“Advances in direct CP violation"

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Workshop on Future of Fundamental Physics
Crete, Kolymbari, Greece
6th International Conference on New Frontiers in Physics (ICNFP 2017)
08/28/17
DIRECT CP: Long-standing challenge for theorists
outline

• Intro: Recapitulate, different manifestations of CPV

• In B-physics after many failed attempts, ADS et al: from brown muck to data driven precise deduction of strong phases with maximal interference & O(1) direct CP...leading to ν....a “standard candle”

• In K=>ππ decays, direct CP, ε’: From mud to uniquely precious beacon of new physics; primarily due to significant progress in lattice calculations after decades of relentless effort. Resolution of LONG STANDING (~60 Years) text book problems and extreme sensitivity to new physics.....major focus of this talk
Dedicated to the memory of Myron Bander, who decades ago started me off in the interesting and important path of Direct CP.

My 1st paper on B-Physics

**CP Noninvariance in the Decays of Heavy Charged Quark Systems**

Myron Bander, D. Silverman, and A. Soni
Department of Physics, University of California, Irvine, California 92717
(Received 9 May 1979)

Within the context of a six-quark model combined with quantum chromodynamics we study the asymmetry in the decay of heavy charged mesons into a definite final state as compared with the charge-conjugated mode. We find that, in decays of mesons involving the $b$ quark,
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 entails new phase(s)

• Examples: 4G SM: + 2; LRS: at least + 1; 2HDM: neutral scalar sector as well as charged sector can have new phases; SUSY or WEXD: tens of new CP-odd phases in general may be there

• SM cannot account of baryogenesis.....CKM CP not enough

• Due to all of the above (and some more), searching for BSM phases is just about the best way to look for NP.....an early realization & a driving force for past few decades
Different manifestations of CP

• Mixing: Indirect CPV

\[ |\epsilon_K| \approx 2.2 \times 10^{-3} \]

BNL '64

I. \[ K_\mu \rightarrow \pi^+ \pi^- \]

For B: Bander, Silverman, A.S, PRL'79 for B-decays

Carter & Sanda, PRL'80

Bigi & Sanda, NPB'81

Highly instrumental in the dramatic success of the B-factories and the KM Nobel Prize

II. \[ \Re(\epsilon'/\epsilon) \sim 1.65 \times 10^{-3} \]

CERN + FNAL ~ 2004

• Decay (direct, time-integrated)

For K: Gilman + Wise PLB, PRD '79; Wise Stanford thesis

• Mixing and decay (time-dependent)

\[ S(B^0 \rightarrow 4 K^0) = \sin \varphi \approx 0.673 \]
Simple ex. Of DCP in B-Physics: Tree-Penguin Interference

$$A = |A_1| \exp[i(\delta_1 + \phi_1)] + |A_2| \exp[i(\delta_2 + \phi_2)]$$

$$\overline{A} = |A_1| \exp[i(\delta_1 - \phi_1)] + |A_2| \exp[i(\delta_2 - \phi_2)].$$

$$\alpha_{PRA} = \frac{\mathcal{B}(B \rightarrow f) - \mathcal{B}(\overline{B} \rightarrow \overline{f})}{\mathcal{B}(B \rightarrow f) + \mathcal{B}(\overline{B} \rightarrow \overline{f})} = \frac{2|A_1||A_2| \sin \delta \sin \phi}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2| \cos \delta \cos \phi},$$

Bander, Silverman and A. S. PRL ’79

Measureable asymmetries may arise. This would present the first evidence for CP non-invariance in charged systems.

Babar, Belle 1st obs ~ 2007

$$\alpha (B^0 \rightarrow K^+\pi^-) = -0.082 \pm 0.006$$

5 orders $\approx \mathcal{E}_K$!!

Regrettably still cannot be used to reliably test the SM-CKM
By now multitude of channels with large DCP ...$b\rightarrow s$ and $b\rightarrow d$

\begin{align*}
A_{CP}(B^0 \rightarrow K^+ \pi^-) &= -0.082 \pm 0.006 \\
A_{CP}(B^0 \rightarrow \eta K^*(892)^0) &= 0.19 \pm 0.05 \\
A_{CP}(B^0 \rightarrow K^*(892)^+ \pi^-) &= -0.22 \pm 0.06 \\
A_{CP}(B^+ \rightarrow \eta K^+) &= -0.37 \pm 0.08 \\
A_{CP}(B^+ \rightarrow K^+ \pi^- \pi^+) &= 0.027 \pm 0.008 \\
A_{CP}(B^+ \rightarrow f_2(1270) K^+) &= -0.68^{+0.19}_{-0.17} \\
A_{CP}(B^+ \rightarrow \rho^0 K^+) &= 0.37 \pm 0.10 \\
A_{CP}(B^+ \rightarrow K^+ K^- \pi^+) &= -0.118 \pm 0.022 \\
A_{CP}(B^+ \rightarrow K^+ K^- K^+) &= -0.033 \pm 0.008 \\
A_{CP}(B^+ \rightarrow \pi^+ \pi^- \pi^+) &= 0.057 \pm 0.013 \\
A_{CP}(B^+ \rightarrow f_0(1370) \pi^+) &= 0.72 \pm 0.22 \\
A_{CP}(B_s \rightarrow \pi^+ K^-) &= 0.263 \pm 0.035
\end{align*}

Very large dir CP in many cases!
Direct CP: Long-standing challenge for theorists

\[ A = |T| + |P| \exp \left[ i \delta_{\text{st}} + i \delta_{\text{wk}} \right] \]

\[ \bar{A} = |T| + |P| \exp \left[ i \delta_{\text{st}} - i \delta_{\text{wk}} \right] \]

\[ a_{\text{CP}}(\text{PRA}) = \frac{B[i \rightarrow f] - B[i \rightarrow \bar{f}]}{B[i \rightarrow f] + B[i \rightarrow \bar{f}]} \]

\[ = \frac{|T||P| \sin \delta_{\text{st}} \sin \delta_{\text{wk}}}{|T|^2 + |P|^2 + 2|T||P| \cos \delta_{\text{st}} \cos \delta_{\text{wk}}} \]

\text{UNKNOWNS 4:} \ \mu, \ |P|, \ \delta_{\text{st}}, \ \delta_{\text{wk}}

\text{OBSERVABLES 3} \ \ |T|^2, \ |P|^2, \ a_{\text{CP}}(\text{PRA}) \ \ \text{DESPERATELY NEED } \delta_{\text{st}}!
• From Theory need non-perturbative framework.
• For K (ε’/ε) on going lattice efforts for ~35 years!
• also significant progress [by RBC-UKQCD] in related problem of the Δl = 1/2 PUZZLE
• Lattice methods not yet available for D, B though considerable attention
• For B, many pheno. attempts, see e.g. I. Resonance dominance .... width contains info of δ_{st}
  Eilam, Hewett, AS, PRL’91; Atwood+AS, Zphys’94
• II. B=>D K channels .....O(1) dir CP! With most precise determination of γ
  Atwood,Dunietz,AS, PRL’97 .........

Now δ_{st} 70 ± 10°

Expected Theory precision √ few x 10^{-3}!
In practice, by now, with $O(10^9)$ B-pairs, many common D0 modes, as well as closely related methods due Gronau and Wyler and Giri, Grossman, Soffer and Zupan... Combination leads to data driven direct determination of $\gamma \sim 70 \pm 8$ degrees.

For 2 decay modes of $D^0, \bar{D}^0$, $i=1,2$, you have 4 unknowns:

\[
\left\{ \xi^K_{f_1}, \xi^K_{f_2}, b(K), \gamma \right\}
\]

2 strong phases, a suppressed $B\eta$ and the precious CP phase $\gamma$.

**ADS:** PRL 1997; PRD 2001

Data Driven method for extracting gamma; DESIGNED FOR O(1) CP!
A great personal treat; thanks to LHCb

**ForMin** data driven metrics

\[ A_{\text{ADS}(K)}^{\pi K} = -0.403 \pm 0.056 \pm 0.011 \]

Huge direct CP [tailor made] \sim 20 years ago!
ADS PRL’97

[Recall \( \epsilon' \sim 10^{-2} \) !] **DESIGNED FOR MAXIMAL INTERFERENCE**

**FIG. 1.** Diagrams for the two interfering processes: \( B^- \rightarrow K^- D^0 \) (color-allowed) followed by \( D^0 \rightarrow K^+ \pi^- \) (double Cabibbo suppressed) and \( B^- \rightarrow K^- \overline{D}^0 \) (color-suppressed) followed by \( \overline{D}^0 \rightarrow K^+ \pi^- \) (Cabibbo allowed).
Efforts to overconstrain the CKM Matrix & UT continue

Key new results from LHCb

Precision on $\sin(2\beta)$ approaches that of B-factories: $0.73 \pm 0.04 \pm 0.02$

- A world-leading measurement of $\gamma$ is made from a combination of LHCb analysis, concluding with

$$\gamma = 70.9^{+7.1}_{-8.5}$$

which improved the previous LHCb-only conclusion by $2\degree$

- Inline with B-factory conclusions from $B \rightarrow DK$,
  - BaBar: $\gamma = (70\pm18)\degree$
  - Belle: $\gamma = (73^{+13}_{-15})\degree$

Compatible with SM-CKM to $\sim15\%$ accuracy

O(5-10%) new physics is possible and is HUGE

BELLE-II & LHCb(upgrade) $\rightarrow \delta B 0/10, still long way to go before ultimate precision
ICHEP2014: Similar results from UFIT (D. Derkach) as well from G. Eigen et al.

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: $BF = 2 \times 10^{-3}$

A failure of imagination? Lack of patience?
II. Dir CP in K=\(\pi\pi\), i.e. \(\epsilon'/\epsilon\)

In this case the key, in large part, is advances in lattice calculations...Extremely arduous path that took decades to develop
\[\epsilon' / \epsilon: \text{Direct CPV} \]

\[\eta_{++} = |\eta_{++}| e^{i\phi_{++}} = \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)}\]

\[\eta_{00} = |\eta_{00}| e^{i\phi_{00}} = -\frac{A(K_L \rightarrow \pi^0\pi^0)}{A(K_S \rightarrow \pi^0\pi^0)}\]

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

\[\epsilon' = \frac{1}{3} \left( \eta_{++} - \eta_{00} \right) \Rightarrow O(10^3) - O(10^5) \Rightarrow 10^{-6}\]

\[\epsilon = \frac{1}{3} \left[ 2\eta_{++} + \eta_{00} \right]\]
\[ \text{Re} \left( \frac{\epsilon'}{\epsilon} \right) = \frac{\omega}{\sqrt{2} \epsilon} \left[ \frac{\text{Im}(A_2)}{\text{Re}(A_2)} - \frac{\text{Im}(A_0)}{\text{Re}(A_0)} \right] \]

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

\[ \text{Re} (\epsilon'/\epsilon) = 1.65(26) \times 10^{-3}. \]

FROM THEORY

\[ I = 2 \text{ amp} \]

\[ I = 0 \text{ amp} \]

\[ \omega = \frac{\text{Re} A_2}{\text{Re} A_0} \]

INDIRECT CP

\[ \text{BNL'84} \]

Crumlin+Fitch

NP

DIRECT CP

\[ \epsilon \sim O(10^{-6})! \]

CERN+FNAL \( \sim \) 2004

K \( \rightarrow \) 2\( \pi \)

\[ \frac{\text{Re} A_D}{\text{Re} A_2} \approx 25 \]

\[ \Delta I = 1/2 \text{ Puzzle} \]
### I. Wilson Fermions with Bernard ~‘82
See also Martinelli et al [WF] Broweret al Sharpe et al [Stag F]

| II (a) DWF with Blum ~’95 | LOχPT; Quenched approx.[QA] Same QA is disastrous for this physics [Golterman-Pallante] pathologies; NPR of full ΔS=1 accomplished for the 1st time used since then. | CRAY @ NERSC QCDSP ~ 1 TF |
| II(b) DWF with RBC[with Blum, Christ and Mawhinney became “flagship” project of RBC] ~’97. | | |

### III. DWF with full QCD RBC, ~ ‘02

| Used LOχPT + full QCD Large chiral corrections | QCDSP ~ 1TF |

### IV. DWF with full QCD RBC + UKQCD, ~ ‘06

| Direct K=>ππ, [Lellouch-Luscher method] @ threshold | QCDOC ~ 10 TF |

### V. DWF with full QCD, RBC + UKQCD ~ ‘11

| Direct K=>ππ, [Lellouch-Luscher method] ; physical kinematics | BG/Q ~ 100TF@BNL; RBRC;ANL; Edinburgh |

### VI. Same ~now

| Same | new hardware ~1.5PF;NERSC;ANL;UK |

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*HUGE # of obstacles had to be overcome*
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 + 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) + many PD’s & junior facets.. obstacles & challenges (and mistakes!) ad infinitum……

- Started with CWB (Wilson); for this physics Chiral symm on the lattice is a pre-requisite [off-shoot B-physics] => on to DWF (with Tom B) => RBC with ChPT + quenched => huge quench pathologies=full QCD is mandatory for this physics; full QCD + ChPT => large chiral corrections => RBC-UKQCD direct K=> 2 π a la Lellouch- Luscher @ threshold=> @physical kinematics……
WHY FOCUS with SUCH intense DETERMINATION

Underlying Realization

$\epsilon'$: most likely a gem in search of new phenomena
Its presumed importance:

• lies in its very small size => Perhaps new phenomena has a better chance of showing up
• Smallness also renders it exceedingly important monitor of flavor – alignment
• Simple naturalness arguments strongly suggest $\varepsilon'$ very sensitive to BSM – CP odd phases
• In many ways $\varepsilon'$ is rather analogous to nedm.......both being very sensitive to BSM phases; however, key diff for (now) nedm expt is the key, theory is less critical, in sharp contrast to $\varepsilon'$
• Understanding $\varepsilon'$, nedm are extremely important for learning how naturalness really works in nature
• **MOREOVER: large accidental cancellations significantly enhances sensitivity of $\varepsilon'$ to NP [see later]**
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
For simplicity: 1st strategy via CHPT

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

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.

USE lasted 20 years
A monumental experimental achievement!

\[ \text{Re}(\varepsilon'/\varepsilon) \]

- Woods E731 A
- Burkhardt NA31
- Barr NA31
- kTeV 1999
- NA48 2001
- NA48 final
- kTeV 2003
- average

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

PDG 2014

Komad Kleinknecht "Uncertainty"

Lattice work started
Basic calculational framework
\[ \Delta S = 1 \ H_W \]

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

\[ m_i = \langle k | Q_i | \pi \rangle \text{ Needed} \]

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

W C to NLO
Buchalla, Buras, Lautenbacher
RMP 1961 Cinchietti 95
$$Q_1 = (\bar{s}_\alpha d_\alpha)_L (\bar{u}_\beta u_\beta)_L,$$
$$Q_2 = (\bar{s}_\alpha d_\beta)_L (\bar{u}_\beta u_\alpha)_L,$$
$$Q_3 = (\bar{s}_\alpha d_\alpha)_L \sum_{q=u,d,s} (\bar{q}_\beta q_\beta)_L,$$
$$Q_4 = (\bar{s}_\alpha d_\beta)_L \sum_{q=u,d,s} (\bar{q}_\beta q_\alpha)_L,$$
$$Q_5 = (\bar{s}_\alpha d_\alpha)_L \sum_{q=u,d,s} (\bar{q}_\beta q_\beta)_R,$$
$$Q_6 = (\bar{s}_\alpha d_\beta)_L \sum_{q=u,d,s} (\bar{q}_\beta q_\alpha)_R,$$
$$Q_7 = \frac{3}{2} (\bar{s}_\alpha d_\alpha)_L \sum_{q=u,d,s} e_q (\bar{q}_\beta q_\beta)_R,$$
$$Q_8 = \frac{3}{2} (\bar{s}_\alpha d_\beta)_L \sum_{q=u,d,s} e_q (\bar{q}_\beta q_\alpha)_R,$$
$$Q_9 = \frac{3}{2} (\bar{s}_\alpha d_\alpha)_L \sum_{q=u,d,s} e_q (\bar{q}_\beta q_\beta)_L,$$
$$Q_{10} = \frac{3}{2} (\bar{s}_\alpha d_\beta)_L \sum_{q=u,d,s} e_q (\bar{q}_\beta q_\alpha)_L,$$

$$T=0 \quad \Rightarrow \quad \text{QCDP}$$

$$T=2$$

$$\Rightarrow \quad \text{EWP}$$

$$\Rightarrow \quad \text{const}$$

$$\Rightarrow \quad m \rightarrow 0$$

$$\Rightarrow \quad m_q \rightarrow 0$$

$$\Rightarrow \quad \text{EWP}$$

$$\frac{S M d}{\Theta_{CP}}$$

$$\frac{S M d}{\Theta_{CP}}$$
Acknowledge many significant contributions off & on the lattice

• While focus is on lattice calculations of $K \rightarrow \pi \pi$ primarily by our RBC-UKQCD Collab

• Over the years many important contributors, in particular:

• (Mary K) Gaillard, (Ben) Lee; Altarelli, Maiani; Shifman, Vainshtein, Zhakrov; Gilman + Wise; Buras & Co; Martinelli & Co; (Claude) Bernard; de Rafael; Pich, Bijnens......
Key difficulties

- $\Delta S=1 \Rightarrow$ deadly mixing with LDO in the absence (on the lattice) of
- chiral symmetry $\Rightarrow [\overline{3d\bar{d}u}] \leftrightarrow (5q)$, $[5x\bar{d}]$
- Applications to heavy-light physics which led to precision lattice applications for the UT
- For $K \Rightarrow \pi \pi$ and epsilon $\Rightarrow$ DWF with [controllable very precise] $\chi S$
- Even with chiral symmetry, mixing amongst dim-$6$ operators can exist and is fatal ....requiring the need for full [not quenched] i.e dynamical QCD
- Blum + AS '97
- A measure of computational difficulty: $32^3 \times 64 \times 16 \times 50 \times 10 \times 5/6 \times 3 \times 17 \sim 10^8$
<k(\bar{s}v_{ud})^2 | \bar{r}r> 

\[ \frac{d}{dx} \text{K}\bar{K} \Rightarrow \text{FINE TUNING PROBLEM} \]
Lattice study of semileptonic decays of charm mesons into vector mesons

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Aida X. El-Khadra
Theory Group, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510

Amarjit Soni
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(Received 30 September 1991)

We present our lattice calculation of the semileptonic form factors for the decays $D \to K^*$, $D_1 \to \phi$, 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 $A_1(0)/A_0(0)=0.70 \pm 0.16$. Results for other form factors and ratios are also given.
A chance (crucial) meeting: Yigal Shamir visits me in Haifa ~94 summer

- Way to overcome the fine-tuning problem of Wilson Fermions
- Furman + Shamir: hep-lat/9405004
- See also Yigal Shamir, hep-lat 9303005
Axial Symmetries in Lattice QCD with Kaplan Fermions

Vadim Furman
School of Physics and Astronomy
Beverly and Raymond Sackler Faculty of Exact Sciences
Tel-Aviv University, Ramat Aviv 69978, ISRAEL

and

Yigal Shamir*
Department of Physics
Weizmann Institute of Science, Rehovot 76100, ISRAEL

practical reasons. To elucidate the importance of such framework, we can mention for example the problems involved in measuring weak matrix elements on the lattice with Wilson fermions [9, 7]. The fine tuning problem is not over when the bare masses have been fixed. Because of the hard breaking of the axial symmetries, the

WAY FORWARD: ABANDON WILSON FERMIONS ADOPT "DOMAIN WALL" F
QCD with domain wall quarks

T. Bhutia* and A. Soni†
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(Received 27 November 1996)

We present lattice calculations in QCD using Shamir's variant of Kaplan fermions which retain the continuum SU(N)\(c\) x SU(N)\(s\) 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 \(K_0\bar{K}_0\) mixing have the expected behavior in the chiral limit, even on lattices with modest extent in the extra dimension, e.g., \(N_c = 10\). [S0556-2821(97)00113-6]

1st Simulation with DWQ

Excellent Chiral Symmetry with N10 Sites in 5th Aim.
K-lambda violation

K \rightarrow 2 \tau \nu

with DWO

physical review D 68, 114036 (2003)

1st endpoint

K-matrix elements and CP violation from quenched lattice QCD: The 3-flavor case

P. Blum, T. Cunnin, C. Dawson, G. Fleming, J. A. M. Mawhinney, S. Ohm, G. Stupart, A. Soni

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Department of Physics, University of the City, New York, NY 10035, USA

Received: 19 July 2002, published: 30 December 2003

We report the results of a calculation of the K \rightarrow \tau \nu matrix elements using the lattice-QCD NJL model. The value we find for the sum of all contributions to the leading (K \rightarrow \tau \nu) matrix element is 2.2. We also include the lattice-QCD results for the K \rightarrow \tau \nu decay constants. The results are in good agreement with the experimental data. We find that the lattice-QCD results for the K \rightarrow \tau \nu decay constants are in good agreement with the experimental data. The results are in good agreement with the experimental data.
TABLE XLIX. Our final values for physical quantities using one-loop full QCD extrapolations to the physical kaon mass (choice 2) and a value of $\mu = 2.13$ GeV for the matching between the lattice and continuum. The errors for our calculation are statistical only.

<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>$(1.172 \pm 0.053) \times 10^{-8}$</td>
</tr>
<tr>
<td>$\omega^{-1}$</td>
<td>$22.2$</td>
<td>$(25.3 \pm 1.8)$</td>
</tr>
<tr>
<td>Re($\epsilon'/\epsilon$)</td>
<td>$(15.3 \pm 2.6) \times 10^{-4}$ (NA 48)</td>
<td>$(-4.0 \pm 2.3) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>$(20.7 \pm 2.8) \times 10^{-4}$ (KTEV)</td>
<td></td>
</tr>
</tbody>
</table>
Extremely serious quench pathology

- Most important for Q6 as it LR=> (S+P)(S-P); AND it makes the most important contribution to $\varepsilon'$

Source of problem is that $H_{\text{eff}}$ for $\Delta S=1$ has operators such as Q6 with Quark content

\[
\begin{pmatrix}
\bar{u}d \\
\end{pmatrix} \rightarrow \text{quark loop from weak interaction}
\]

Quench approx

\[
Q_6 \text{ get unphysical contribution to } Q_8
\]
**Conclusion**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>This analysis</th>
<th>Quenched</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ReA_0$ (GeV)</td>
<td>$4.5(11)(53) \times 10^{-7}$</td>
<td>$2.96(17) \times 10^{-7}$</td>
<td>$3.33 \times 10^{-7}$</td>
</tr>
<tr>
<td>$ReA_2$ (GeV)</td>
<td>$8.57(99)(300) \times 10^{-9}$</td>
<td>$1.172(53) \times 10^{-8}$</td>
<td>$1.50 \times 10^{-8}$</td>
</tr>
<tr>
<td>$ImA_0$ (GeV)</td>
<td>$-6.5(18)(77) \times 10^{-11}$</td>
<td>$-2.35(40) \times 10^{-11}$</td>
<td></td>
</tr>
<tr>
<td>$ImA_2$ (GeV)</td>
<td>$-7.9(16)(39) \times 10^{-13}$</td>
<td>$-1.264(72) \times 10^{-12}$</td>
<td></td>
</tr>
<tr>
<td>$1/\omega$</td>
<td>$50(13)(62)$</td>
<td>$25.3(1.8)$</td>
<td>$22.2$</td>
</tr>
<tr>
<td>$Re(\epsilon'/\epsilon)$</td>
<td>$7.6(68)(256) \times 10^{-4}$</td>
<td>$-4.0(2.3) \times 10^{-4}$</td>
<td>$1.65 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

- ChPT approach to $K \rightarrow \pi \pi$ faces **severe difficulties**.
- RBC/UKQCD studying **physical $\pi \pi$ final states**.
- DWF on coarse lattices and large volumes: $4 \rightarrow 5$ fm?
- Vranas auxiliary determinant (Renfrew talk on Wed.)

**LARGE SYSTEMATIC ERRORS DUE CHPT**
Direct $K \to \pi\pi$ (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.
UKQCD Collaboration

- Edinburgh
  - Peter Boyle
  - Luigi Del Debbio
  - Julien Frison
  - Jamie Hudspith
  - Richard Kenway
  - Ava Khamseh
  - Brian Pendleton
  - Karthee Sivalingam
  - Oliver Witzel
  - Azusa Yamaguchi

- Plymouth
  - Nicolas Garron

- York (Toronto)
  - Renwick Hudspith

- Southampton
  - Jonathan Flynn
  - Tadeusz Janowski
  - Andreas Juttner
  - Andrew Lawson
  - Edwin Lizarazo
  - Antonin Portelli
  - Chris Sachrajda
  - Francesco Sanfilippo
  - Matthew Spraggs
  - Tobias Tsang

- CERN
  - Marina Marinkovic
RBC Collaboration

• **BNL**
  - Chulwoo Jung
  - Taku Izubuchi (RBRC)
  - Christoph Lehner
  - Meifeng Lin
  - Amarjit Soni

• **RBRC**
  - Chris Kelly
  - Tomomi Ishikawa
  - Taichi Kawanai
  - Shigemi Ohta (KEK)
  - Sergey Syritsyn

• **Columbia**
  - Ziyuan Bai
  - Xu Feng
  - Norman Christ
  - Luchang Jin
  - Robert Mawhinney
  - Greg McGlynn
  - David Murphy
  - Daiqian Zhang

• **Connecticut**
  - Tom Blum
Results for $\varepsilon'$

Using $\text{Re}(A_0)$ and $\text{Re}(A_2)$ from experiment and our lattice values for $\text{Im}(A_0)$ and $\text{Im}(A_2)$ and the phase shifts, we find a discrepancy between lattice and experiment at the 2.1σ level.

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

$\approx 1.38(5.15)(4.43) \times 10^{-4}$, (this work)

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

Bearing in mind the largish errors in this first calculation, we interpret that our result are consistent with experiment at $\sim 2\sigma$ level.

Computed $\text{Re}A_2$ excellent agreement with expt
Computed $\text{Re}A_0$ good agreement with expt
Offered an “explanation” of the Delta $I=1/2$ enhancement.

LARGE CANCELLATION!! (80-85%)
For obtaining $\varepsilon'$, 6 entities must be calculated non-perturbatively

- Re $A_0$, Re $A_2$, Im $A_0$, Im $A_2$
- $\delta_0$, $l=0$, $\pi\pi$ scattering phase shift
- $\delta_2$, $l=2$, $\pi\pi$ scattering phase shift
- Of these Re $A_0$ and Re $A_2$ are directly known from experiment and $\delta_0$, $\delta_2$ have been computed phenomenologically
- A good non-perturbative method such as the lattice should be able to compute all 6 entities ....that is exactly what we have been doing....4 of the 6 provide useful checks on our work
Rest of talk

• More details of important aspects

• Efforts of past ~2 years for significant improvement with (substantially) improved results expected ~end ‘17

• Some implications
Details of key important aspects of the calculation
While ReA0 and ReA2 and $\delta 2$ agree well with expt a possible difficulty: $\delta 0$

- The continuum and our lattice determinations of strong phase difference differs at the $\sim 2\sigma$ level:

\[
\phi_{\epsilon'} = \delta_2 - \delta_0 + \frac{\pi}{2} = \begin{cases} 
(42.3 \pm 1.5)^0 & \text{PDG[2]} \\
(54.6 \pm 5.8)^0 & \text{RBC[47, 48]} 
\end{cases}
\]

$\delta_2 \sim 43.5 \pm 0.5$

Fortunately, due to the central value of the combination $\delta_2 - \delta_0 + \pi/2 - \phi_{\epsilon}$ and to the large uncertainties in the determination of the various matrix elements, these two choices yield almost identical results; for definiteness, we refer

Lehner, Lunghi & As, 1508-01801

mit direkter accessbility expt Colangelo et al
Sensitivity of $\varepsilon'$ to strong phase(s)

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

\[
\cos (\delta_2 - \delta_0 + \pi/2 - \phi_\varepsilon)
\]

\[
\phi_\varepsilon = 42.3 \pm 1.5 \,^\circ \quad \text{Colangelo, Gusa, Lentwylu}
\]

\[
\Rightarrow \cos (\quad) \Rightarrow 0.999978 \quad ; \quad \phi_\varepsilon' = 54.6 \pm 5.8 \,^\circ \quad \text{RBC-UKQCD}
\]

Diff $\approx 2.1$ on $\varepsilon'$

\[
\Rightarrow 0.981
\]

\[
\text{phase diff of 26 BUT $\varepsilon'$ totally insensitive}!!
\]
# Table II

Representative, fractional systematic errors for the individual operator contributions to $\text{Re}(A_0)$ and $\text{Im}(A_0)$.

<table>
<thead>
<tr>
<th>Description</th>
<th>Error</th>
<th>Description</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finite lattice spacing</td>
<td>12%</td>
<td>Finite volume</td>
<td>7%</td>
</tr>
<tr>
<td>Wilson coefficients</td>
<td>12%</td>
<td>Excited states</td>
<td>$\leq$ 5%</td>
</tr>
<tr>
<td>Parametric errors</td>
<td>5%</td>
<td>Operator renormalization</td>
<td>15%</td>
</tr>
<tr>
<td>Unphysical kinematics</td>
<td>$\leq$ 3%</td>
<td>Lellouch-Lüscher factor</td>
<td>11%</td>
</tr>
<tr>
<td>Total (added in quadrature)</td>
<td></td>
<td></td>
<td>27%</td>
</tr>
</tbody>
</table>
\[ Q_2 = \frac{\text{some expression}}{n} \]

LARGE DOUBLE cancelOut

\[ \text{is dominant} \]

<table>
<thead>
<tr>
<th>i</th>
<th>( \text{Re}(A_0)(\text{GeV}) )</th>
<th>( \text{Im}(A_0)(\text{GeV}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.02(0.20)(0.07) ( \times 10^{-7} )</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>3.63(0.91)(0.28) ( \times 10^{-7} )</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>-1.19(1.58)(1.12) ( \times 10^{-10} )</td>
<td>1.54(2.04)(1.45) ( \times 10^{-12} )</td>
</tr>
<tr>
<td>4</td>
<td>-1.86(0.63)(0.33) ( \times 10^{-9} )</td>
<td>1.82(0.62)(0.32) ( \times 10^{-11} )</td>
</tr>
<tr>
<td>5</td>
<td>-8.72(2.17)(1.80) ( \times 10^{-10} )</td>
<td>1.57(0.39)(0.32) ( \times 10^{-12} )</td>
</tr>
<tr>
<td>6</td>
<td>3.33(0.85)(0.22) ( \times 10^{-9} )</td>
<td>-3.57(0.91)(0.24) ( \times 10^{-11} )</td>
</tr>
<tr>
<td>7</td>
<td>2.40(0.41)(0.00) ( \times 10^{-11} )</td>
<td>8.55(1.45)(0.00) ( \times 10^{-14} )</td>
</tr>
<tr>
<td>8</td>
<td>-1.33(0.04)(0.00) ( \times 10^{-10} )</td>
<td>-1.71(0.05)(0.00) ( \times 10^{-12} )</td>
</tr>
<tr>
<td>9</td>
<td>-7.12(1.90)(0.46) ( \times 10^{-12} )</td>
<td>-2.43(0.65)(0.16) ( \times 10^{-12} )</td>
</tr>
<tr>
<td>10</td>
<td>7.57(2.72)(0.71) ( \times 10^{-12} )</td>
<td>-4.74(1.70)(0.44) ( \times 10^{-13} )</td>
</tr>
<tr>
<td>Tot</td>
<td>4.66(0.96)(0.27) ( \times 10^{-7} )</td>
<td>-1.90(1.19)(0.32) ( \times 10^{-11} )</td>
</tr>
</tbody>
</table>

**TABLE I.** Contributions to \( A_0 \) from the ten continuum, \( \overline{\text{MS}} \) operators \( Q_i(\mu) \), for \( \mu = 1.53 \) \( \text{GeV} \). Two statistical errors are shown: one from the lattice matrix element (left) and one from the lattice to \( \overline{\text{MS}} \) conversion (right).
Regarding ReA0: understanding the $\Delta l=1/2$ rule

- Lattice calculation [over and over again over the past ~16 years] show that at a scale greater than about 1.5 GeV, contribution of penguin operators, to Re A0 is completely negligible...$<O(\sim 1\%)$...only tree operators matter

Re A0 $\sim c_1 Q_1 + c_2 Q_2$ to an excellent approximation!
The simpler ReA2 & EWP computation much more advanced & accurate
For ReA2, $\Delta I = \frac{3}{2}$ only a single type of quark flow diagrams.

No disconnected contribution.

Maybe 100 times simpler than ReA2.
Re($A_2$) = 1.50(4)_{stat}(14)_{sys} \times 10^{-8} \text{ GeV}

Im($A_2$) = -6.99(20)_{stat}(84)_{sys} \times 10^{-13} \text{ GeV}

10\%, 12\% total errors on Re, Im!

- Systematic error completely dominated by perturbative error on NPR and Wilson coefficients!
- Future considerations:
  - Higher order PT calculation of NPR and Wilson coeffs.
  - Step-scaling NPR to higher energy scale.

<table>
<thead>
<tr>
<th>Systematic errors in Im$A_2$/Re$A_2$</th>
<th>48$^3$</th>
<th>64$^3$</th>
<th>cont</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPR (nonperturbative)</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>NPR (perturbative)</td>
<td>7.6%</td>
<td>6.7%</td>
<td>7.6%</td>
</tr>
<tr>
<td>Finite volume corrections</td>
<td>3.5%</td>
<td>3.5%</td>
<td>3.5%</td>
</tr>
<tr>
<td>Unphysical kinematics</td>
<td>1.8%</td>
<td>4.6%</td>
<td>4.6%</td>
</tr>
<tr>
<td>Wilson coefficients</td>
<td>12.0%</td>
<td>10.5%</td>
<td>12.0%</td>
</tr>
<tr>
<td>Derivative of the phase shift</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>14.7%</td>
<td>13.7%</td>
<td>15.3%</td>
</tr>
</tbody>
</table>

TABLE XIII: Systematic error breakdown for Im$A_2$/Re$A_2$.
Dissecting 3/2 Amp on the lattice

Simplest basic step is significantly different from phenomenological expectations.

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

Brute force
32X32X32X
64X16

PLATEAU
Compare $A_2$ and $A_0/22.5$
Sources of ReA0/ReA2 enhancement

• Factor of about 5 suppression of ReA2 due to cancellation between the 2 contractions

• Factor of 2 + some perturbative running for ReA0 vs ReA2 .....See Gaillard + Lee; Altarelli + Maiani; both ’74; Shifman, Vainshtein, Zakharov ‘75

• Factor of around 2 to 3 in the matrix elements for I=1/2 versus 3/2 .....diagrams
Large cancellation in $\varepsilon'$ significantly enhances sensitivity to NP
• Examination of resulting matrix elements shows that $I=0$ and $I=2$ contributions to $\varepsilon'$ suffer large (~80%) cancellation!
• Cancellation due in large part to large mass of the top quark

Different avenues for deviation from SM:
A) New BSM CP-phase
B) CP-conserving contribution to Delta $S=1$

So long as a reliable precise calculation of SM prediction is available both the above avenues can be probed...
That is why it is of the utmost importance to improve the precision of our lattice calculation
IF YOU BUILD IT THEY WILL COME
If there is new physics around below $\sim 5$ TeV, there is an excellent chance that $\varepsilon'$ will find it!

[of course requires accurate theory calculation…
RBC-UKQCD plans for X5 in stat and appreciable improvements in systematic in $\sim 2$ years]
Past over 2 years vigorous pursuit for improvement in statistics as well as in systematics
plan

• Accumulate ~1000 measurements (previous PRL result based on 216)

• In parallel in the intervening period improve systematics AMAP.
Where are we now with respect to this plan?
### Progress in the calculation of $\epsilon'$ on the lattice

<table>
<thead>
<tr>
<th>Resource</th>
<th>Million BG/Q equiv core-hours</th>
<th>Independent cfgs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>USQCD (BNL 512 BG/Q nodes)</td>
<td>50</td>
<td>220</td>
</tr>
<tr>
<td>RBRC/BNL (BNL 512 BG/Q nodes)</td>
<td>17</td>
<td>50</td>
</tr>
<tr>
<td>UKQCD (DiRAC 512 BG/Q nodes)</td>
<td>17</td>
<td>50</td>
</tr>
<tr>
<td>NCSA (Blue Waters)</td>
<td>108</td>
<td>380</td>
</tr>
<tr>
<td>KEK (KEKSC 512 BG/Q nodes)</td>
<td>74</td>
<td>296</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>266</strong></td>
<td><strong>996</strong></td>
</tr>
</tbody>
</table>

Table 1: A breakdown of the various resources we intend to utilize. Note that we require 4 molecular dynamics time units per independent configuration.

So far $\approx$ 1000 new confiss

$\approx$ 500 new measurement

Total 700
Efforts to improve systematics

TABLE II. Representative, fractional systematic errors for the individual operator contributions to $\text{Re}(A_0)$ and $\text{Im}(A_0)$.

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<td>Total (added in quadrature)</td>
<td></td>
<td></td>
<td>27%</td>
</tr>
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$[M = 1.53 \text{ GeV}]$

2014 $\rightarrow 8[\ln m A_2] \sim 3/[s^2] \sim [12/3]$

2020 $\rightarrow 8[\ln m A_2] \rightarrow 5\%$

E. Latt"o\textsuperscript{a}, M. Bruno\textsuperscript{b}
Progress towards improved determination of $A_0$

- PRL 2015 with 216 measurements $\delta[\text{Im}A_0] \Rightarrow \sim60\% (\text{stat})$
- Now $\sim$ around 700 measurements $\delta[\text{Im}A_0] \sim30\%$ (stat)...
- Also $\delta(\text{Re}A_0)$ was $\sim21\%$ (stat) in the PRL 2015
- Now around 17%
- Target $\sim1000$ measurements by end of 2017 ...aim a new result
Proof of the pudding: underlying method is systematically improvable

• BK in full QCD with DWF ’07  RBC-UKQCD error O(7%)
• Since ~2012 many discretizations ,  WA error O(1-2%)
• Re A2 from ~25% around 2012 to now ~10% (now no longer due to lattice but only only due to perturbation theory error upto NLO!)
• Kl3, A2, fB’s , BB’s........
• Quark masses; in particular ms no longer anywhere around ~150 MeV [used to be PDG value] but now

• No doubt that A0 and ε’ will also  go that way for quite sometime to come.........to ~10% total in a matter of a few years. After that EM& isospin effects need to be ascertained quantitatively; WIP
Power of the lattice: Only method to systematically reduce the NP error!

Historical example: $B_K$

$B_K = \langle k (154.0)^2 / 8 \rangle_{\text{stat}} \pm \text{m}_{kk}$

ONE ILLUSTRATION
Lattice $\varepsilon'/\varepsilon$ & SUT: CIRCA 2015

$\text{SUT} = \text{Standard UT}$

i.e. B-UT
Example one implication: K-UT
K-UT: A dream for some

Construction of a Kaon UT

Fig. 14. Unitarity triangle.

Instead of (or in addition to) $K_{S0}^0$, can now plan on using $e^+$
Sketch of an emerging $K$-UT: 3 key kaonic inputs.

I. $\varepsilon_K$ induced CP

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

BNL

III. $\text{Re} \left( \frac{\varepsilon'}{\varepsilon} \right)_K = \begin{cases} (16.7 \pm 1.6) \times 10^{-4} & \text{PDG 2015} \\ (1.36 \pm 5.21_{\text{stat}} \pm 4.49_{\text{syst}}) \times 10^{-4} & \text{ABC+UK @CD '15} \end{cases}$

LLS '15

ICNFP (CRETE) Aug 2017; HET-BNL;soni
Assumed: NA62, 100 events with ~7% error
RBC-UKQCD,
$\delta(\text{Im}A0)\sim18\%$
[current $\sim60\%$]

Lehnen, Lunghi+AS PLB'16
Summary & Outlook

• Traditional challenges of direct CP due to QCD for theory persist though significant progress has been made in two important arenas.

• In B-physics data driven methods have been developed for deducing very precise value for the CKM-phase- gamma which should serve as a “STANDARD” candle for testing our understanding of CPV phenomena.

• Also after decades of relentless effort, in the past several years, RBC-UKQCD collab has demonstrated significant progress in lattice methods enabling us to successfully tackle outstanding problems of $\varepsilon'/\varepsilon$, (and the related puzzle of the $\Delta I=1/2$ rule)

• Note also, the significant progress that is anticipated in lattice calculation of $\varepsilon'$ soon and in near future suggests that the experimental community should re-examine the determination of $\varepsilon'$ to better than the current accuracy of ~15%...

• Upcoming BELLE-II (with 40-50 X more luminosity) and (of course) LHCb and upgrades & strides being made in lattice calculations means significantly improve precision

• All these efforts should lead to more stringent tests of the SM and likely even to discovery of new phenomena & or a sharper understanding of naturalness.
EXTRAS
Can ReA0 from expt be used to eliminate Q4?

As suggested in Buras, Gorbahn, Jager and Jamin, arXiv:1507.06345

- ReA0 = c1 \times Q1 + c2 \times Q2, holds to an excellent approx....use ReA0 expt
- **Useful op identity and its uses**: Q4 = Q3 + Q2 – Q1, to get rid of Q4

- But, current lattice cal show rather largish central value for [- Q1/Q2] with appreciable errors compared to expectation from large N

- Also Q3/Q4 is small but with largish errors

- Moreover, lattice explicitly shows that large N for K=>ππ does (or need) not work; see ReA2 explicit demonstration
Parenthetically note

- Buras, Gorbahn, Jager and Jamin, arXiv:1507.06345....
  Suggest our results imply a ~2.8 σ deviation from expt ...plausible but significant caveats from our perspective

- In a similar vein, see also, Kitahara, Nierste and Tremper, arXiv: 1604.07400
Given its unique importance

It’d be good for others on the lattice to get into.

Recently, Ishizuka et al arXiv:1505.05289, exploit CPS symmetry with Wilson fermions along the lines proposed by Bernard, TD, GH & AS (‘87) and Dawson, GM, CTS, SS et al [‘98] to study $K \rightarrow \pi \pi$ and $\epsilon'$ AT THRESHOLD......a good start

Consistent within large errors with RBC-UKQCD

Threshold done in 2012
Mass depends on $\text{Re}A_2$, $A_0$

Due to the cancellation, $3/2$ amplitude decreases significantly as the pion mass is lowered towards its physical value.

<table>
<thead>
<tr>
<th></th>
<th>$a^{-1}$ [GeV]</th>
<th>$m_\pi$ [MeV]</th>
<th>$m_K$ [MeV]</th>
<th>$\text{Re}A_2$ [$10^{-8}$ GeV]</th>
<th>$\text{Re}A_0$ [$10^{-8}$ GeV]</th>
<th>$\frac{\text{Re}A_0}{\text{Re}A_2}$</th>
<th>notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$16^3$ Iwasaki</td>
<td>1.73(3)</td>
<td>422(7)</td>
<td>878(15)</td>
<td>4.911(31)</td>
<td>45(10)</td>
<td>9.1(2.1)</td>
<td>threshold calculation</td>
</tr>
<tr>
<td>$24^3$ Iwasaki</td>
<td>1.73(3)</td>
<td>329(6)</td>
<td>662(11)</td>
<td>2.668(14)</td>
<td>32.1(4.6)</td>
<td>12.0(1.7)</td>
<td>threshold calculation</td>
</tr>
<tr>
<td>IDSDR</td>
<td>1.36(1)</td>
<td>142.9(1.1)</td>
<td>511.3(3.9)</td>
<td>1.38(5)(26)</td>
<td>-</td>
<td>-</td>
<td>physical kinematics</td>
</tr>
<tr>
<td>Experiment</td>
<td>--</td>
<td>135-140</td>
<td>494-498</td>
<td>1.479(4)</td>
<td>33.2(2)</td>
<td>22.45(6)</td>
<td></td>
</tr>
</tbody>
</table>

TABLE I: Summary of simulation parameters and results obtained on three DWF ensembles.
<table>
<thead>
<tr>
<th></th>
<th>1.32 GeV 24I</th>
<th>1.33 GeV 32ID</th>
<th>1.53 GeV 32ID</th>
<th>2.29 GeV 24I</th>
<th>2.29 GeV stepscaled, no $G_1$</th>
<th>2.29 GeV stepscaled inc. $G_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1,1)</td>
<td>0.06076(15)</td>
<td>0.063454(63)</td>
<td>0.05978(13)</td>
<td>0.036954(41)</td>
<td>0.03948(16)</td>
<td>0.03948(16)</td>
</tr>
<tr>
<td>(2,2)</td>
<td>0.203(19)</td>
<td>0.204(15)</td>
<td>0.300(68)</td>
<td>0.0795(70)</td>
<td>0.080(33)</td>
<td>0.092(35)</td>
</tr>
<tr>
<td>(2,3)</td>
<td>0.310(21)</td>
<td>0.317(16)</td>
<td>0.363(76)</td>
<td>0.1486(59)</td>
<td>0.153(36)</td>
<td>0.161(42)</td>
</tr>
<tr>
<td>(2,4)</td>
<td>0.0120(48)</td>
<td>0.0076(42)</td>
<td>0.030(22)</td>
<td>0.0033(23)</td>
<td>0.0083(89)</td>
<td>0.0086(93)</td>
</tr>
<tr>
<td>(2,5)</td>
<td>0.0120(42)</td>
<td>0.0005(31)</td>
<td>0.015(20)</td>
<td>0.0039(15)</td>
<td>0.0074(53)</td>
<td>0.0081(77)</td>
</tr>
<tr>
<td>(3,2)</td>
<td>0.283(22)</td>
<td>0.268(15)</td>
<td>0.264(87)</td>
<td>0.1547(42)</td>
<td>0.143(23)</td>
<td>0.174(26)</td>
</tr>
<tr>
<td>(3,3)</td>
<td>0.391(25)</td>
<td>0.414(17)</td>
<td>0.44(11)</td>
<td>0.2207(39)</td>
<td>0.238(25)</td>
<td>0.297(32)</td>
</tr>
<tr>
<td>(3,4)</td>
<td>0.0012(59)</td>
<td>0.0002(34)</td>
<td>0.019(27)</td>
<td>0.0077(13)</td>
<td>0.0057(59)</td>
<td>0.0017(66)</td>
</tr>
<tr>
<td>(3,5)</td>
<td>0.0128(62)</td>
<td>0.0264(43)</td>
<td>0.008(27)</td>
<td>0.0190(11)</td>
<td>0.0247(46)</td>
<td>0.0090(68)</td>
</tr>
<tr>
<td>(4,2)</td>
<td>0.118(70)</td>
<td>0.094(53)</td>
<td>0.24(25)</td>
<td>0.037(24)</td>
<td>0.07(10)</td>
<td>0.06(11)</td>
</tr>
<tr>
<td>(4,3)</td>
<td>0.113(76)</td>
<td>0.073(62)</td>
<td>0.26(30)</td>
<td>0.026(20)</td>
<td>0.08(11)</td>
<td>0.09(13)</td>
</tr>
<tr>
<td>(4,4)</td>
<td>0.006(20)</td>
<td>0.006(16)</td>
<td>0.076(88)</td>
<td>0.0318(80)</td>
<td>0.024(30)</td>
<td>0.023(31)</td>
</tr>
<tr>
<td>(4,5)</td>
<td>0.023(18)</td>
<td>0.019(12)</td>
<td>0.046(79)</td>
<td>0.0014(50)</td>
<td>0.033(19)</td>
<td>0.027(26)</td>
</tr>
<tr>
<td>(5,2)</td>
<td>0.239(28)</td>
<td>0.205(28)</td>
<td>0.19(17)</td>
<td>0.0957(84)</td>
<td>0.048(63)</td>
<td>0.033(74)</td>
</tr>
<tr>
<td>(5,3)</td>
<td>0.404(34)</td>
<td>0.347(37)</td>
<td>0.25(20)</td>
<td>0.1885(90)</td>
<td>0.101(77)</td>
<td>0.075(99)</td>
</tr>
<tr>
<td>(5,4)</td>
<td>0.0106(80)</td>
<td>0.0174(98)</td>
<td>0.039(62)</td>
<td>0.0028(26)</td>
<td>0.044(20)</td>
<td>0.031(23)</td>
</tr>
<tr>
<td>(5,5)</td>
<td>0.0810(100)</td>
<td>0.0740(93)</td>
<td>0.016(56)</td>
<td>0.0303(23)</td>
<td>0.012(15)</td>
<td>0.062(21)</td>
</tr>
<tr>
<td>(6,6)</td>
<td>0.00461(21)</td>
<td>0.005040(92)</td>
<td>0.006154(96)</td>
<td>0.001631(63)</td>
<td>0.00185(24)</td>
<td>0.00185(24)</td>
</tr>
<tr>
<td>(6,7)</td>
<td>0.002132(46)</td>
<td>0.003396(25)</td>
<td>0.002073(59)</td>
<td>0.001567(12)</td>
<td>0.002002(43)</td>
<td>0.002002(43)</td>
</tr>
<tr>
<td>(7,6)</td>
<td>0.02221(12)</td>
<td>0.024916(60)</td>
<td>0.02413(91)</td>
<td>0.018826(21)</td>
<td>0.02260(20)</td>
<td>0.02260(20)</td>
</tr>
<tr>
<td>(7,7)</td>
<td>0.127052(87)</td>
<td>0.133903(52)</td>
<td>0.12284(25)</td>
<td>0.080743(12)</td>
<td>0.08705(11)</td>
<td>0.08705(11)</td>
</tr>
</tbody>
</table>

Table 2: Preliminary values of $\Xi$ obtained using the renormalization matrices obtained at various scales on the 32ID and 24I lattices, as well as using the step-scaled matrices with and without $G_1$. 
More on $\Delta l=3/2$ continuum 2012-2015


\[
\begin{align*}
\text{Re}(A_2) &= 1.38(5)_{\text{stat}}(26)_{\text{sys}} \times 10^{-8} \text{ GeV} \\
\text{Im}(A_2) &= -6.54(46)_{\text{stat}}(120)_{\text{sys}} \times 10^{-13} \text{ GeV}
\end{align*}
\]

20% sys error dominated by 15% discretization error

**PRD '12**

$32^3 \times 64 \times 16$, \( a^{-1} = 1.364 \text{ GeV} \)

146 Conf. sys; \( m_r = 142.1 \text{ MeV} \)

\( m_K = 505.5 \text{ MeV} \)

| TABLE IX. Systematic error budget for ReA$_2$ and ImA$_2$. |
|---------------------------------|----------------|----------------|
| Lattice artifacts               | 15%            | 15%            |
| Finite-volume corrections       | 6.0%           | 6.5%           |
| Partial quenching               | 3.5%           | 1.7%           |
| Renormalization                 | 1.8%           | 5.6%           |
| Unphysical kinematics           | 0.4%           | 0.8%           |
| Derivative of the phase shift   | 0.97%          | 0.97%          |
| Wilson coefficients             | 6.6%           | 6.6%           |
| Total                           | **18%**        | **19%**        |

ICNFP (CRETE) Aug 2017; HET-BNL;soni
0 the Continuum

- Calculation has now been repeated on RBC & UKQCD 48^3 \times 96 and 64^3 \times 128 Mobius DWF ensembles with (5 \text{ fm})^3 volumes and a=0.114 \text{ fm}, a=0.084 \text{ fm}.
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 $\epsilon'/\epsilon$.\(^6,8\)
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]
计划

- I. DCP in B: 从泥沼到标准蜡烛
- II. DCP in K: 从泥到一个极敏感的发光灯塔，用于BSM现象

For pragmatic reasons:

Completely different strategies $\Rightarrow$ Extremely powerful tests of SM & search for NP
More demands on the calculation

• ~ The 1995 discovery of the huge top mass accentuated the cancellation of $I=0$ and $I=2$ contributions to $\varepsilon'$ significantly, putting additional demands on the calculation but also enhancing the potential for discovery of new physics

\[
c_8 \propto \frac{m_t^2}{M_w^2}
\]
Isoscalar $\pi\pi$ Scattering and the $\sigma$ Meson Resonance from QCD

Raul A. Briceno, Jozef J. Dudek, Robert G. Edwards, and David J. Wilson
(for the Hadron Spectrum Collaboration)

$\delta_0$

$m_\pi = 391$ MeV

$m_\pi = 236$ MeV

expt.

$p^2 / \text{GeV}^2$
Improvements in lattice $\varepsilon'$ determination underway for past ~2 years

- Statistics $X [> \sim 5]$ now aiming for
- Systematics.....some already done..
- EM+ isospin....
- Completely diff method(s)
  - A) excited pipi state
  - B) Revisit ChPT

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