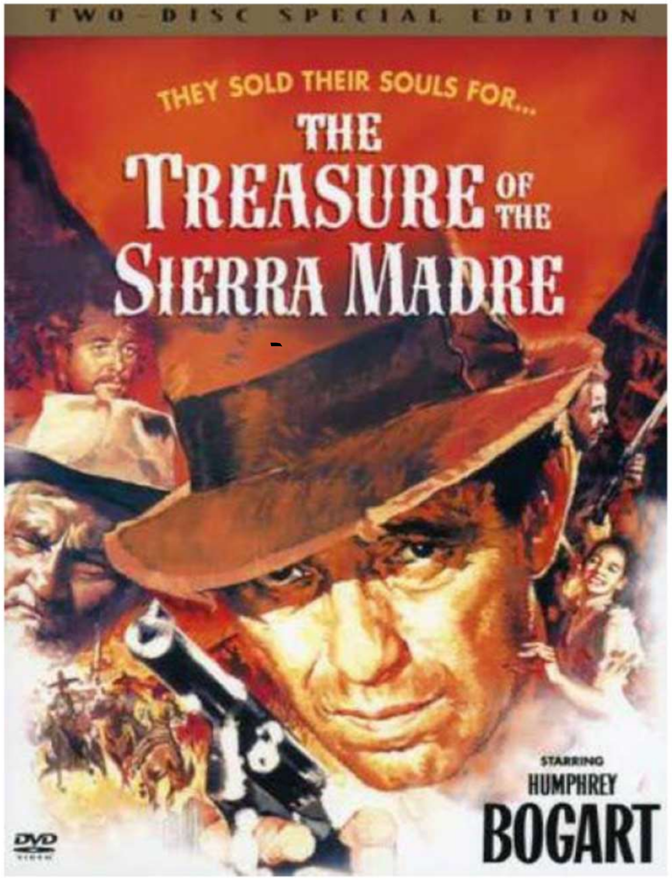
Amarjit Soni

HET Lunch Seminar 07/17/20

1)[More] Treasures from Kaons

2) RPV3 & the anomalies

[More] Treasures from Kaons



Outline

- **Unforgetable Memories!**
- **Exciting history …..**
- **Bagged 2 Nobels for BNL!**
- **Magics of –QM-mixings-K0**
- **A very important consequence of the QM mixing: K_LONG….**

An extremely powerful tool!

- **Delta Mk constraints =>stirs up flavor and CP puzzles of the SM**
- **Lattice BK=> Epsilon_K => precision constraints on the modern day UT fit**
- **Another important consequence of Delta_mk => BK^BSM vs BK_SM**

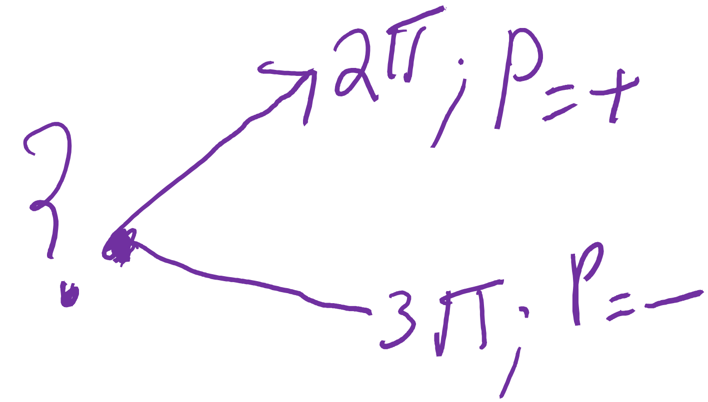
outline

- Basics of Direct CP in K=> $\pi\pi$ i.e. ε'
- Early attempt(s), hurdles & resolution
- I. Breakthrough: Domain wall & chiral symmetric formulation
- II. Another key development: Lellouch-Luscher method
- 1^{st} completion ~2015 & indication of difficulty
- Improved stats & systematic=> new result
- some implications
- Summary + Outlook

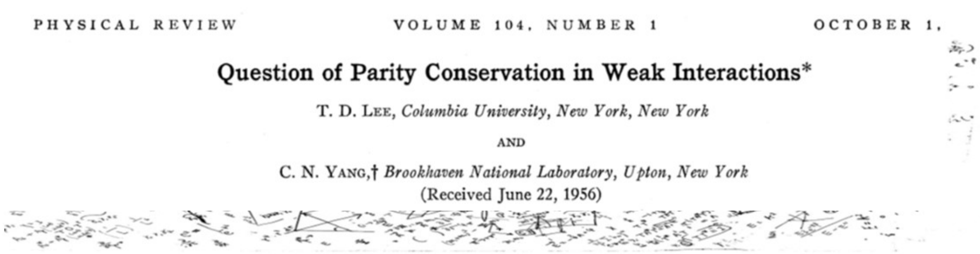
ΔmK^{expt} vs ΔmK^{theory}

- ΔmK^{expt} **extremely precise**
- **ΔmK^{theory} O(50%) errors…….LD, non-local, 4-q OP as OPE is NOT valid ….intermediate pipi states make significant contribution.**
- **Historically, therefore, the very well known experimental # cannot be used as a precision tool for constraining SM or BSM**
- **RBC-UKQCD past ~5 years with new lattice methodology is working to change this situation…CU PhD students 1. JiangLei Yu 2.Ziyuan Bai , 3. Bigeng Wang [NOW] ….δ(ΔmK^{theory}) ~O(20%)……checks underway NOW**

What an exciting history!

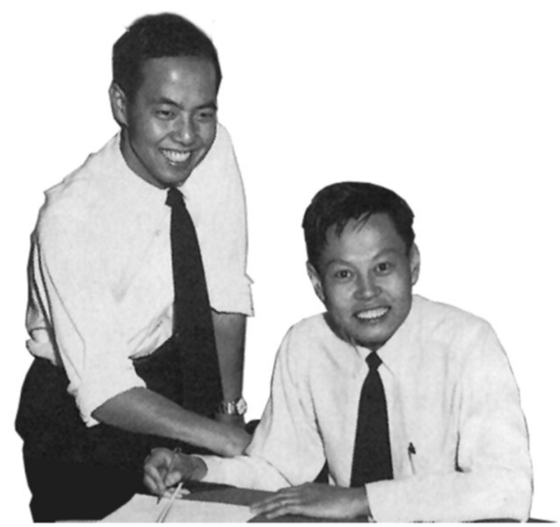


- **Theta – tau puzzle………..Nature does care about L vs R**
- **… the Nobel goes to Kids!**


PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1,

Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*
AND
C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*
(Received June 22, 1956)



K decay violate P!

II $K^0 - \bar{K^0}$ Mixing, Decay, Indirect CP violation

QM mixing
$\Delta S = 2$
$O(G_F^2)$

2 States K_L, K_S If CP is exact

$K_L \equiv \frac{K^0 - \bar{K^0}}{\sqrt{2}}$; $K_S \equiv \frac{K^0 + \bar{K^0}}{\sqrt{2}}$

CP− CP+

$\to 3\pi$ $\to 2\pi$

$\not\to 2\pi$ $\not\to 3\pi$

$\frac{\Delta m_K}{m_K} \sim 7 \times 10^{-15}$ But $\tau_{K_L} / \tau_{K_S} \sim O(500) \gg 1$

The long lifetime of K_L a very important blessing; led to one of the most important discoveries in Particle Physics ie CP violation

$c\tau$ ~15 m!

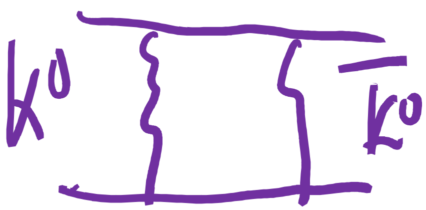
III Indirect CP violation

BNL 1964 Fitch, Cronin, Christensen + Turlay

NOBLE
CRONIN
+
FITCH

$$\frac{A(K_L \to \pi\pi)}{A(K_S \to \pi\pi)} \neq 0 \ !$$

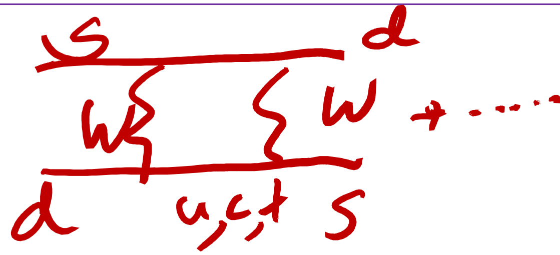
$$\epsilon_K \sim 2.23 \times 10^{-3}$$



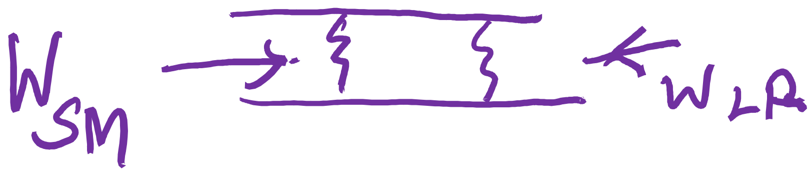
CPV in state mixing, $\Delta S=2$ H_{eff}

ΔmK : a powerful constraint on BSM

In SM $\Delta S=2$



an explicit illustration: LRSM; Beall + Bander + AS PRL 1982



$$\left(\frac{\Delta m_K}{m_K}\right)^{expt} \approx 10^{-14}!!$$

$\Rightarrow m_R \gtrsim 1.6\, TeV$

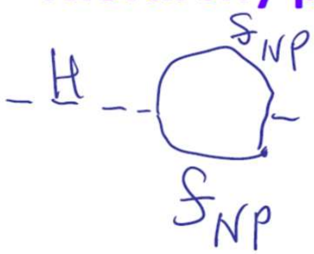
$\Rightarrow$ precision to flavor & CP problem

MR > ~20 MW

- **A remarkable story of several factors of a few all going in one direction**
- **Starting point was factor of O(5) from LXR =-2 [S+P]X[S-P]**
- **Initial Black Board intuitive argument M_LR => Const as mq=>0 whereas M_LL i.e. SM =>0 as m_q => with grad student Greg Beall in field theory class**
- **GB comes back later with X2 from graphs X log[M_R/M_W]…**
- **Very soon these factors pile up to O(20)**
- **NLO QCD enhances also => a PRL is born**

Outstanding Th.puzzles of our times

- **Hierarchy puzzle**



$\sim \frac{g^2_{NP}}{16\pi^2}\Lambda^2_{NP} \Rightarrow \Lambda_{NP} \lesssim$ TeV

to avoid fine tuning m_H

- **Flavor puzzle**

Δ flavor = 2 e.g.

$\sim \frac{g^2_{NP}}{\Lambda^2_{NP}} \Rightarrow \Lambda_{NP} \gtrsim 10^3$ TeV

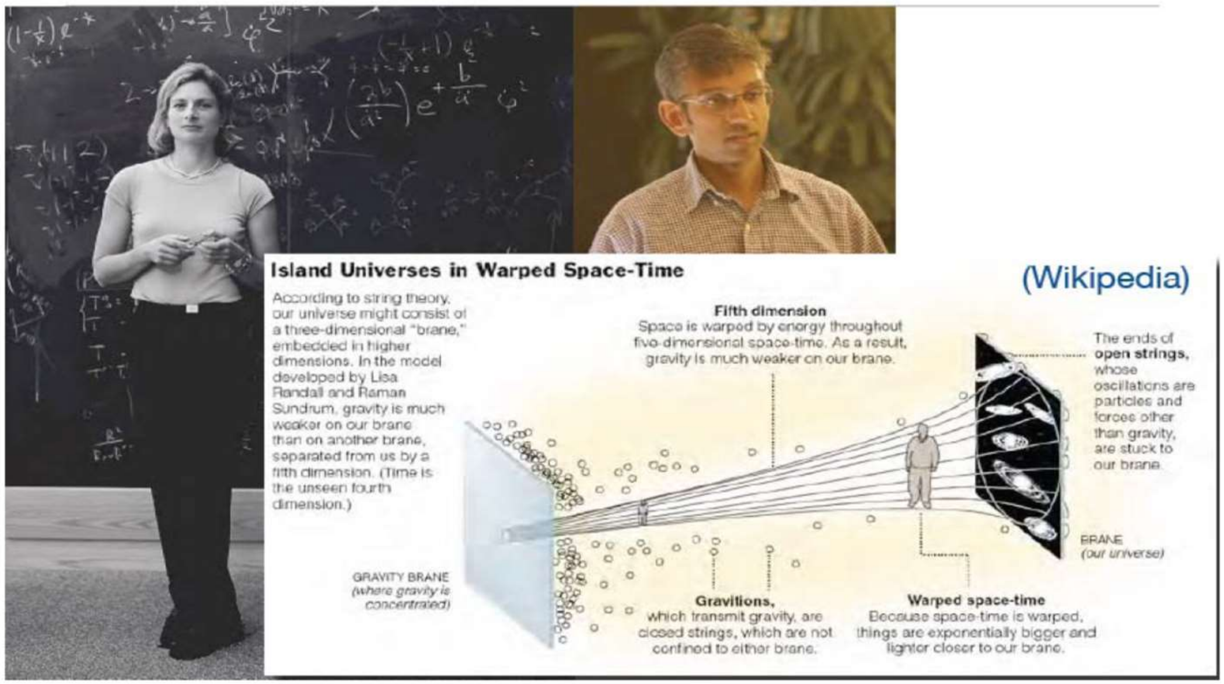
to avoid constraint from Δm_K

$\Rightarrow$ "NO LOSE Thm"

IGNORE FLAVOR

scalars'13; 9/13/13 A. Soni HET-BNL 12

The Randall-Sundrum (RS) idea



[Stolen from Neubert]

9/13/13 A. Soni HET-BNL 13

PHYSICAL REVIEW D **71,** 016002 (2005)

Flavor structure of warped extra dimension models

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(Received 14 September 2004; published 6 January 2005)

We recently showed that warped extra-dimensional models with bulk custodial symmetry and few TeV Kaluza-Klein (KK) masses lead to striking signals at B factories. In this paper, using a spurion analysis, we systematically study the flavor structure of models that belong to the above class. In particular we find that the profiles of the zero modes, which are similar in all these models, essentially control the underlying flavor structure. This implies that our results are robust and model independent in this class of models. We discuss in detail the origin of the signals in B physics. We also briefly study other new physics signatures that arise in rare K decays ($K \to \pi\nu\nu$), in rare top decays [$t \to c\gamma(Z, \text{gluon})$], and the possibility of CP asymmetries in D^0 decays to CP eigenstates such as $K_S\pi^0$ and others. Finally we demonstrate that with light KK masses, ~3 TeV, the above class of models with anarchic 5D Yukawas has a "CP problem" since contributions to the neutron electric dipole moment are roughly 20 times larger than the current experimental bound. Using AdS/CFT correspondence, these extra-dimensional models are dual to a purely 4D strongly coupled conformal Higgs sector thus enhancing their appeal.

DOI: 10.1103/PhysRevD.71.016002 PACS numbers: 11.25.Wx, 11.30.Hv

Physics Letters B 665 (2008) 67–71

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The little Randall–Sundrum model at the large hadron collider

"LRS"

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ABSTRACT

We present a predictive warped model of flavor that is cut off at an ultraviolet scale $\mathcal{O}(10^3)$ TeV. This "Little Randall–Sundrum (LRS)" model is a volume-truncation, by a factor $y \approx 6$, of the RS scenario and is holographically dual to dynamics with number of colors larger by y. The LRS couplings between Kaluza–Klein states and the Standard Model fields, including the proton constituents, are explicitly calculable without *ad hoc* assumptions. Assuming separate gauge and flavor dynamics, a number of unwanted contributions to precision electroweak, $Zb\bar{b}$ and flavor observables are suppressed in the LRS framework, compared with the corresponding RS case. An important consequence of the LRS truncation, independent of precise details, is a significant enhancement of the clean (golden) di-lepton LHC signals, by $\mathcal{O}(y^3)$, due to a larger "ρ-photon" mixing and a smaller inter-composite coupling.

Little Randall-Sundrum models: ϵ_K strikes again

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(Dated: November 22, 2008)

A detailed phenomenological analysis of neutral kaon mixing in "little Randall-Sundrum" models is presented. It is shown that the constraints arising from the CP-violating quantity ϵ_K can, depending on the value of the ultra-violet cutoff, be even stronger than in the original Randall-Sundrum scenario addressing the hierarchy problem up to the Planck scale. The origin of the enhancement is explained, and a bound $\Lambda_{UV} >$ several 10^3 TeV is derived, below which vast corrections to ϵ_K are generically unavoidable. Implications for non-standard $Z^0 \to b\bar{b}$ couplings are briefly discussed.

PACS numbers: 11.10.Kk,12.60.-i,12.90.+b,13.20.Eb,13.38.Dg

In both cases as in SUSY-like & most BSM, the LXL of SM $\Delta S=2$ becomes LXR-like as in LRSM leading to enhanced MEs for K-$\bar{K}$

Constraint on the Mass Scale of a Left-Right-Symmetric Electroweak Theory from the K_L-K_S Mass Difference

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and

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(Received 21 December 1981)

The K_L-K_S mass difference provides a stringent constraint on the mass (M_R) of the charged right-handed gauge field occurring in a "manifest" left-right-symmetric electroweak theory, yielding $M_R \gtrsim 1.6$ TeV. Taken in the context of a grand-unifying gauge theory, e.g., O(10), such a large bound on M_R, along with the measured value of $\sin^2\theta_W$, implies that $M_R \gtrsim 10^9$ GeV.

PACS numbers: 12.10.Ck, 11.30.Ly, 14.80.Er

$$O_{LL} \equiv [\bar{\psi}_s{}^{\alpha}\gamma_{\mu}\tfrac{1}{2}(1-\gamma_5)\psi_d{}^{\alpha}][\bar{\psi}_s{}^{\beta}\gamma^{\mu}\tfrac{1}{2}(1-\gamma_5)\psi_d{}^{\beta}].$$

$$\mathfrak{M}_{LL} \simeq \mathfrak{M}_{LL}{}^{\text{vac}} = \tfrac{2}{3} f_K{}^2 m_K{}^2/2m_K. \qquad (5)$$

⇐ SM

To evaluate the LR contribution we also use the divergence equation $\bar{\psi}_1\gamma_5\psi_2 = -i\partial_{\mu}(\bar{\psi}_1\gamma^{\mu}\gamma_5\psi_2)/(m_1+m_2)$ to obtain

$$\mathfrak{M}_{LR} \simeq \mathfrak{M}_{LR}{}^{\text{vac}} = \tfrac{1}{2}[m_K{}^2/(m_s+m_d)^2 + \tfrac{1}{6}] f_K{}^2 m_K{}^2/2m_K \simeq 7.7\mathfrak{M}_{LL}{}^{\text{vac}}, \qquad (6)$$

7.7

$$A_{LR}(d\bar{s}\to\bar{d}s) = \left(\frac{g}{\sqrt{2}}\right)^4\left(\frac{O_{LR}}{8\pi^2 M_R{}^4}\right)\sum_{i,j=u,c,t}\sum m_i U_{is}{}^{R*}U_{id}{}^{L} m_j U_{js}{}^{L*}U_{jd}{}^{R}$$

$$\times\left[\frac{\beta\ln\beta}{(1-\beta)(\epsilon_i-\beta)(\epsilon_j-\beta)} + \frac{\epsilon_i\ln\epsilon_i}{(1-\epsilon_i)(\beta-\epsilon_i)(\epsilon_j-\epsilon_i)} + \frac{\epsilon_j\ln\epsilon_j}{(1-\epsilon_j)(\beta-\epsilon_j)(\epsilon_i-\epsilon_j)}\right], \qquad (2)$$

$$O_{LR} \equiv [\bar{\psi}_s{}^{\alpha}\tfrac{1}{2}(1-\gamma_5)\psi_d{}^{\alpha}][\bar{\psi}_s{}^{\beta}\tfrac{1}{2}(1+\gamma_5)\psi_d{}^{\beta}]$$

⇐ LRSM

used $m_s = 150$ MeV

$\frac{M_{LRM}}{M_{sm}} \sim 7.7$

PRL 1981-82

P. Boyle et al 1812.04981

the five operators O_i. In our framework we are interested only in the parity-even operators. In the so-called SUSY basis introduced in [2], the parity-even operators are,

$$O_1 = (\bar{s}_a\gamma_\mu(1-\gamma_5)d_a)(\bar{s}_b\gamma_\mu(1-\gamma_5)d_b)$$
$$O_2 = (\bar{s}_a(1-\gamma_5)d_a)(\bar{s}_b(1-\gamma_5)d_b)$$
$$O_3 = (\bar{s}_a(1-\gamma_5)d_b)(\bar{s}_b(1-\gamma_5)d_a) \tag{1.2}$$
$$O_4 = (\bar{s}_a(1-\gamma_5)d_a)(\bar{s}_b(1+\gamma_5)d_b)$$
$$O_5 = (\bar{s}_a(1-\gamma_5)d_b)(\bar{s}_b(1+\gamma_5)d_a).$$

⇐ SM (for O_1)

⇒ LRM (for O_4)

$$\frac{M_i^{BSM}}{M^{SM}} \sim 2$$

Table 3: Comparison of the results of this work in $\overline{\text{MS}}(\mu = 3\text{GeV})$ alongside our collaboration's previous results presented in [5].

	RBC-UKQCD16[5]	This Work
N_f =	2+1	2+1
scheme	RI-SMOM	RI-SMOM
R_2	-19.48(44)(52)	-18.83(17)(55)
R_3	6.08(15)(23)	5.815(63)(125)
R_4	43.11(89)(230)	41.58(37)(119)
R_5	10.99(20)(88)	10.81(9)(37)

LRM is an extremely interesting extension of SM ⇒ $m_\nu \neq 0$

II. $K \Rightarrow \pi\pi$, $\Delta I = \frac{1}{2}$ Rule & ε'

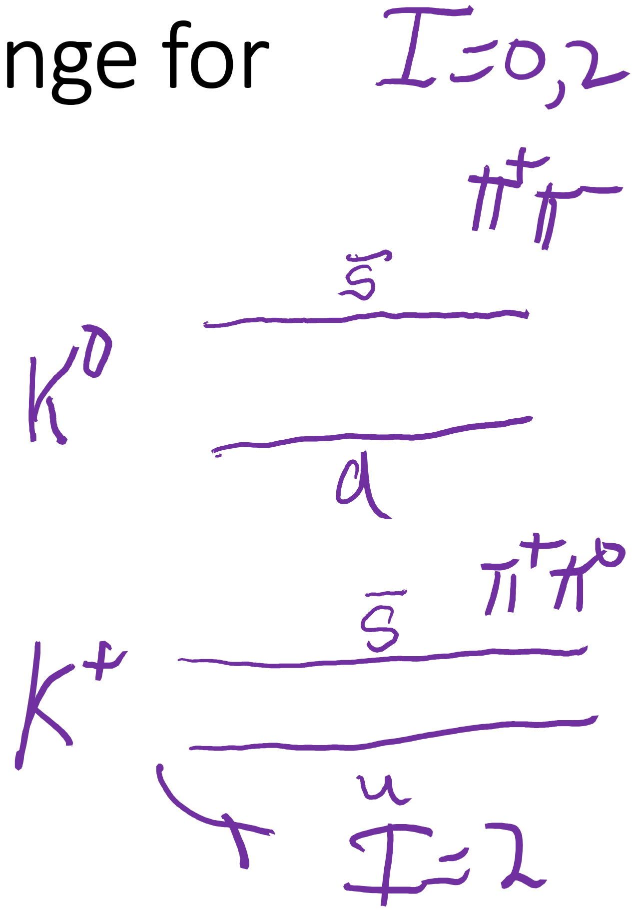
Delta I=1/2 rule (puzzle): a challenge for generations

MAIN MODES | τ

- K_s — $\pi^+\pi^-$ — $\sim 0.9\times10^{-10}$ s — $\Delta I = 1/2, 3/2$
- K^+ — $\pi^+\pi^0$ — $\Delta I = 3/2$ — $\sim 1.2\times10^{-8}$ s

K_L — $\pi^+\pi^-\pi^0$ — $\sim 5\times10^{-8}$ s

phase space suppressed



IV: ε' / ε: Direct CPV — EXPERIMENTAL ROUTE

$$\eta_{+-} = |\eta_{+-}| e^{i\phi_{+-}} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)}$$

$$\eta_{00} = |\eta_{00}| e^{i\phi_{00}} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}$$

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

$$\epsilon' \simeq \frac{1}{3}\left[\eta_{+-} - \eta_{00}\right] \Rightarrow O(10^{-3}) - O(10^{-3}) \Rightarrow 10^{-6}$$

$$\epsilon = \frac{1}{3}\left[2\eta_{+-} + \eta_{00}\right]$$

BSM-CP: Theoretical motivation

- **To the extent that SM is not a complete theory, BSM-CP phase(s) are exceedingly likely to exist**
- **Adding fermions, scalars or gauge bosons as a rule entails new phase(s)**
- **Explicit examples: 4G SM: + 2; LRS : at least + 1; 2HDM : neutral scalar sector**

as well as charged sector can have new phases; SUSY or WEXD [see e.g Agashe, Perez & AS, PRD '04; c also Neubert et al'08; Buras et al '08] : tens of new O(1) CP-odd phases arise *naturally* → MORE BIT later

- **SM cannot account for baryogenesis…..CKM CP not enough**
- **Due to all of the above (and some more), searching for BSM CP-phase(s) is just about the most powerful way to look for NP…..*an early realization & a driving force for past few decades***

→ not a compelling argument; Naturalness compelling!

$K \to 2\pi$

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \mathrm{Re}\left\{\frac{i\omega e^{i(\delta_2-\delta_0)}}{\sqrt{2}\varepsilon}\left[\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]\right\}$$

I=2 (ImA_2), I=0 (ImA_0)

Use lattice to calculate 6 quantities:
ReA0, ReA2 known from expt; δ0,δ2 via ChPT etc..So very good checks;
ImA. ImA2 unknown

$\omega \equiv \mathrm{Re}A_2/\mathrm{Re}A_0 \sim 0.045$

$$|\epsilon| = 2.228(11) \times 10^{-3},$$

Indirect CP

$$\mathrm{Re}(\epsilon'/\epsilon) = 1.65(26) \times 10^{-3}.$$

DIRECT CP

$\epsilon' << \epsilon$

$\epsilon' \sim 10^{-6}$!

A.S. in Proceedings of Lattice '85 (FSU)..1st Lattice meeting ever attended

The matrix elements of some penguin operators control in the standard model another CP violation parameter, namely ϵ'/ϵ.[6,8] Indeed efforts are now underway for an improved measurement of this important parameter.[10] In the absence of a reliable calculation for these parameters, the experimental measurements, often achieved at tremendous effort, cannot be used effectively for constraining the theory. It is therefore clearly important to see how far one can go with MC techniques in alleviating this old but very difficult

With C. Bernard [UCLA]

Serves as a template for the need of Lattice calculations for more economical use of almost all experimental data From IF

ODE to YESTERYEARS!

MOTHER of all (lattice) calculations to date: A Personal Perspective

- Calculation K=> ππ & ε′ were the reasons I went into lattice over 1/3 of a century ago!
- *9 + (3 new) PhD thesis*: Terry Draper (UCLA'84), George Hockney(UCLA'86), Cristian Calin (Columbia=CU'01), Jack Laiho(Princeton'04), Sam Li(CU'06), Matthew Lightman(CU'09), Elaine Goode(Southampton'10), Qi Liu(CU'12), Daiqian Zhang(CU'15)+ [new ones starting from CU, U Conn and Southampton] + many PD's & junior facs.. obstacles & challenges (and of course "mistakes"!) ad infinitum.....

Tianle WANG, Dan Hoying

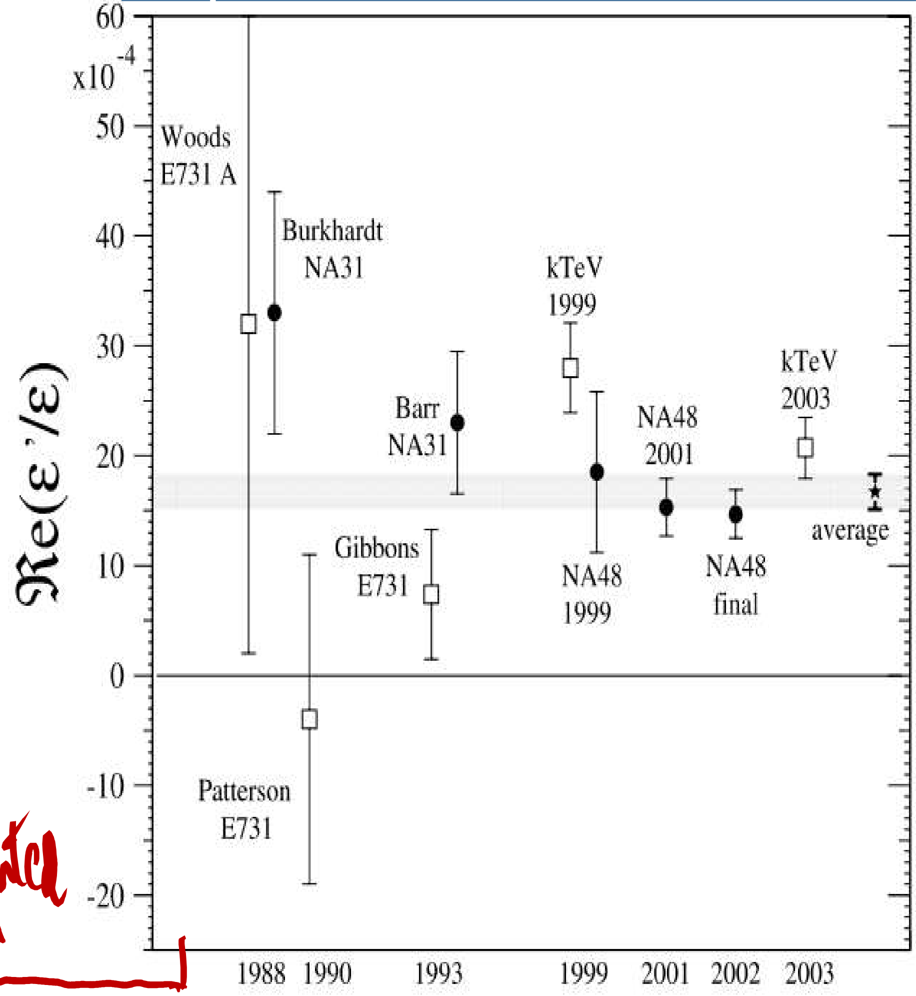
A key point to emphasize is that overcoming each major obstacle led to significant application to phenomenology and/or lattice

[necessity is the parent of……]

EXTREMELY valuable inputs from countless:

- **Fred Gilman and Mark Wise**
- **Andrzej Buras et al**
- **Guido Martinelli et al**
- **Yigal Shamir**
- **Laurent Lellouch + Martin Luscher**
- **……**
- **……..**
- **……..**

A monumental experimental achievement!



LATTICE work started

Konrad Kleinknecht "Uncovering CPV"

$16.6(2.3)\times 10^{-4}$

PDG 2014

Basic calculational framework

Δ S=1 H_W

WC to NLO
Buchalla, Buras, Lautenbacher RMP '96; Ciuchini et al 95

$$H_W = \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \sum_{i=1}^{10} \left[z_i(\mu) + \tau y_i(\mu) \right] Q_i(\mu).$$

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

$M_i = \langle K | Q_i | \pi\pi \rangle$ Needed to all orders in α_s

Tree

$$Q_1 = (\bar{s}_\alpha d_\alpha)_L (\bar{u}_\beta u_\beta)_L,$$

$$Q_2 = (\bar{s}_\alpha d_\beta)_L (\bar{u}_\beta u_\alpha)_L,$$

QCDP

$$Q_3 = (\bar{s}_\alpha d_\alpha)_L \sum_{q=u,d,s} (\bar{q}_\beta q_\beta)_L,$$

$$Q_4 = (\bar{s}_\alpha d_\beta)_L \sum_{q=u,d,s} (\bar{q}_\beta q_\alpha)_L,$$

$$Q_5 = (\bar{s}_\alpha d_\alpha)_L \sum_{q=u,d,s} (\bar{q}_\beta q_\beta)_R,$$

$$Q_6 = (\bar{s}_\alpha d_\beta)_L \sum_{q=u,d,s} (\bar{q}_\beta q_\alpha)_R,$$

EWP

$$Q_7 = \frac{3}{2} (\bar{s}_\alpha d_\alpha)_L \sum_{q=u,d,s} e_q (\bar{q}_\beta q_\beta)_R,$$

$$Q_8 = \frac{3}{2} (\bar{s}_\alpha d_\beta)_L \sum_{q=u,d,s} e_q (\bar{q}_\beta q_\alpha)_R,$$

$$Q_9 = \frac{3}{2} (\bar{s}_\alpha d_\alpha)_L \sum_{q=u,d,s} e_q (\bar{q}_\beta q_\beta)_L,$$

$$Q_{10} = \frac{3}{2} (\bar{s}_\alpha d_\beta)_L \sum_{q=u,d,s} e_q (\bar{q}_\beta q_\alpha)_L,$$

I=2

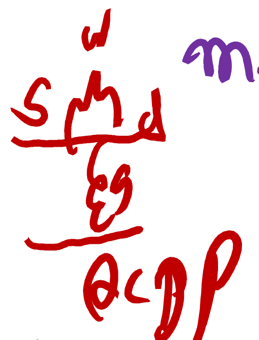
I=0

→ const

$m \to 0$

→ 0

$m_q \to 0$



Why EWK cannot be neglected: 3 Reasons

- **Despite $\alpha_{QED,EWK}$ << α_{QCD} , EWK contributions are extremely important and CANNOT be neglected:**
- **EWK are (8,8) and QCD are (8,1), and (8,8) go to constant whereas (8,1) vanish in the chiral limit**
- **EWK, i.e. those due Z exch have Wilson coeff that go as mt^2/mW^2**
- **In ε' they enter as**

$$\left[\frac{\mathrm{Im}A_2}{\mathrm{ReA}_2} - \frac{\mathrm{Im}A_0}{\mathrm{ReA}_0}\right]$$

EWP → $\mathrm{Im}A_2$; QCDP → $\mathrm{Im}A_0$

small ← ReA_2; large ← ReA_0

$$\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} \sim 22$$

Why EWK cannot be neglected : 3 Reasons

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- **EWK are (8,8) and QCD are (8,1), and (8,8) go to constant whereas (8,1) vanish in the chiral limit**
- **EWK, i.e. those due Z exch have Wilson coeff that go as mt^2/mW^2**
- **In ε' they enter as**

$$\left[\frac{\mathrm{Im}A_2}{\mathrm{ReA}_2} - \frac{\mathrm{Im}A_0}{\mathrm{ReA}_0}\right]$$

EWP → $\mathrm{Im}A_2$; $\mathrm{Im}A_0$ → QCDP

Small ← ReA_2; ReA_0 → large

$\frac{ReA_0}{ReA_2} \sim 22$

For Simplicity: 1st Strategy via ChPT

PHYSICAL REVIEW D VOLUME 32, NUMBER 9 1 NOVEMBER 1985

Application of chiral perturbation theory to $K \to 2\pi$ decays

⇒ LEEFT

BDSPW-85

Claude Bernard, Terrence Draper,* and A. Soni
Department of Physics, University of California, Los Angeles, California 90024

H. David Politzer and Mark B. Wise
Department of Physics, California Institute of Technology, Pasadena, California 91125

(Received 3 December 1984)

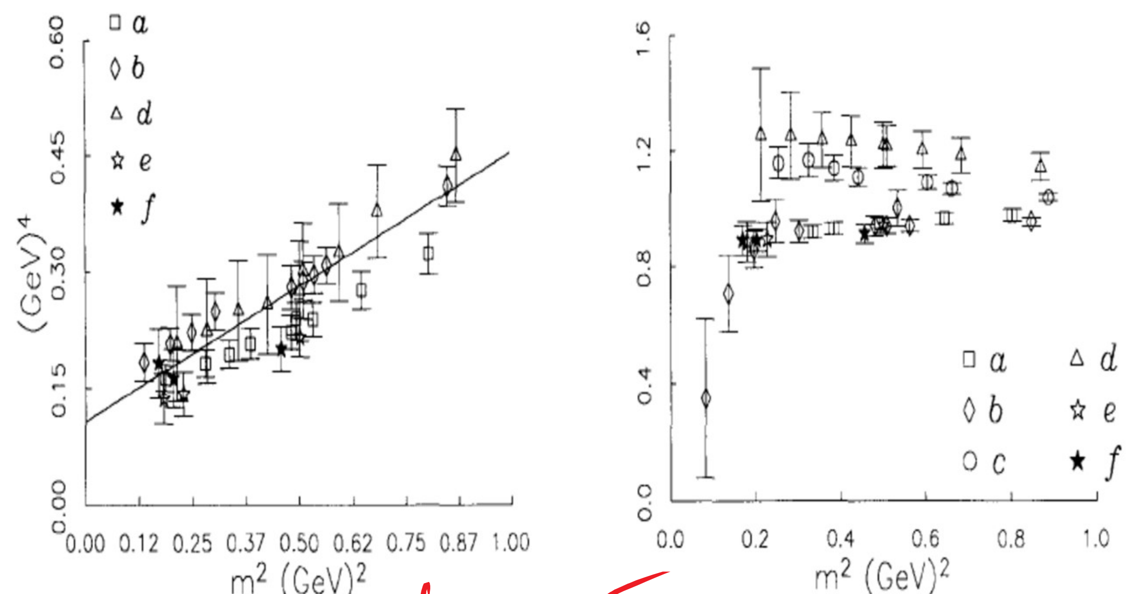
Chiral perturbation theory is applied to the decay $K \to 2\pi$. It is shown that, to quadratic order in meson masses, the amplitude for $K \to 2\pi$ can be written in terms of the unphysical amplitudes $K \to \pi$ and $K \to 0$, where 0 is the vacuum. One may then hope to calculate these two simpler amplitudes with lattice Monte Carlo techniques, and thereby gain understanding of the $\Delta I = \frac{1}{2}$ rule in K decay. The reason for the presence of the $K \to 0$ amplitude is explained: it serves to cancel off unwanted renormalization contributions to $K \to \pi$. We make a rough test of the practicability of these ideas in Monte Carlo studies. We also describe a method for evaluating meson decay constants which does not require a determination of the quark masses.

12/20/2017 USED extensively on lattice for ~20 years ⇒ NLO J. LAIHO PhD Thesis ~'03

$\langle K | (\bar{s}\gamma_\mu L d)^2 | \bar{K} \rangle$

'88

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



χS Violation by K-$\bar{K}$ ⇒ FINE TUNING PROBLEM

Lattice computation of the decay constants of B and D mesons

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(Received 1 July 1993)

Semileptonic decays on the lattice: The exclusive 0^- to 0^- case

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(Received 21 December 1990)

PHYSICAL REVIEW D VOLUME 45, NUMBER 3 1 FEBRUARY 1992

Lattice study of semileptonic decays of charm mesons into vector mesons

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(Received 30 September 1991)

We present our lattice calculation of the semileptonic form factors for the decays $D \to K^*$, $D_s \to \phi$, and $D \to \rho$ using Wilson fermions on a $24^3 \times 39$ lattice at $\beta = 6.0$ with 8 quenched configurations. For $D \to K^*$, we find for the ratio of axial form factors $A_2(0)/A_1(0) = 0.70 \pm 0.16^{+0.20}_{-0.13}$. Results for other form factors and ratios are also given

PIONEERING WORKS Leading to Modern Day UT ?

PHYSICAL REVIEW D, VOLUME 58, 014501

SU(3) flavor breaking in hadronic matrix elements for B-$\bar{B}$ oscillations

Later ΔM_s CDF, DØ

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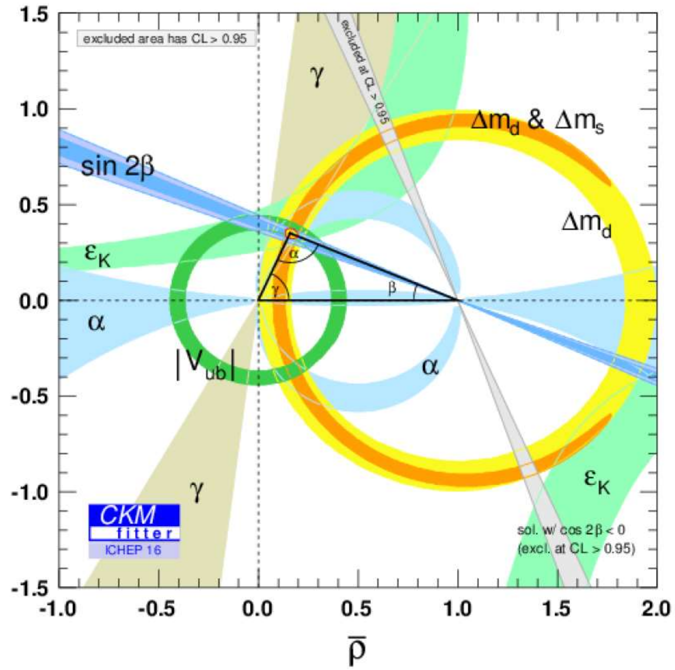
(Received 28 January 1998; published 5 May 1998)

12/20/2017 IMSC; HEP BNL,Soni

Use exptal data + lattice WME to test SM & search for new physics

http://ckmfitter.in2p3.fr
see also http://www.utfit.org

Looks great; but looks can be deceiving…
In fact at level of O(2σ) tension(s) exist



O(10-15%) new physics is possible and is HUGE!

LaT Expt

f_B Δm_B

$\frac{f_{B_s}}{f_B}$ … $\frac{\Delta m_{B_s}}{\Delta m_{Bd}}$

$f(q^2), f_0(q^2) \Rightarrow B \to l \nu \pi$ (D)

$B_K \to \epsilon_K$

Δm_K NOT used

Two key papers

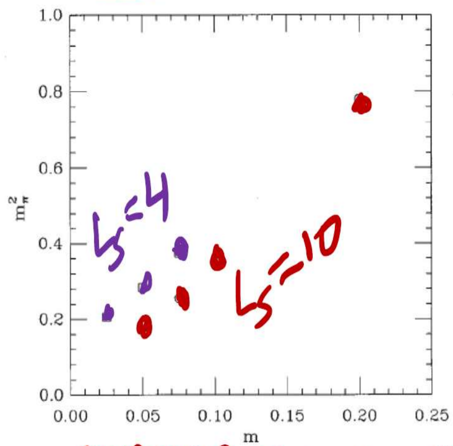
PHYSICAL REVIEW D VOLUME 56, NUMBER 1 1 JULY 1997

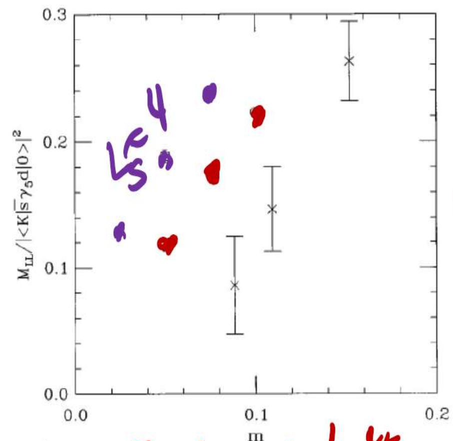
QCD with domain wall quarks

1st Simulation with DWQ 96-'97

T. Blum* and A. Soni†
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 27 November 1996)

We present lattice calculations in QCD using Shamir's variant of Kaplan fermions which retain the continuum $SU(N)_L \times SU(N)_R$ chiral symmetry on the lattice in the limit of an infinite extra dimension. In particular, we show that the pion mass and the four quark matrix element related to K_0-$\overline{K_0}$ mixing have the expected behavior in the chiral limit, even on lattices with modest extent in the extra dimension, e.g., $N_s = 10$. [S0556-2821(97)00113-6]





excellent Chiral symmetry with ~10 sites in 5th dim.

12/20/2017

MAJOR BREAKTHROUGH FOR K→ππ Lattice Calculations

→ i.e. No ChPT

→ CMP/01. ← a new method

another major development for K→ππ on lattice

Direct K-> $\pi\pi$ (a la Lellouch-Luscher), using finite volume correlation* functions, [i.e. w/o ChPT] RBC initiates around 2006

CONTINUED BY RBC-UKQCD {(mostly) Edinburgh – Southampton}

* Allows to bypass Maini-Testa theorem

COMMON Interest : Use of DWQ for simulations

Relating lattice ME to physical amplitudes

$$A_{2/0} = F\frac{G_F}{\sqrt{2}}V_{ud}V_{us}\sum_{i=1}^{10}\sum_{j=1}^{7}\left[\Big(z_i(\mu)+\tau y_i(\mu)\Big)Z_{ij}^{\mathrm{lat}\to\overline{\mathrm{MS}}}M_j^{\frac{3}{2}/\frac{1}{2},\mathrm{lat}}\right]$$

F is the Lellouch-Luscher factor which relates finite volume ME to the infinite volume

F

$$A = \frac{1}{\pi q}\sqrt{\frac{\partial\phi}{\partial q}+\frac{\partial\delta}{\partial q}}\sqrt{m_K}E_{\pi\pi}L^{2/3}M$$

Phase shift

A/M is LL factor F

$q = \frac{pL}{2\pi}$;

$\sim \frac{\delta}{q}$ for small p

φ is a somewhat complicated function of q and boundary Conditions [See Daiqian Zhang thesis]

12/20/2017 IMSC; HET-BNL;soni 98

RBC-UKQCD PRL2015

Results for ε'

- Using Re(A_0) and Re(A_2) from experiment and our lattice value for Im(A_0) and Im(A_2) and the phase shifts,

EWP

QCDP ~80% {Central Value}

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \mathrm{Re}\left\{\frac{i\omega e^{i(\delta_2-\delta_0)}}{\sqrt{2}\varepsilon}\left[\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]\right\}$$

$$= 1.38(5.15)(4.43) \times 10^{-4},$$

$$16.6(2.3) \times 10^{-4}$$

LARGE CANCELLATION!!

RBC-UKQCD PRL'15 EDITOR'S CHOICE

Bearing in mind the largish errors in this first calculation, we interpret that our result are consistent with experiment at ~2σ level

with expt
Computed ReA0 good agreement with expt
Offered an "explanation" of the Delta I=1/2 enhancement

$$\omega = \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0} \sim 0.045$$

A UNIQUE ASPECT OF THIS CALCULATION

- **REAL A0, the strong phase (δ0) and Im A0 are being calculated simultaneously from 1st principles in the same calculation**
- **Re A0 is also known from EXPERIMENT…& strong phase deduced via ChPT + expt**
- **So those provide a powerful check [amongst many] of what we are doing**
- **If a non-perturbative calculation of ImA0 and of eps' is done w/o also calculating ReA0 & δ0 in the same framework, then its repercussions for eps' (in the very least) raises questions.**

A possible difficulty: strong phases

- **The continuum and our lattice determinations of strong phase**

differ

- $$\phi_{\epsilon'} = \delta_2 - \delta_0 + \frac{\pi}{2} = \begin{cases} (42.3 \pm 1.5)^{\circ} & \text{[redacted] [2]} \\ (54.6 \pm 5.8)^{\circ} & \text{RBC [47, 48]} \end{cases}$$

Colangelo et al ChPT etc

RBC-UKQCD

OK

off by ≃ 2σ ⇒ a Concern

Statistics increase

CKelly @ LAT '18

- Original goal was a 4x increase in statistics over 216 configurations used in 2015 analysis.
- 4x reduction in configuration generation time obtained via algorithmic developments (exact one-flavor implementation) → ① Murphy
- Large-scale programme performed involving many machines:

SCs over 3 continents

Source	Determinant computation	Independent configs.
Blue Waters	RHMC	34+18+4+3
KEKSC	RHMC	106
BNL	RHMC	208
DiRAC	RHMC	151
KEKSC	EOFA	275+215
BNL	EOFA	245
		1259 total

- Measurements performed using IBM BG/Q machines at BNL and the Cori computer (Intel KNL) at NERSC largely complete.
- Including original data, now have 6.7x increase in statistics!

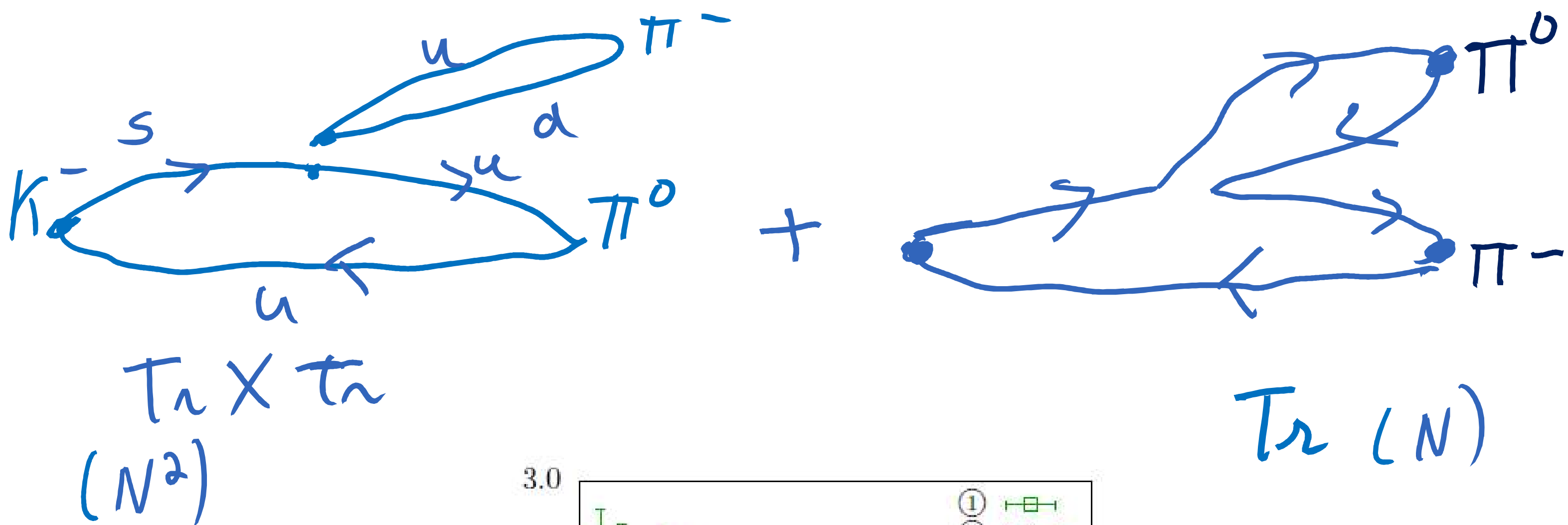
NOW ~1440 g.c

Implications for K→ππ and resolution

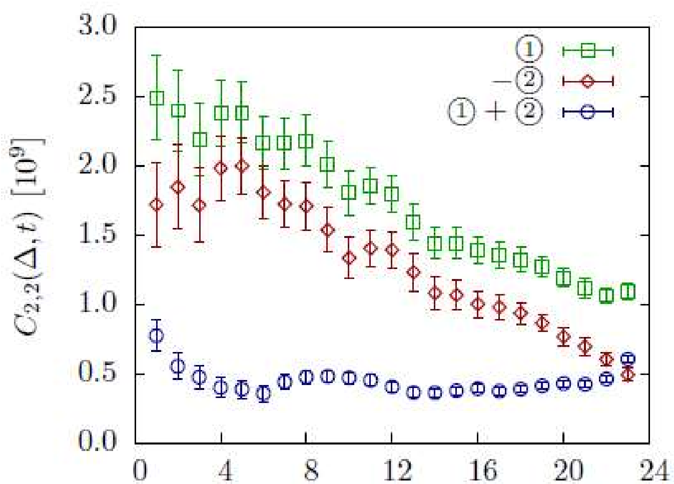
- Despite vast increase in statistics, *this second state cannot be resolved from the time dependence using only a single ππ operator.*
- Possibly a significant underestimate of excited state systematic error in K→ππ calculation that can only be resolved by adding additional operators.
- In response we have **expanded the scope of the calculation**:
    - Added K→σ matrix elements
    - Added K→ππ matrix element of new ππ operator with larger relative pion momenta (still p_{CM}=0)
- Result is **3x increase in the number of I=0 ππ operators in K→ππ calc.**
- Also added ππ 2pt functions with non-zero total ππ momenta.
  Calculate phase shift at several (smaller) additional center-of-mass energies.
    - Additional points that can be compared to dispersive result / experiment
    - Improve ~11% systematic on Lellouch-Luscher factor associated with slope of phase shift.
- Currently have 152 measurements with new operators! Adding ~100/month

Unravelling the $\Delta I=1/2$ rule

Dissecting (the much easier) ΔI=3/2 [I=2 ππ] Amp on the lattice: 2 contributing topologies only

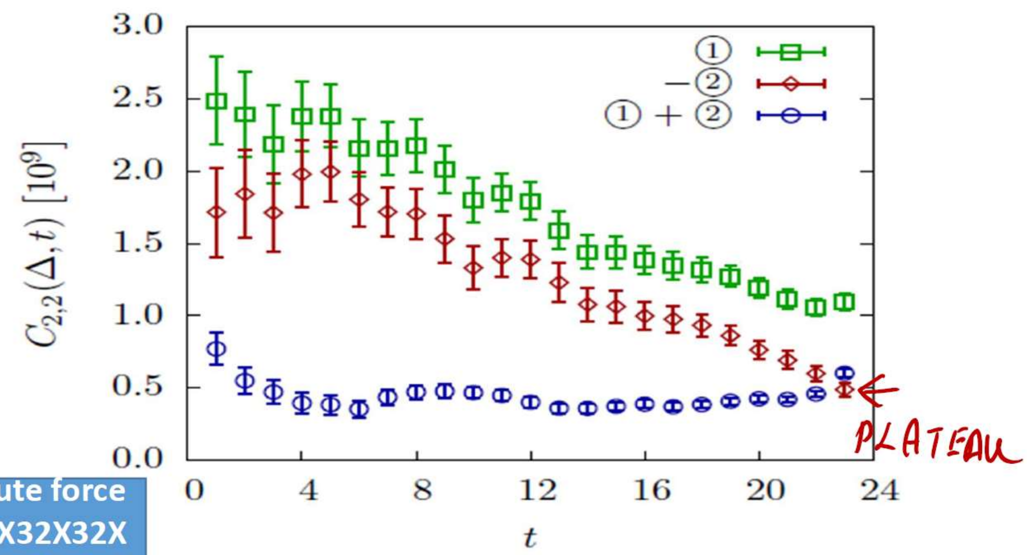


Simplest basic step is Significantly different from phenomenological Expectations!



DRAMATIC CANCELLATION!
($m_\pi \sim 140$ MeV)

RBC-UKQCD PRL 2012: Unravelling the origin of the textbook Delta I=1/2 Puzzle: Unnatural("accidental") suppression of ReA2 at m_pi ~140 MeV



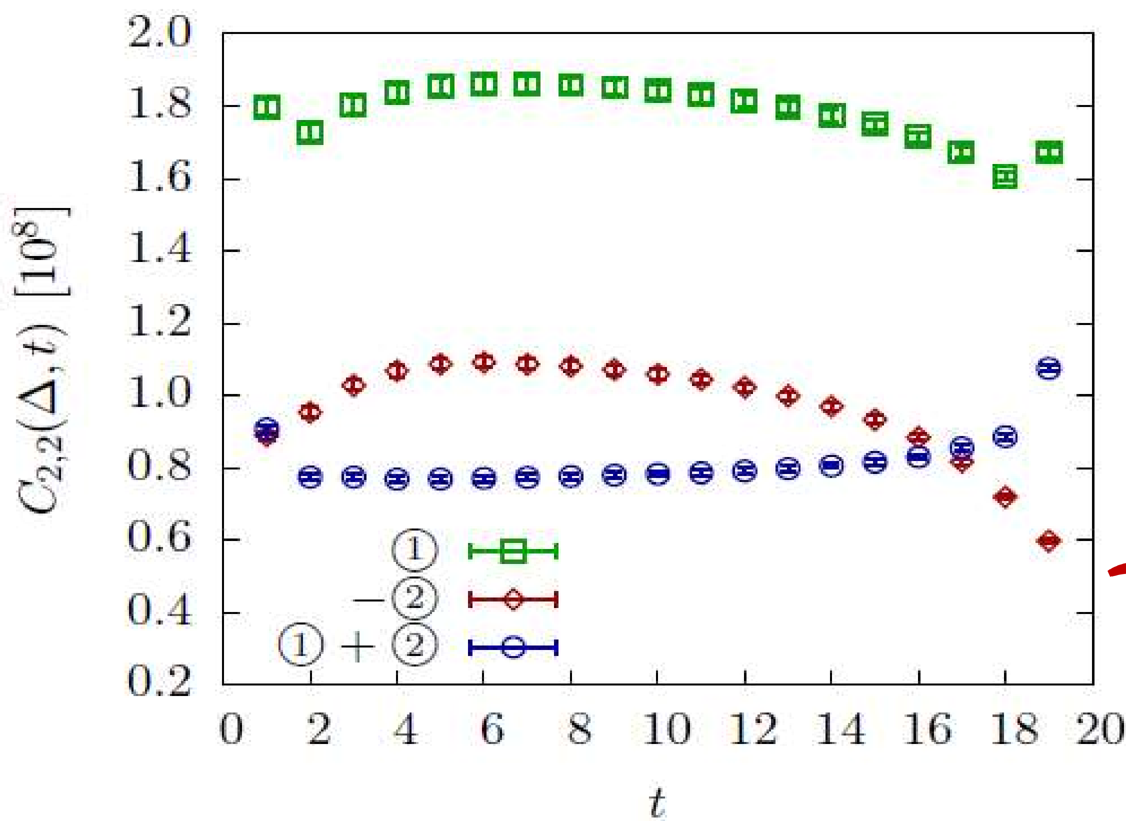
Brute force 32X32X32X 64X16

FIG. 2: Contractions ①, -② and ① + ② as functions of t from the simulation at physical kinematics and with $\Delta = 24$.

QCDOC 10 Tf

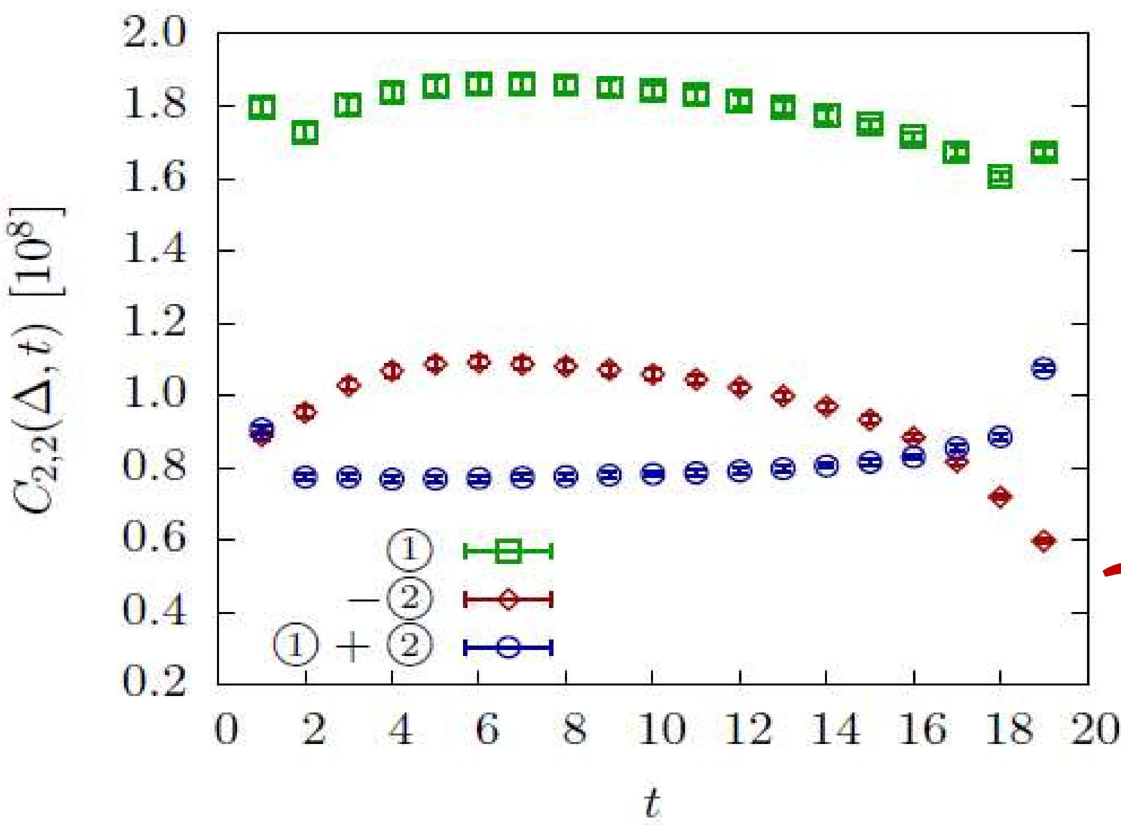
12/20/2017 IMSC; HET-BNL;soni 96

UNLIKE WHAT TEXT BOOKS SAY, INFACT NAÏVE FACTORIZATION FAILS IN I=2 K=> 2 pi decays



For heavier π, $m_\pi \sim 330$ MeV
less cancellation
bet. N^2 & N
Large N begins
to improve!

FIG. 3: Contractions ①, -② and ① + ② as functions of t from the simulation at threshold with $m_\pi \simeq 330\,\text{MeV}$ and $\Delta = 20$.

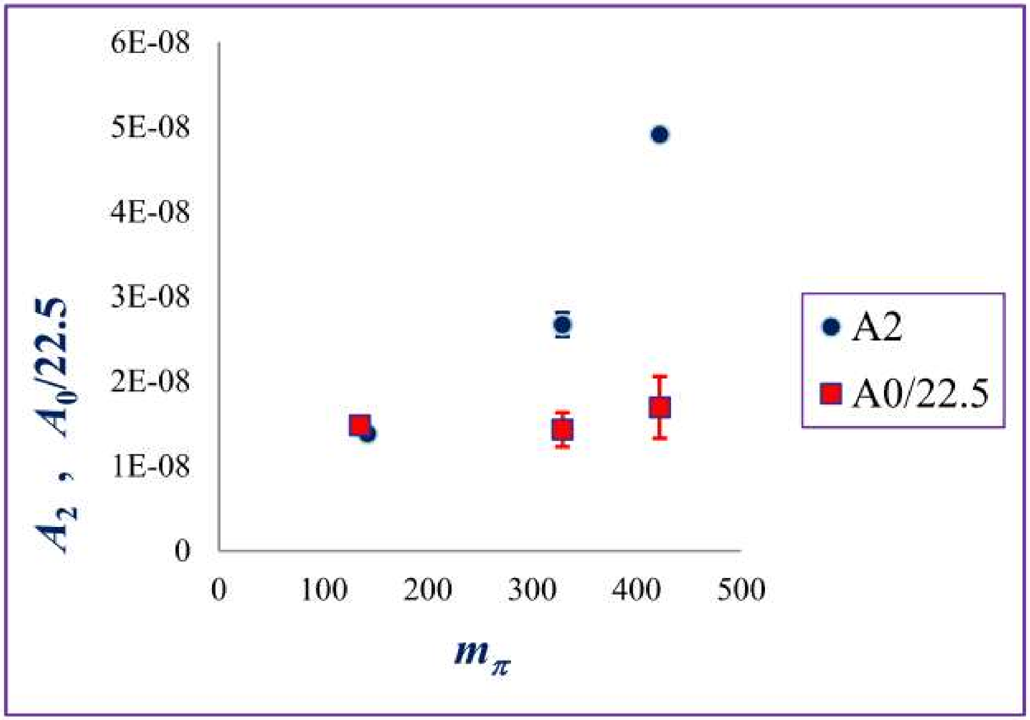


For heavier π, $m_\pi \sim 330$ MeV
less cancellation
bet. N^2 & N
Large N begins
to improve!

FIG. 3: Contractions ①, -② and ① + ② as functions of t from the simulation at threshold with $m_\pi \simeq 330\,\text{MeV}$ and $\Delta = 20$.

Because of mass dependent cancellation $\mathrm{Re}A_2$ changes with m_π dramatically. $\mathrm{Re}A_0$ is mild

Compare A_2 and $A_0/22.5$



NHCC
KITP
Aug '15

Net effect

- **This large cancellation between N^2 and N [N=3,for QCD] leads to a reduction in ReA2 compared to "naïve expectations" by a factor of about 4 to 5 in the original effect of around 22.5**
- **Then there is a factor of 2 to 3 from renorm…=> bringing the total to [8 to 15] of the needed 22.5**
- **The remaining factor of ~ [1.5 to 2.8] … comes from ReA0 over "naïve expectations"**

More on A0

$Q_2 \equiv$ 

- **Another important fact about Re A0 is that at a scale of ~1.3 GeV or more,**

the contribution from penguin operators, Q3,Q4,Q5,Q6,is negligibly small.

- **Indeed, ~85% of ReA0 originates at these scales from Q2 which is just the original Weak interaction 4-q operator: [s-bar gamma_muL u]X[d-bar gamma_uL u], which originates from integrating out the W-boson.**
- **The essential moral is that if you take the original weak interaction 4q operraor**

and non-pertubatively compute its matrix element between K to pi pi in the I=0 channel then it accounts for most (~85%) of Re A0…..

- **Lastly, but equally importantly, it should be stressed that the SVZ-penguin operator Q6 is in fact the dominant contributor to Im A0**.

Im A0 & ε’

arXiv: 2004.09440

RBC-UKQCD 2020

14

Parameter	Value	
	2-state fit	3-state fit
Fit range	6-15	4-15
$A^0_{\pi\pi(111)}$	0.3682(31)	0.3718(22)
$A^0_{\pi\pi(311)}$	0.00380(32)	0.00333(27)
A^0_{σ}	−0.0004309(41)	−0.0004318(42)
E_0	0.3479(11)	0.35030(70)
$A^1_{\pi\pi(111)}$	0.1712(91)	0.1748(67)
$A^1_{\pi\pi(311)}$	−0.0513(27)	−0.0528(30)
A^1_{σ}	0.000314(17)	0.000358(13)
E_1	0.568(13)	0.5879(65)
$A^2_{\pi\pi(111)}$	—	0.116(29)
$A^2_{\pi\pi(311)}$	—	0.063(10)
A^2_{σ}	—	0.000377(94)
E_2	—	0.94(10)
p-value	0.314	0.092

TABLE III: Fit parameters in lattice units and the p-values for multi-operator fits to the $I = 0$ $\pi\pi$ two-point functions. Here E_i are the energies of the states and A^i_α represents the matrix element of the operator α between the state i and the vacuum, given in units of $\sqrt{1 \times 10^{13}}$. The second column gives the parameters for our primary fit which uses two-states and three operators. The third column shows a fit with the same three operators and one additional state that is used to probe the systematic effects of this third state on the $K \to \pi\pi$ matrix element fits.

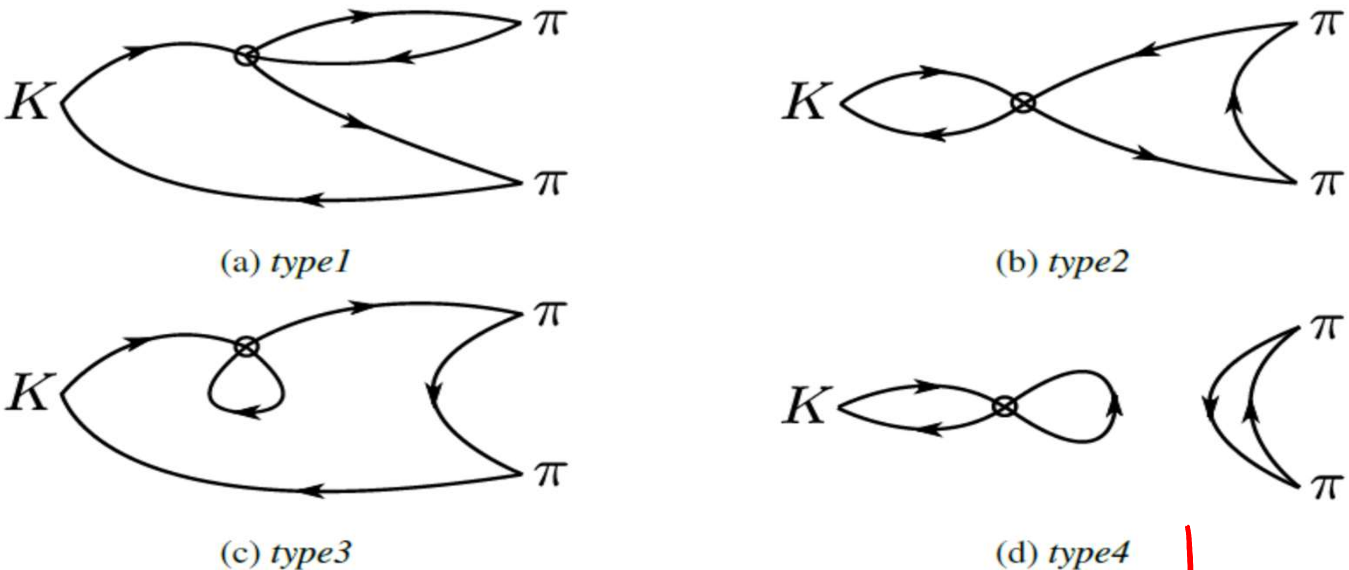
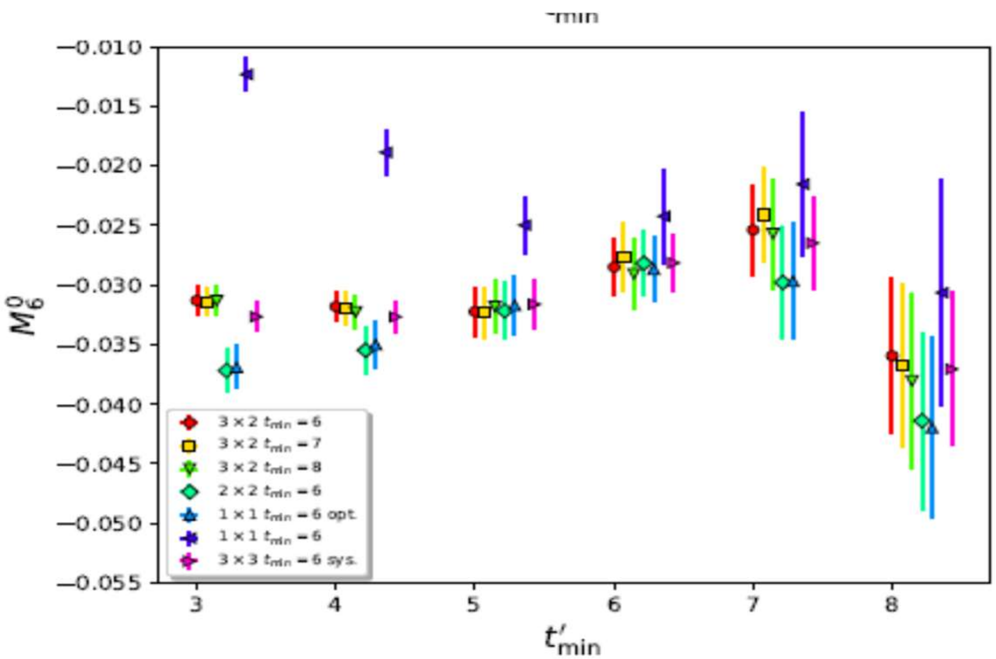


FIG. 2: The four classes of $K \to \pi\pi$ Wick contractions.

ALL ARE INCLUDED!

↑ "DISCONNECTED"
very difficult



−0.010
−0.015
−0.020
−0.025
−0.030
−0.035
−0.040
−0.045
−0.050
−0.055
M_6^0
3
4
5
6
7
8
t'_{min}
3×2 $t_{min}=6$
3×2 $t_{min}=7$
3×2 $t_{min}=8$
2×2 $t_{min}=6$
1×1 $t_{min}=6$ opt.
1×1 $t_{min}=6$
3×3 $t_{min}=6$ sys.

7-ops. 10-ops.

i	SMOM($\not{q},\not{q}$) (GeV^3)	SMOM(γ^μ,γ^μ) (GeV^3)	$\overline{\text{MS}}$ via SMOM($\not{q},\not{q}$) (GeV^3)	$\overline{\text{MS}}$ via SMOM(γ^μ,γ^μ) (GeV^3)
1	0.060(39)	0.059(38)	−0.107(22)	−0.093(18)
2	−0.125(19)	−0.106(16)	0.147(15)	0.143(14)
3	0.142(17)	0.128(14)	−0.086(61)	−0.053(44)
4	-	-	0.185(53)	0.200(40)
5	−0.351(62)	−0.313(48)	−0.348(62)	−0.311(48)
6	−1.306(90)	−1.214(82)	−1.308(90)	−1.272(86)
7	0.775(23)	0.790(23)	0.769(23)	0.784(23)
8	3.312(63)	3.092(58)	3.389(64)	3.308(63)
9	-	-	−0.117(20)	−0.114(19)
10	-	-	0.137(22)	0.123(19)

TABLE XIV: Physical, infinite-volume matrix elements in the SMOM($\not{q},\not{q}$) and SMOM(γ^μ,γ^μ) schemes at $\mu = 4.006$ GeV given in the 7-operator chiral basis, as well as those converted perturbatively into the $\overline{\text{MS}}$ scheme at the same scale in the 10-operator basis. The errors are statistical only.

2 Schemes

Q_i Re A_0 Im A_0

	Re(A_0)		Im(A_0)	
i	$(\not{q},\not{q})$ ($\times 10^{-7}$ GeV)	(γ^μ,γ^μ) ($\times 10^{-7}$ GeV)	$(\not{q},\not{q})$ ($\times 10^{-11}$ GeV)	(γ^μ,γ^μ) ($\times 10^{-11}$ GeV)
1	0.383(77)	0.335(64)	0	0
2	2.89(30)	2.81(28)	0	0
3	0.0081(58)	0.0050(42)	0.20(14)	0.12(10)
4	0.081(23)	0.088(17)	1.24(35)	1.34(27)
5	0.0380(68)	0.0339(53)	0.552(99)	0.492(77)
6	−0.410(28)	−0.398(27)	−8.78(60)	−8.54(57)
7	0.001863(56)	0.001900(56)	0.02491(75)	0.02540(75)
8	−0.00726(14)	−0.00708(13)	−0.2111(40)	−0.2060(39)
9	$-8.7(1.5)\times 10^{-5}$	$-8.5(1.4)\times 10^{-5}$	−0.133(22)	−0.128(21)
10	$2.37(38)\times 10^{-4}$	$2.13(32)\times 10^{-4}$	−0.0304(49)	−0.0273(41)
Total	2.99(32)	2.86(31)	−7.15(66)	−6.93(64)

TABLE XVIII: The contributions of each of the ten four-quark operators to Re(A_0) and Im(A_0) for the two different RI-SMOM intermediate schemes. The scheme and units are listed in the column headers. The errors are statistical, only.

Error source	Value
Excited state	-
Unphysical kinematics	5%
Finite lattice spacing	12%
Lellouch-Lüscher factor	1.5%
Finite-volume corrections	7%
Missing G_1 operator	3%
Renormalization	4%
Total	15.7%

TABLE XXV: Relative systematic errors on the infinite-volume matrix elements of $\overline{\text{MS}}$-renormalized four-quark operators Q'_j.

Systematic errors

Re A_0 → ~20%

Error source	Value	
	Re(A_0)	Im(A_0)
Matrix elements	15.7%	15.7%
Parametric errors	0.3%	6%
Wilson coefficients	12%	12%
Total	19.8%	20.7%

Im A_0 → ~21%

TABLE XXVI: Relative systematic errors on Re(A_0) and Im(A_0).

Quantity	Value
$\mathrm{Re}(A_0)$	$2.99(0.32)(0.59)\times 10^{-7}$ GeV
$\mathrm{Im}(A_0)$	$-6.98(0.62)(1.44)\times 10^{-11}$ GeV
$\mathrm{Re}(A_0)/\mathrm{Re}(A_2)$	19.9(2.3)(4.4)
$\mathrm{Re}(\varepsilon'/\varepsilon)$	0.00217(26)(62)(50)

→ due IB see foll pages

TABLE I: A summary of the primary results of this work. The values in parentheses give the statistical and systematic errors, respectively. For the last entry the systematic error associated with electromagnetism and isospin breaking is listed separately as a third error contribution.

IB+EM effects…..not yet from lattice

We use

$$\frac{\varepsilon'}{\varepsilon} = \frac{i\omega e^{i(\delta_2-\delta_0)}}{\sqrt{2}\varepsilon}\left[\frac{\mathrm{Im}(A_2)}{\mathrm{Re}(A_2)} - \frac{\mathrm{Im}(A_0)}{\mathrm{Re}(A_0)}\right]$$

→ isospin sym ~~formula~~.

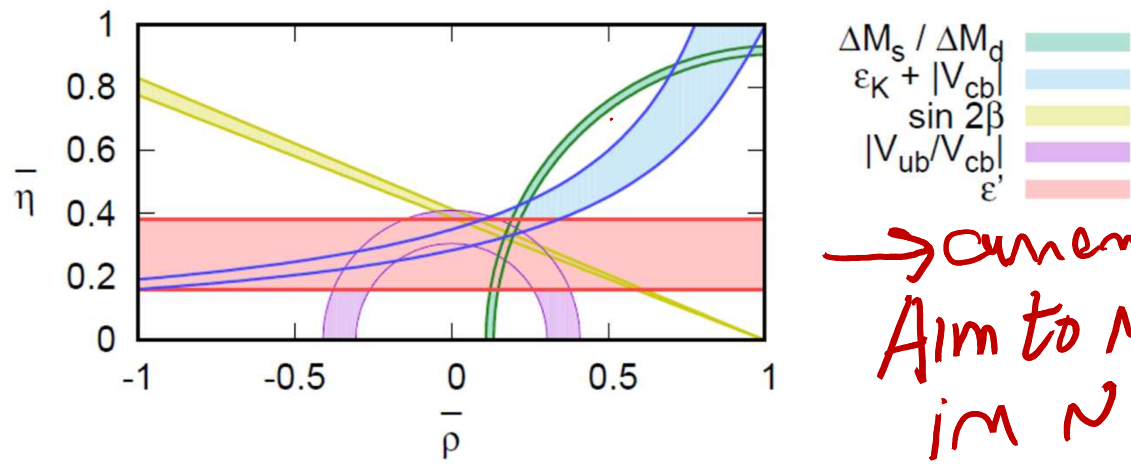
IB + EM eff

$$\Rightarrow \quad \frac{\varepsilon'}{\varepsilon} = \frac{i\omega_+ e^{i(\delta_2-\delta_0)}}{\sqrt{2}\varepsilon}\left[\frac{\mathrm{Im}(A_2^{\mathrm{emp}})}{\mathrm{Re}(A_2^{(0)})} - \frac{\mathrm{Im}(A_0^{(0)})}{\mathrm{Re}(A_0^{(0)})}\left(1-\hat{\Omega}_{\mathrm{eff}}\right)\right].$$

$\sim (17 \pm 9.1) \times 10^{-2}$

See Cirigliano et al 1911.01359

THIS IS NOT our work ← WE CHOOSE TO include THIS in our syst error



→ current syst error ~35%.
Aim to reduce this
in ~3 yrs to ≈15%.

FIG. 12: The horizontal-band constraint on the CKM matrix unitarity triangle in the $\bar{\rho} - \bar{\eta}$ plane obtained from our calculation of ε', along with constraints obtained from other inputs [6, 70, 71]. The error bands represent the statistical and systematic errors combined in quadrature. Note that the band labeled ε' is historically (e.g. in Ref. [72]) labeled as ε'/ε, where ε is taken from experiment.

Naturalness: an important consideration

A firm believer in naturalness

- **Used to be OSCILL8   (through the 80's while @UCLA)**

Implications for NP & Naturalness

DRAWING STRONG CONCLUSIONS BASED on 20% tests is TOO RISKY!

& Too Premature

OR 35%

scalars'13; 9/13/13 A. Soni HET-BNL 9

A lesson from history (I)

"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \rightarrow \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

-Lev Okun, "The Vacuum as Seen from Moscow"

1964: BF= 2×10^{-3}

A failure of imagination ? Lack of patience ?

CHristenson, Cronin, FITCH + TURLAY BNL '64

Icing on the cake

CERN-TH-2020-058, MIT-CTP/5197

Direct CP violation and the $\Delta I = 1/2$ rule in $K \to \pi\pi$ decay from the Standard Model

R. Abbott,[1] T. Blum,[2,3] P.A. Boyle,[4,5] M. Bruno,[6] N.H. Christ,[1]
D. Hoying,[3,2] C. Jung,[4] C. Kelly,[4] C. Lehner,[7,4] R.D. Mawhinney,[1]
D.J. Murphy,[8] C.T. Sachrajda,[9] A. Soni,[4] M. Tomii,[2] and T. Wang[1]
(RBC and UKQCD Collaborations)
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(Dated: April 21, 2020)

Report of the Referee -- DS12692/Abbott

In their manuscript “Direct CP violation ... ", Abbott et al present a new lattice calculation of the real and imaginary parts of the isospin 0, K->\pi\pi amplitude, A_0. Combined with earlier results for the I=2 amplitude, A_2, this calculation allows the authors to present new results for \epsilon', the measure of direct CP-violation in K->\pi\pi decays, and for the Delta I=1/2 enhancement ratio, Re A_0/Re A_2.

This is an impressive piece of work presented in a beautifully written manuscript. The paper reports on a hugely challenging lattice QCD calculation which is a near culmination of decades of developments and innovations from members of the team, as well as from the larger lattice QCD community. Its results also represent a landmark for particle physics: the first controlled calculation, in the standard model, of \epsilon'/\epsilon, whose measurement was evidence of direct CP violation and took over 20 years of experimental ingenuity to establish at the level of 5 standard deviations; the confirmation of their 2015 work on the standard model origin of the Delta I=1/2 enhancement.

The authors should also be highly commended for clearly debugging the result of their 2015 work on the same subject, and for showing how the many improvements which they have implemented allow them to get a much better handle on systematic errors. In that work, the team published a result for Im A_0 that is 2.2 combined standard deviations (including possibly double counted errors) or 3.7 times smaller than the result presented here. They also had presented a result for the I=0, \pi\pi-scattering phase shift, \delta_0^0, that is 1.6 combined standard deviations (including possibly double counted errors) smaller. While their 2015 results displayed some tension with experiment, their new result for \epsilon'/\epsilon, with a 40% error, and for \delta_0^0, with a 6% error, no longer do. The main aspect which is missing for this calculation to claim a full control over systematic errors is one, preferably two, finer lattices spacings for the matrix element calculations as well as a continuum limit for the step scaling.

Nonetheless, given the conservative errors on their final results, I can only very strongly recommend the publication of this manuscript in Physical Review D.

Relate to KL=>pi0 nu nu; K+; ε, ε'…….

- WIP with E Lunghi

K-UT: A dream for some

Blucher, Winstein and Yamanaka '09; see also Buras

Construction of a Kaon UT

LITTENBERG PRD '89

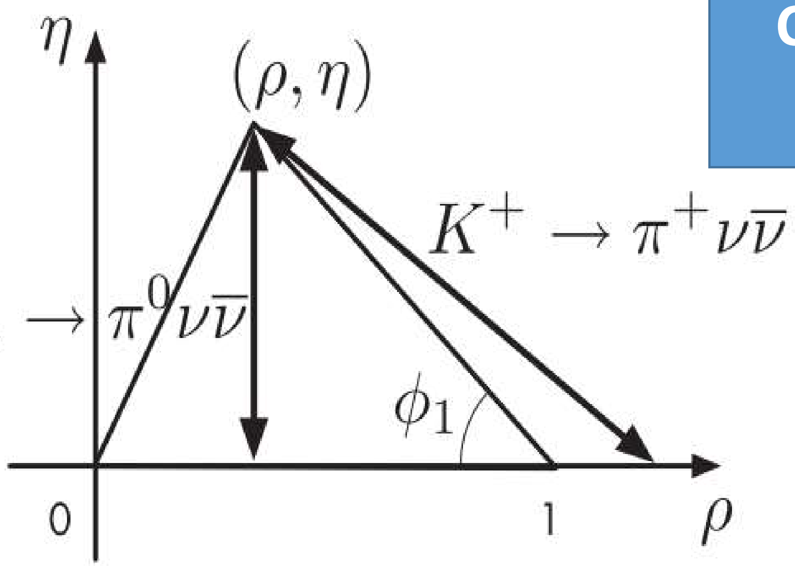


Fig. 14. Unitarity triangle.

Lehner+Lunghi+AS PLB '2016

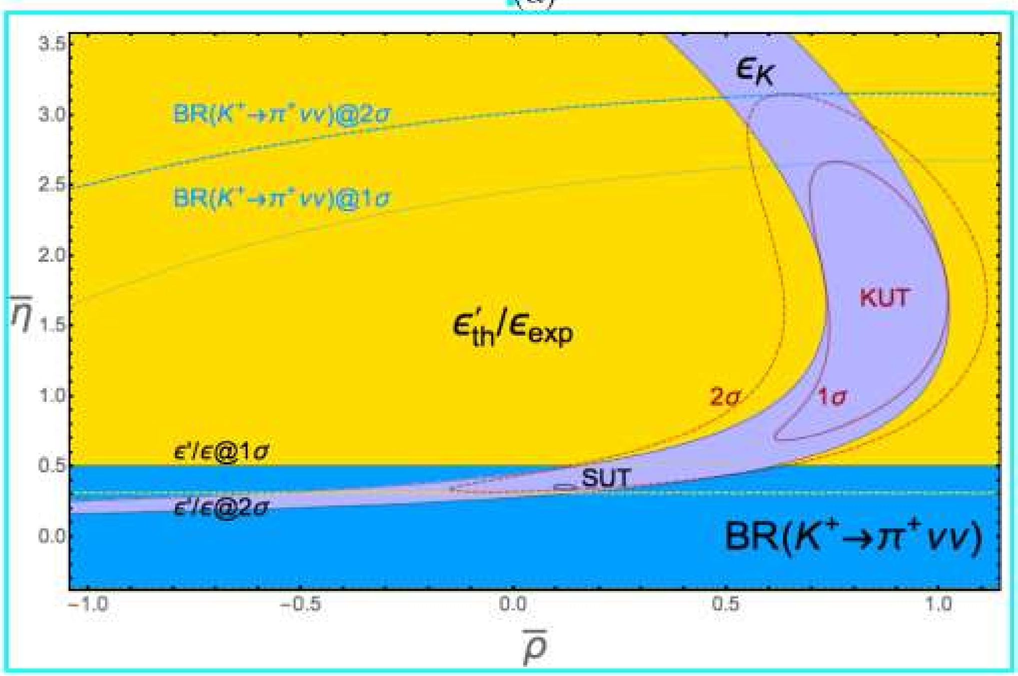
Instead of [or in addition to] $K_L \to \pi^0 \nu\bar{\nu}$ can now plan on using ϵ'/ϵ

Sketch of an emerging K-UT: 3 key Kaonic inputs.

I ϵ_K Indirect CP

II $$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \begin{cases} (8.64 \pm 0.60) \times 10^{-11} & \text{SM} \\ (17.3^{+11.5}_{-10.5}) \times 10^{-11} & \text{E949} \end{cases}$$ BNL

(a)

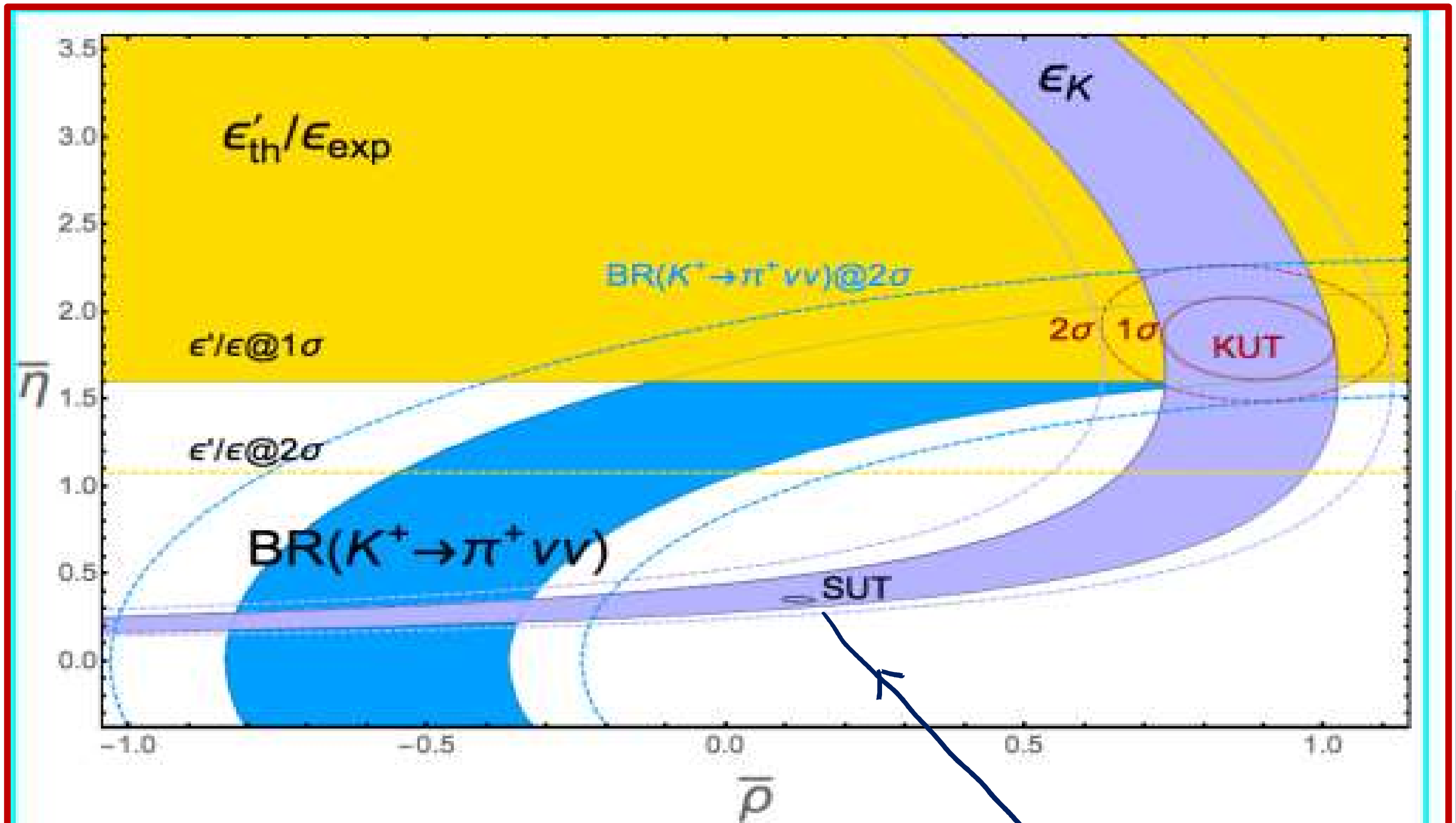


III $$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)_K = \begin{cases} (16.7 \pm 1.6) \times 10^{-4} \\ (1.36 \pm 5.21_{\mathrm{stat}} \pm 4.49_{\mathrm{syst}}) \times 10^{-4} \end{cases}$$

PDG 2015

RBC+UKQCD '15

Possible KUT circa 2020: due NA62 + RBC-UKQCD



NO unique ρ, η

Assumed: NA62, 100 events with ~7% error
RBC-UKQCD, δ(ImA0)~18%
[current ~60%]

"Standard" (B) UT

Lehner, Lunghi + AS PLB'16

Summary + Outlook 1 of 2 pages

- **After decades of effort, overcoming major hurdles, using DWQ with essentially continuum-like fermions along with improved renormalization methodology, cutting edge statistical analysis and algorithmic advances, RBC-UKQCD is presenting an updated result on SM-eps' ~ 21.7(26)(62)(50)X10^{-4} which is compatible [within errors] with the measured value 16.6(2.3)X10^{-4}**
- **Bearing in mind that this is an extremely treacherous calculation loaded with numerous avenues of errors and oversights, an independent calculation has been in process for about ~3 years within RBC-UKQCD. This effort is led by Tom Blum with (then g.s.) Dan Hoying/Masaaki Tomii, U Conn-BNL, Taku Izubuchi et al. This path uses PBC unlike the currently finished result which used GPBC…we hope to have 1st results from PBC in ~ 2 years.**
- **Also GPBC effort will be continued at other lattice spacing(s)**

Summary + Outlook

- **Lattice efforts to incorporate IB + EM effects are being studied but have some ways to go before they can tackle K=> pi pi and eps'**
- **With physical pions, kaons and such first glance at lattice ChPT is quite encouraging, see RBC-UKQCD, David Murphy et al 2015 and DM, PhD thesis, Columbia Univ**
- **This begs the question that much simpler path could now be used via BDSPW [LO ChPT] and/or L+S [NLOChPT] to address eps'…This could be tens of times simpler though at some cost in accuracy……….all this needs to be studied…Mattia Bruno, Christoph Lehner + AS et al**
- **Hope to have an improved result on eps' with O(15%) errors in ~3 years**

EXTRAS

The RBC & UKQCD collaborations

BNL and BNL/RBRC

Yasumichi Aoki (KEK)
Taku Izubuchi
Yong-Chull Jang
Chulwoo Jung
Meifeng Lin
Aaron Meyer
Hiroshi Ohki
Shigemi Ohta (KEK)
Amarjit Soni

UC Boulder

Oliver Witzel

CERN

Mattia Bruno

Columbia University

Ryan Abbot
Norman Christ
Duo Guo
Christopher Kelly
Bob Mawhinney
Masaaki Tomii
Jiqun Tu

Bigeng Wang
Tianle Wang
Yidi Zhao

University of Connecticut

Tom Blum
Dan Hoying (BNL)
Luchang Jin (RBRC)
Cheng Tu

Edinburgh University

Peter Boyle
Luigi Del Debbio
Felix Erben
Vera Gülpers
Tadeusz Janowski
Julia Kettle
Michael Marshall
Fionn Ó hÓgáin
Antonin Portelli
Tobias Tsang
Andrew Yong
Azusa Yamaguchi

UAM Madrid

Julien Frison

University of Liverpool

Nicolas Garron

MIT

David Murphy

Peking University

Xu Feng

University of Regensburg

Christoph Lehner (BNL)

University of Southampton

Nils Asmussen
Jonathan Flynn
Ryan Hill
Andreas Jüttner
James Richings
Chris Sachrajda

Stony Brook University

Jun-Sik Yoo
Sergey Syritsyn (RBRC)

RBC
R=RIKEN-BNL-Research Center
B=BNL-HET
C=Columbia

UKQCD
Subgroup that of UKQCD that uses DWQ

Edinburgh
Southampton

UDCSTBGZ Has been since '89 (while @ BNL)

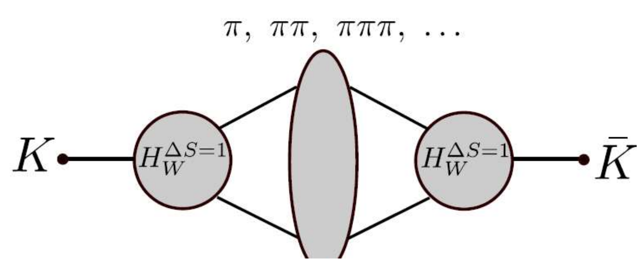
CK@CKM'18

B.Wang@ LAT'18

- Neutral kaon mixing induced by 2[nd] order weak processes gives rise to mass difference between K_L and K_S

$$\Delta M_K = 2 \sum_n \frac{\langle \overline{K}^0 | H_W | n \rangle \langle n | H_W | K^0 \rangle}{M_K - E_n}$$

- FCNC → highly suppressed in SM due to GIM mechanism: $\Delta m_K = 3.483(6)\text{x}10^{-12}$ MeV small and highly sensitive to new BSM FCNC.
- PT calc using weak EFT with $\Delta S=2$ eff. Hamiltonian (charm integrated out) dominated by $p \sim m_c$: poor PT convergence at charm scale → ~36% PT sys error.
- PT calc neglects long-distance effects arising when 2 weak operators separated by distance $\sim 1/\Lambda_{QCD}$.
- Use lattice to evaluate matrix element of product of $H_W^{\Delta S=1,\,\text{eff}}$ directly:

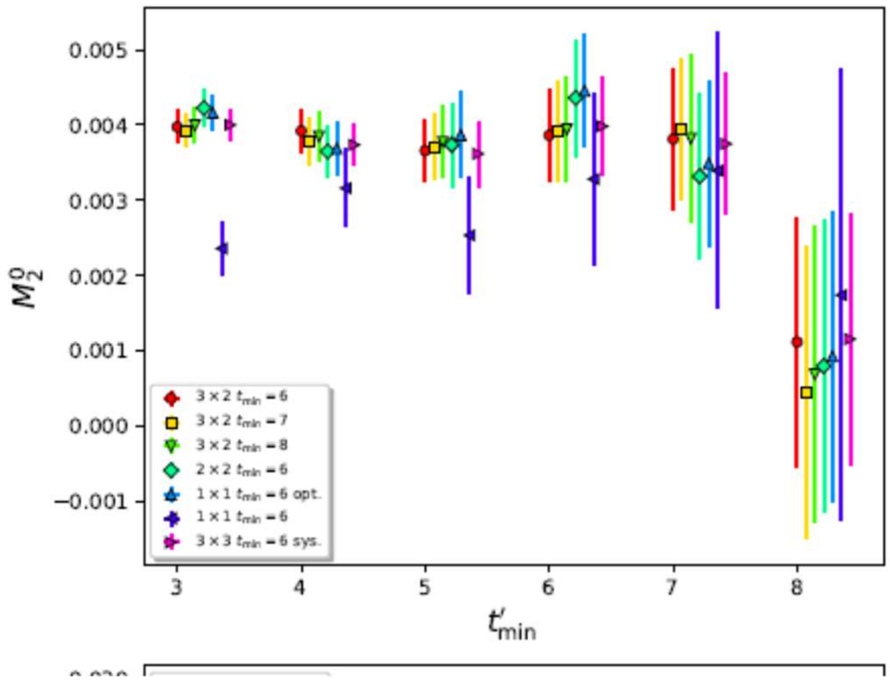


Remarks

- **In the past ~6 years, RBC-UKQCD developed methods for extended applications of Lellouch-Lusher method to 2 insertions of the weak operator for tackling non-local matrix elements [NLME]**
- **ALL loop suppressed transitions in the SM receive some**

no

- **ΔmK extremely sensitive to BSM 'cause as a rule they contain [unlike SM] non-$(V\text{-}A)^2$; see Beall, Bander, AS PRL'82 => 1st target of our effort for NLME has been therefore ΔmK**
- **Pert. Theory @ NNLO [see Brod + Gorbahn, PRL 2012] estimates ~40% LD contamination; not reliable as NLO estimates [Herrlich + Nierste] were about the same…may well be indicating poor convergence of pert. Theory.**


0.005
0.004
0.003
0.002
0.001
0.000
−0.001
M_2^0
3
4
5
6
7
8
$t'_{\rm min}$
3 × 2 $t_{\rm min}$ = 6
3 × 2 $t_{\rm min}$ = 7
3 × 2 $t_{\rm min}$ = 8
2 × 2 $t_{\rm min}$ = 6
1 × 1 $t_{\rm min}$ = 6 opt.
1 × 1 $t_{\rm min}$ = 6
3 × 3 $t_{\rm min}$ = 6 sys.

Quantity	Value
$\mathrm{Re}(A_0)$	$2.99(0.32)(0.59)\times10^{-7}$ GeV
$\mathrm{Im}(A_0)$	$-6.98(0.62)(1.44)\times10^{-11}$ GeV
$\mathrm{Re}(A_0)/\mathrm{Re}(A_2)$	19.9(2.3)(4.4)
$\mathrm{Re}(\varepsilon'/\varepsilon)$	0.00217(26)(62)(50)

TABLE I: A summary of the primary results of this work. The values in parentheses give the statistical and systematic errors, respectively. For the last entry the systematic error associated with electromagnetism and isospin breaking is listed separately as a third error contribution.

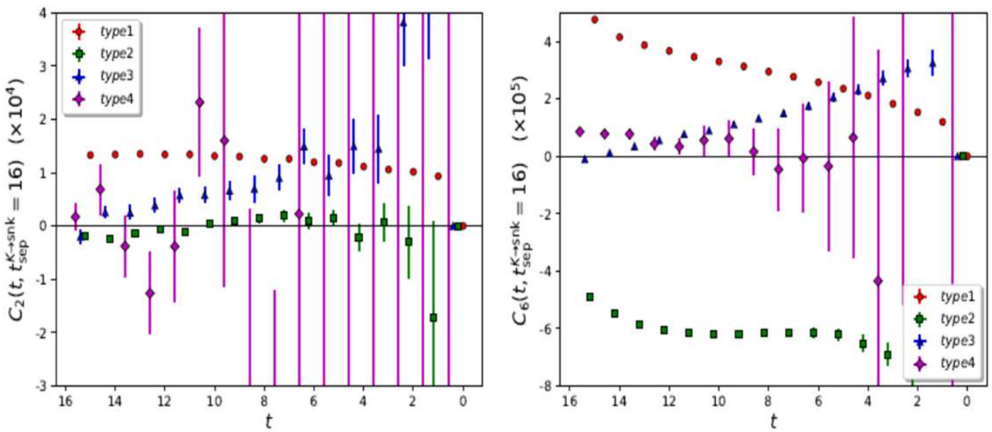


FIG. 3: The contributions of the four Wick contraction topologies *type1*-*type4* to the C_2 (left) and C_6 (right) three-point functions with the $\pi\pi(111)$ sink operator, plotted as a function of the time separation between the kaon and the four-quark operator, t, at fixed $t_{\text{sep}}^{K\to\text{snk}} = 16$. For clarity we plot with an inverted x-axis such that the $\pi\pi$ sink operator is on the left-hand side. These correlation functions include the subtraction of the pseudoscalar operator.

SHOULD WE BE SHOCKED TO FIND THAT THE SCALE OF NEW PHYSICS IS NOT ~ 1 TEV & APPEARS TO BE HIGHER?

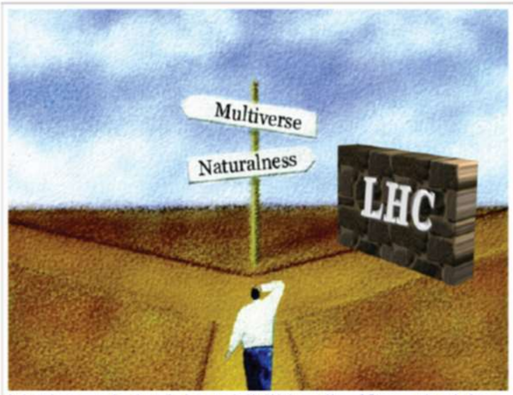
scalars'13; 9/13/13 A. Soni HET-BNL 11

Is Nature Unnatural?

Decades of confounding experiments have physicists considering a startling possibility: The universe might not make sense.

by: Natalie Wolchover

May 24, 2013 email print



Is the universe natural or do we live in an atypical bubble in a multiverse? Recent results at the Large Hadron Collider have forced many physicists to confront the latter possibility. (Illustration: Giovanni Villadoro)

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Science Lives

Localization parameters of the 3-families of quarks

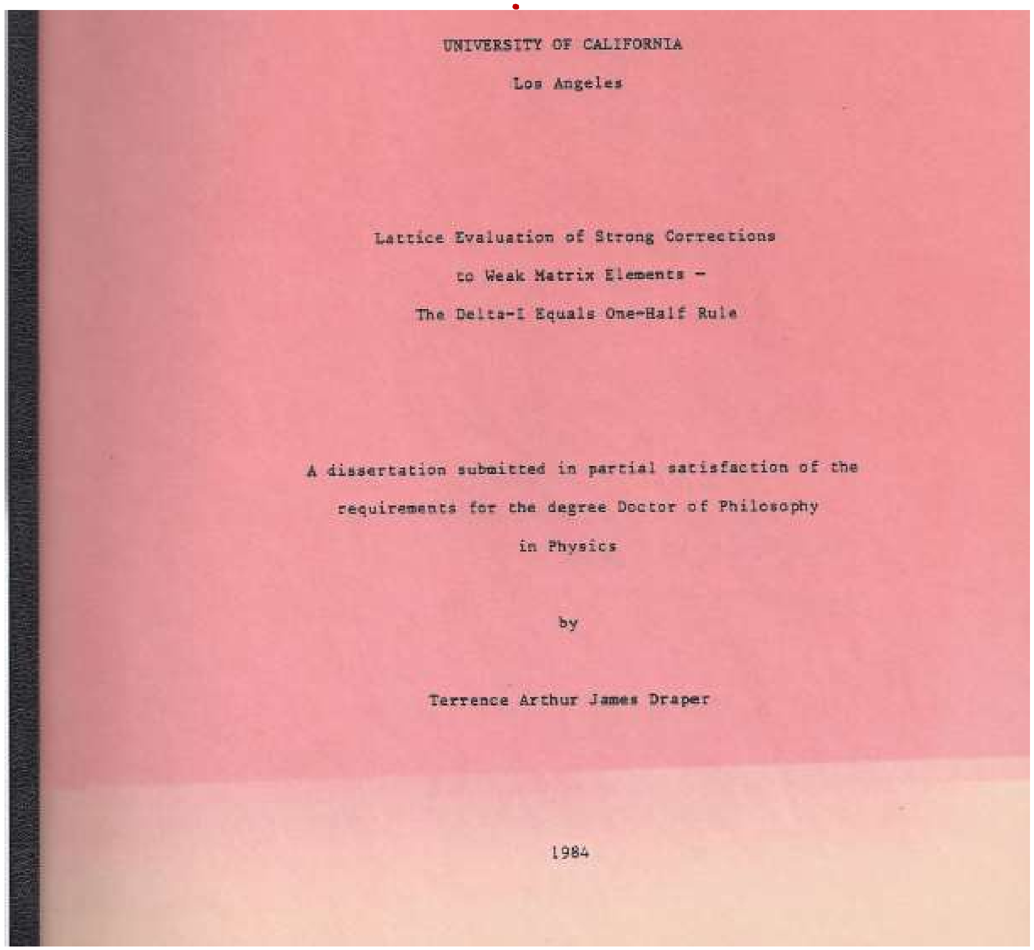
$c_{Q_1} = -0.579\,,$	$c_{Q_2} = -0.517\,,$	$c_{Q_3} = -0.473$
$c_{u_1} = -0.742\,,$	$c_{u_2} = -0.558\,,$	$c_{u_3} = +0.339$
$c_{d_1} = -0.711\,,$	$c_{d_2} = -0.666\,,$	$c_{d_3} = -0.553$

Table from M. Neubert @Moriond09

⇒ masses of the 6 quarks in RS!

[HOWEVER, it does *not* predict masses]

The 1st PhD Thesis



UNIVERSITY OF CALIFORNIA

Los Angeles

Lattice Evaluation of Strong Corrections

to Weak Matrix Elements –

The Delta-I Equals One-Half Rule

A dissertation submitted in partial satisfaction of the

requirements for the degree Doctor of Philosophy

in Physics

by

Terrence Arthur James Draper

1984

Grew from End of year Beer Party ~ June 20, 1982!!

[UCLA]

Beware of End of year Beer Parties!

Fermion "geography" (localization) naturally explains:

Grossman&Neubert; Gherghetta&Pomarol; Davoudiasl, Hewett & Rizzo

- **Why they are light (or heavy)**
- **FCNC for light quarks are severely suppressed automatically**
- **RS-GIM MECHANISM (Agashe, Perez,AS'04) flavor changing transitions though at the *tree level* (resulting from rotation from interaction to mass basis)are suppressed roughly to the same level as the loop in SM=> CKM mixings (& mass) hierarchy.**
- **O(1) CP ubiquitous;…..nedm, in fact ALL DIR-CP [ε'/ε, γ, ΔACP(B=>Kπ),Δ(Sin2β);S[B=>K* $\rho\gamma$]; ΔACP(D)..] are an exceedingly important path to BSM-phase and new physics**
- **Most flavor violations are driven by the top**

-> ENHANCED t-> cZ(h) ….A VERY IMPORTANT "GENERIC" PREDICTION, Agashe, Perez, AS'06

$\epsilon_K, \Delta M_K : 10^3$ TeV $\Longrightarrow RS_{Fl} \sim 10$ TeV

EXTENSIVE STUDIES by BURAS et al and by NEUBERT et al