion masses.



Quarks	c^D	c^S	m_q(SM) (GeV)	$m_q^{\rm KK}/m_g^{\rm KK}$
$\begin{pmatrix} u \\ d \end{pmatrix}$	0.5	$\begin{pmatrix} -1.4 \\ -0.7 \end{pmatrix}$	$\begin{pmatrix} 3.5 \times 10^{-14} \\ 4.8 \times 10^{-3} \end{pmatrix}$	1.0, $\begin{pmatrix} 1.5 \\ 1.1 \end{pmatrix}$
$\begin{pmatrix} c \\ s \end{pmatrix}$	0.5	$\begin{pmatrix} -0.53 \\ -0.61 \end{pmatrix}$	$\begin{pmatrix} 1.2 \\ 0.11 \end{pmatrix}$	1.0, $\begin{pmatrix} 1.0 \\ 1.0 \end{pmatrix}$
$\begin{pmatrix} t \\ b \end{pmatrix}$	0.46	$\begin{pmatrix} - \\ -0.5 \end{pmatrix}$	$\begin{pmatrix} 171.2 \\ 4.1 \end{pmatrix}$	1.0, $\begin{pmatrix} - \\ 1.0 \end{pmatrix}$

TABLE I: Sample values for a realistic set of SM bare quark masses. The doublet and singlet profile parameters are denoted by c^D and c^S, respectively. To get the top mass, a 5-d Yukawa coupling $\lambda_5^t = 4.8$ has been assumed; all other $\lambda_5 = 1$. The resulting zero-mode SM quark masses are given in GeV. The last column is the ratio of the level-1 (Doublet, Singlet) KK quark masses to that of the KK gluon (gauge boson). With m_u set to a small value that resolves the $SCPP$, the level-1 singlet u-quark KK state is nearly 50% heavier than any other of its counterparts. Mass splittings from KK-fermion Yukawa couplings have been ignored here.

COLLIDER SIGNATURE

$$q^S_{KK} \to H + q^D$$

$\hookrightarrow$ Jet

Summary & Outlook

- Results on TDCP asy. in B->ψK_S from BF along with some existing exptal #s & lattice WME for the 1st time give a striking quantitative confirmation of the CKM-paradigm of CPV to O (15%)
- More stringent experimental tests at BF now appear difficult to reconcile with the CKM-paradigm and hint at the need for a BSM-CP-odd phase
- Most interesting explanation: ONSET the era of ***WARPED QUANTUM FLAVORDYNAMICS***

HAPPY BIRTHDAY YITP