“Advances in direct CP violation"

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HET-BNL

Workshop on Future of Fundamental Physics
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08/28/17

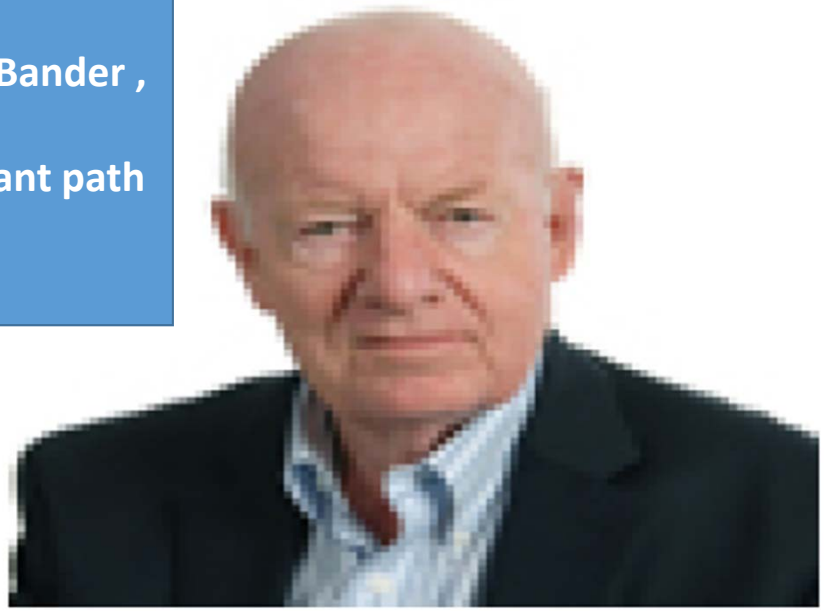
DIRECT CP: Long-standing challenge for theorists

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***

V.V. Brief

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

PRL

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

I. $|\epsilon_K| \approx 2.228 \times 10^{-3}$

$K_L \to \pi\pi$

BNL '64

CRONIN + FITCH NOBEL

- Decay (direct, time-integrated)

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

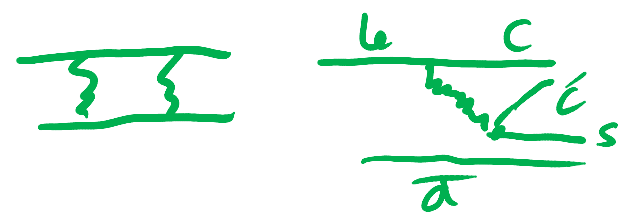
II. $Re(\epsilon'_K/\epsilon_K) \sim 1.65 \times 10^{-3}$

CERN + FNAL ~2004

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

III

- Mixing and decay (time-dependent)

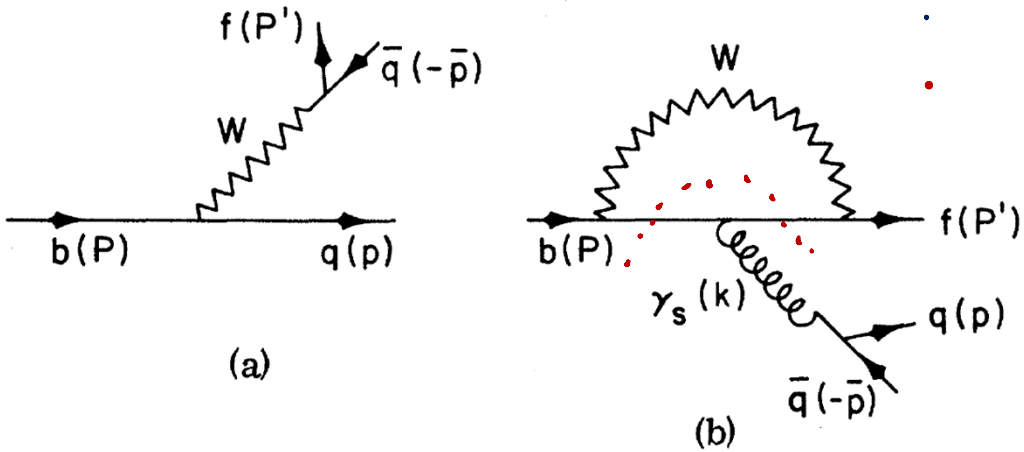


$S(B^0 \to \psi K_0) \simeq \sin 2\beta \sim 0.673$

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

Carter & Sanda, PRL'80
Bigi & Sanda, NPB'81

Simple ex. Of DCP in B-Physics: Tree-Penguin Interference



Bander, Silverman and A. S. PRL '79

"measurable asymmetries may arise. This would present the first evidence for *CP* noninvariance in charged systems."

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

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

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

Babar, Belle 1st obs ~ 2007

$$A_{CP}(B^0 \to K^+\pi^-) = -0.082 \pm 0.006$$

5 orders of mag ϵ'_K !!

REGRETTABLY still CANNOT BE USED TO RELIABLY TEST THE SM-CKM

By now multitude of channels with large DCP ...b=>s and b=>d

$A_{CP}(B^0 \to K^+\pi^-) = -0.082 \pm 0.006$

$A_{CP}(B^0 \to \eta K^*(892)^0) = 0.19 \pm 0.05$

$A_{CP}(B^0 \to K^*(892)^+\pi^-) = -0.22 \pm 0.06$

$A_{CP}(B^+ \to \eta K^+) = -0.37 \pm 0.08$

$A_{CP}(B^+ \to K^+\pi^-\pi^+) = 0.027 \pm 0.008$

$A_{CP}(B^+ \to f_2(1270)K^+) = -0.68^{+0.19}_{-0.17}$

$A_{CP}(B^+ \to \bar{\rho}^0 K^+) = 0.37 \pm 0.10$

$A_{CP}(B^+ \to K^+K^-\pi^+) = -0.118 \pm 0.022$

$A_{CP}(B^+ \to K^+K^-K^+) = -0.033 \pm 0.008$

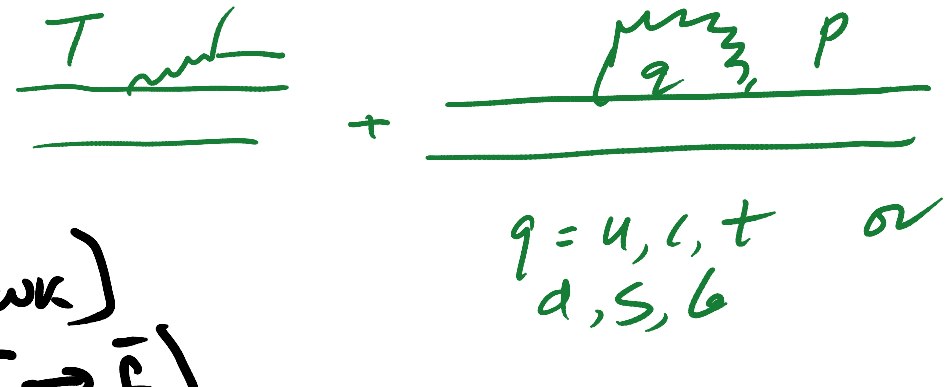
$A_{CP}(B^+ \to \pi^+\pi^-\pi^+) = 0.057 \pm 0.013$

Very large dir CP in many cases!

$A_{CP}(B^+ \to f_0(1370)\pi^+) = 0.72 \pm 0.22$

$A_{CP}(B_s \to \pi^+K^-) = 0.263 \pm 0.035$

Direct CP: Long[2] standing challenge for theorists



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

CP+ CP−

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

$$a_{CP[PRA]} = \frac{B[i \to f] - B[\bar{i} \to \bar{f}]}{+}$$

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

UNKNOWS 4: $|T|$, $|P|$, δ_{st}, δ_{wk}

OBSERVABLES 3 $|A|^2$; $|\bar{A}|^2$ + a_{CP} } DESEPERATELY NEED δ_{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 $\Delta I = 1/2$ 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 $\gamma \sim 70 \pm 10°$

expected Theory precision $\sim$ few $\times 10^{-3}$!!

$B^\pm \to D^0(\bar{D}^0)\, K^\pm$ like modes

$$d(K, f_i) = a(K)c(f_i) + b(K)c(\bar{f}_i) + 2\sqrt{a(K)b(K)c(f_i)c(\bar{f}_i)}\cos(\xi^K_{f_i} + \gamma),$$
$$\bar{d}(K, f_i) = a(K)c(f_i) + b(K)c(\bar{f}_i) + 2\sqrt{a(K)b(K)c(f_i)c(\bar{f}_i)}\cos(\xi^K_{f_i} - \gamma), \quad (3)$$

ADS: PRL 1997; PRD 2001
Data Driven method for extracting gamma; DESIGNED FOR O(1) CP!

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

$$\{\xi^K_{f_1}, \xi^K_{f_2}, b(K), \gamma\}$$

2 strong phases, a suppressed Br and the precious CP phase γ

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 γ ~70 +- 8 degrees

Formin data driven methods

A great personal treat; thanks to LHCb

ADS: $B^{\pm} \to Dh^{\pm}, D \to \pi^+ K^-$

$$A^{\pi K}_{\mathrm{ADS}(K)} = -0.403 \quad \pm 0.056 \quad \pm 0.011$$

8σ

Malcolm John@EW MORIOND '16

Huge *direct CP* [tailor made] ~20 year ago!
ADS PRL'97

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

DESIGNED for MAXIMAL INTERFERENCE

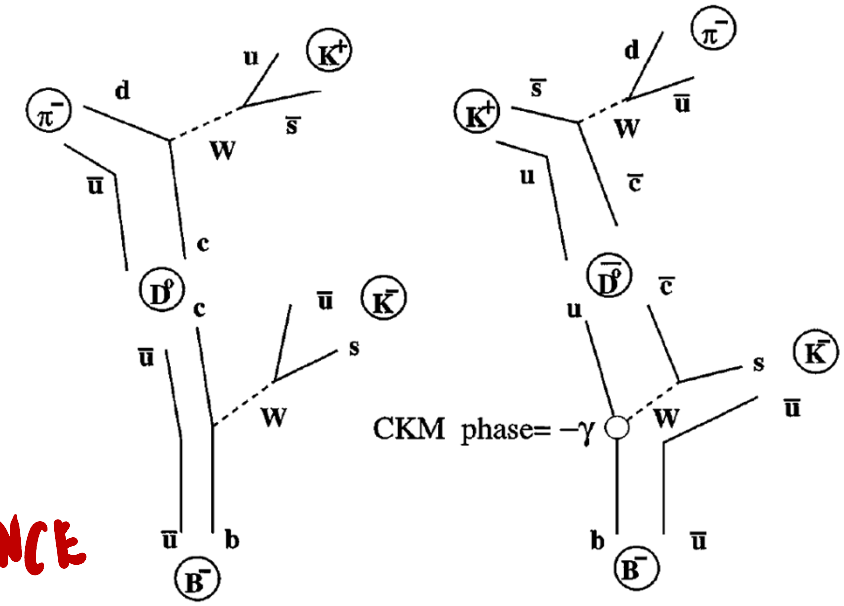
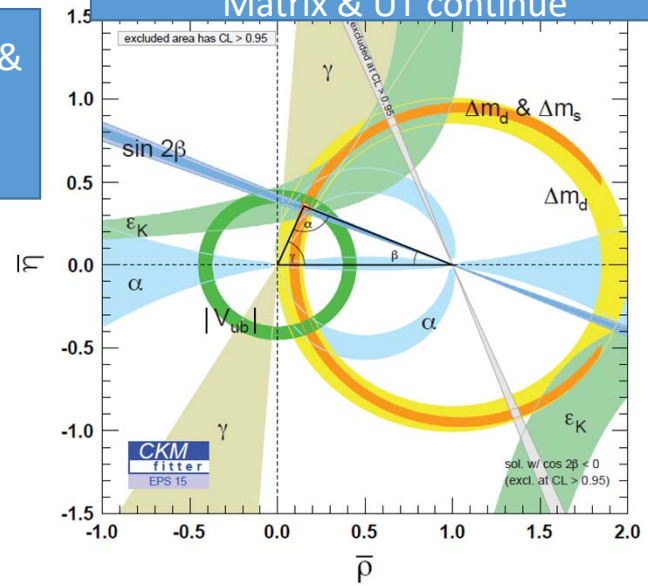


FIG. 1. Diagrams for the two interfering processes: $B^- \to K^- D^0$ (color-allowed) followed by $D^0 \to K^+\pi^-$ (doubl Cabibbo suppressed) and $B^- \to K^- \overline{D}^0$ (color-suppressed followed by $\overline{D}^0 \to K^+\pi^-$ (Cabibbo allowed).

Andreas Hoecker & Malcolm John EW Moriond '16

Efforts to overconstrain the CKM Matrix & UT continue



Compatible with SM-CKM to ~15% accuracy

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

Key new results from LHCb

DATA DRIVEN Methods

Precision on sin(2β) approaches that of B-factories: 0.73 ± 0.04 ± 0.02

ITE ~ 1%
Mannel et al

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

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

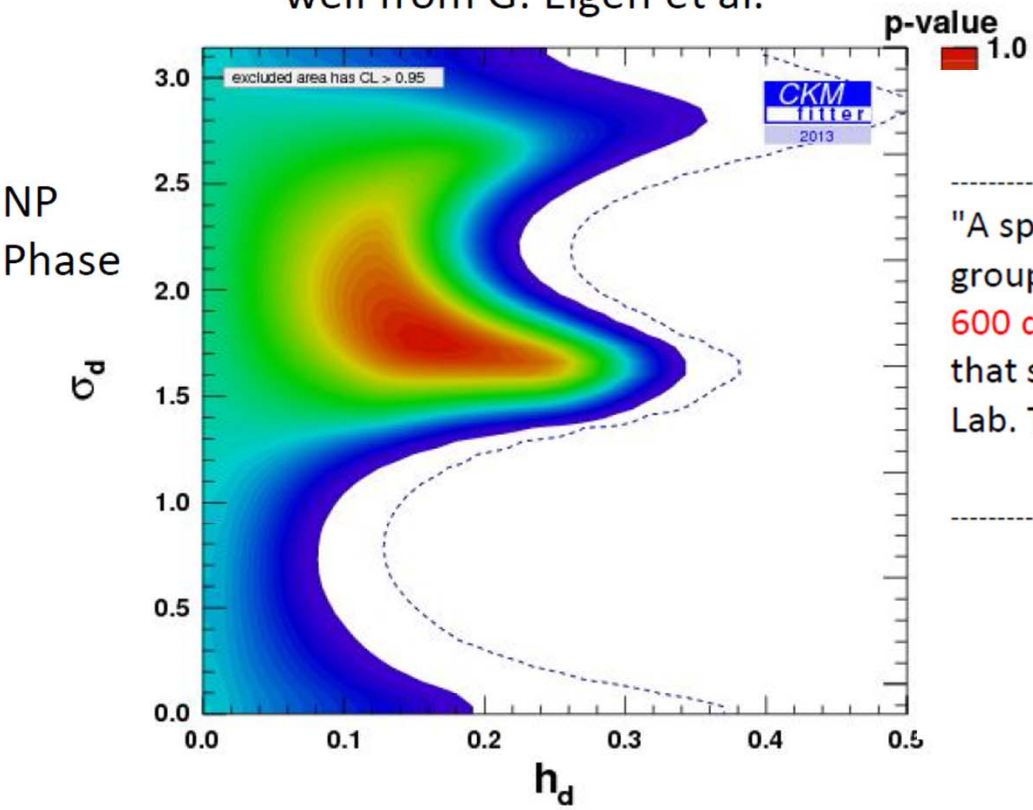
ITE ~10^{-7} !!
Brod Zupan'14
STD. CANDLE

which improved the previous LHCb-only conclusion by 2°

- Inline with B-factory conclusions from $B \to DK$,
  - BaBar: $\gamma = (70 \pm 18)°$
  - Belle: $\gamma = (73^{+13}_{-15})°$

BELLE-II & LHCb(upgrade) ~ $\delta\gamma \sim 1°$, still long way to go before ultimate precision

ICHEP2014: Similar results from UTFIT (D. Derkach) as well from G. Eigen et al.



NP/SM amplitude ratio

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 ?

II. Dir CP in K=> ππ, i.e. ε'/ε

In this case the key, in large part, is advances in lattice calculations…Extremely arduous path that took decades to develop

ε' / ε: Direct CPV

EXPERIMENTAL ROUTE

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

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

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

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

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

FROM THEORY

$K \to 2\pi$

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) = \frac{\omega}{\sqrt{2}|\epsilon|}\left[\frac{\mathrm{Im}(A_2)}{\mathrm{Re}(A_2)} - \frac{\mathrm{Im}(A_0)}{\mathrm{Re}(A_0)}\right]; \quad \omega \simeq \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0}$$

$I=2$ amp

$I=0$ amp

$\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} \sim 25$ $\Delta I = 1/2$ Puzzle

INDIRECT CP
BNL'64
Cronin + Fitch
NP

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

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

DIRECT CP

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

CERN + FNAL $\sim$2004

I. Wilson Fermions with Bernard ~'82 **See also Martinelli et al [WF]** **Broweret al** **Sharpe et al [Stag F]**	**Lattice χ S is a pre-requisite for this physics** **Off-shoot B-physics important observables identified & studied=> evolved into UT**	
II (a) DWF with Blum ~ '95 II(b) DWF with RBC[with Blum, Christ and Mawhinney became "flagship" project of RBC] ~'97.	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
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

HUGE # of OBSTACLES HAS to be overcome

~2006

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 facs.. 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 pathlogies=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

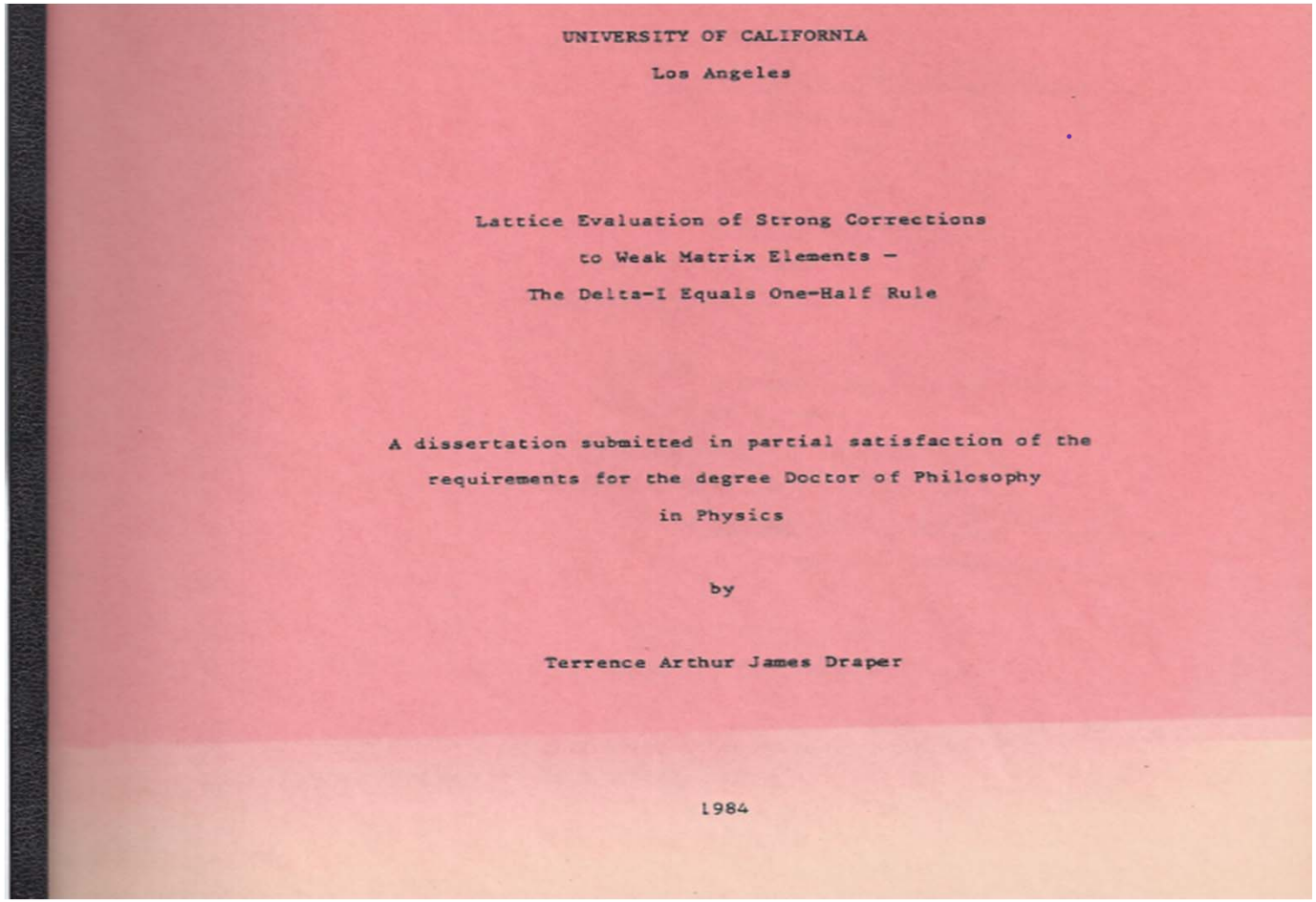
ε': most likely a gem in search of new phenomena

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 ε' very sensitive to BSM – CP odd phases**
- **In many ways ε' 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 ε'**
- **Understanding ε', nedm are extremely important for learning how naturalness really works in nature**

- ***MOREOVER: large accidental cancellations significantly enhances sensitivity of ε' to NP [see later]***

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]

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

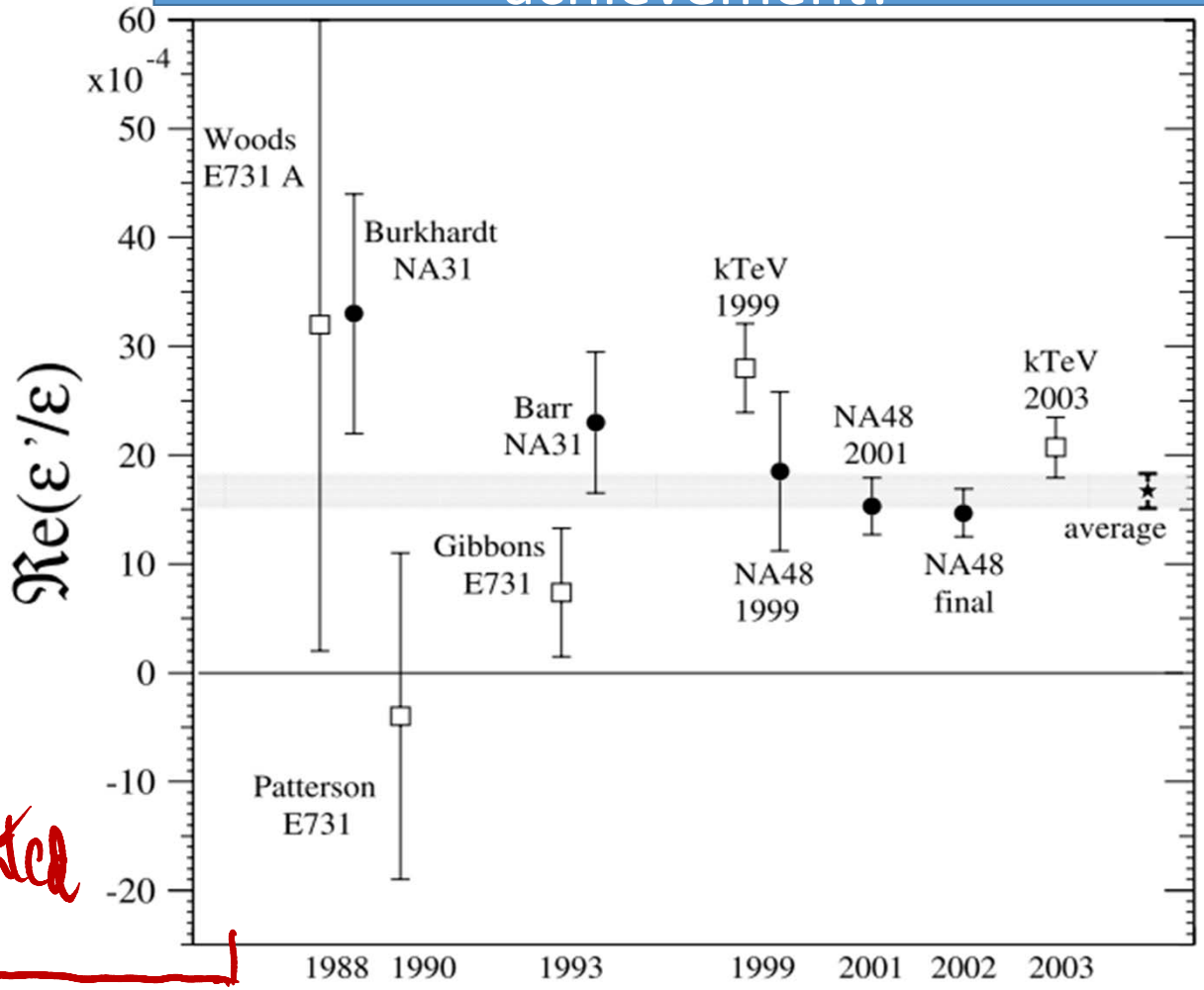
Claude Bernard, Terrence Draper,* and A. Soni
Department of Physics, University of California, Los Angeles, California 90024

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.

US lasted ~ 20 years

A monumental experimental achievement!



Konrad Kleinknecht "Uncovering CPV"

$16.6(2.3) \times 10^{-4}$
PDG 2014

my LATTICE workstation

Basic calculational framework

$\Delta S=1$ H_W

WC to NLO
Buchalla, Buras, Lautenbacher RMP 1996; 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

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

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

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

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

$I=0 \Longrightarrow$

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

$\longrightarrow 0$

$m_q \to 0$

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

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

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

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

EWP

$I=2$

$\longrightarrow$ const

$m \to 0$

EWP

Acknowledge many significant contributions off & on the lattice

- **While focus is on lattice calculations of K=>ππ 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……**

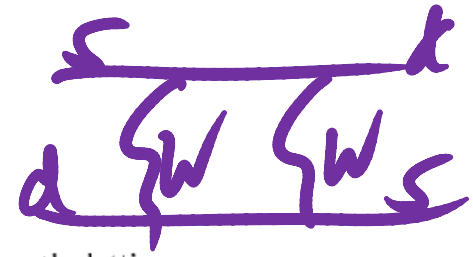
Key difficulties

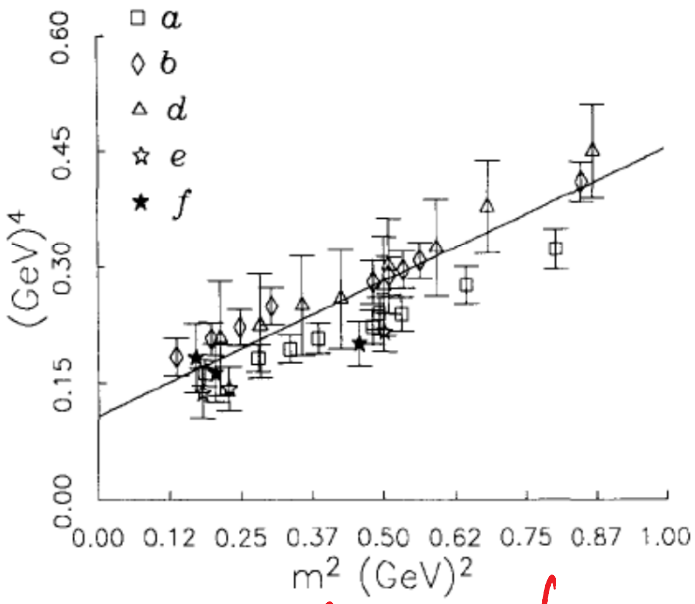
- ΔS=1 => deadly mixing with LDO in the absence (on the lattice) of
- chiral symmetry=> $[\bar{s}d\bar{u}u] \longleftrightarrow (\bar{s}d), [\bar{s}\gamma_5 d]$
- Applications to heavy-light physics which led to precision lattice applications for the UT ⇒ El-Khadra; Lehrenz ... PhD Thesis
- For K=>pi pi and epsilon' => DWF with [controllable very precise] XS

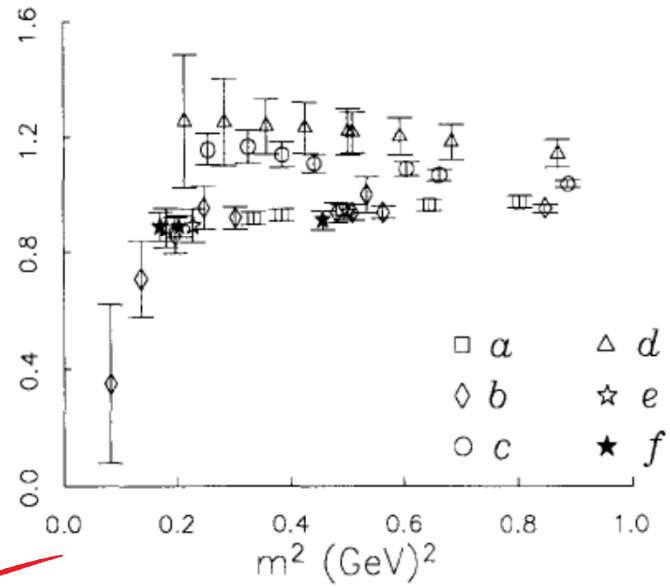
Blum + AS '97

- 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 ~'02
- A measure of computational difficulty: $32^3 X64X16X50X10X5/6^3 X17 \sim 10^8$

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







χS violation by K-K̄ ⇒ FINE TUNING PROBLEM

Lattice computation of the decay constants of B and D mesons

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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.

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)

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

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and

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CB+ASet al

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

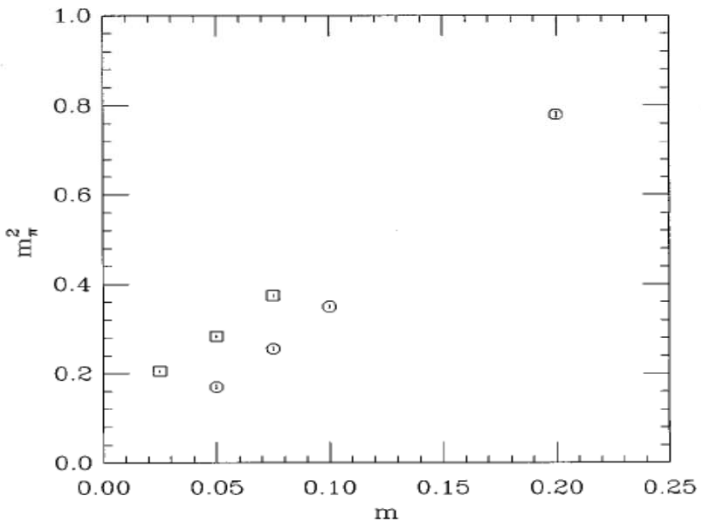
PHYSICAL REVIEW D VOLUME 56, NUMBER 1 1 JULY 1997

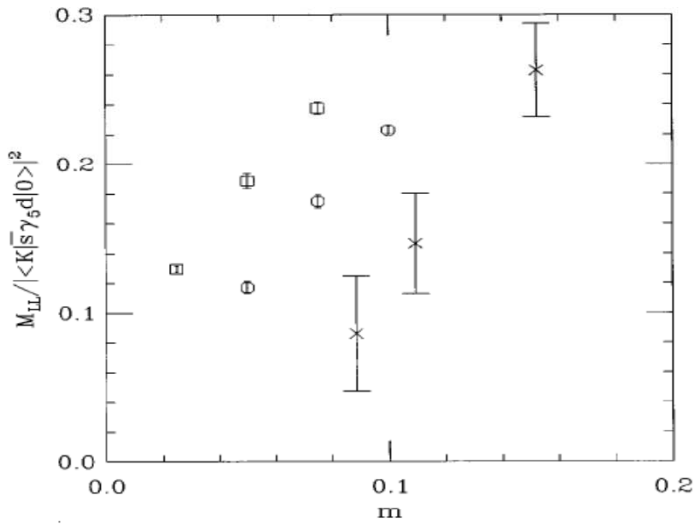
QCD with domain wall quarks

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]

1st Simulation with DWQ → '97





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

$K \to 2\pi$ ChPT

with DWQ in Quench Approx

1st application of BDSPW'84 with DWQ

PHYSICAL REVIEW D 68, 114506 (2003)

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

T. Blum,[1] P. Chen,[2] N. Christ,[2] C. Cristian,[2] C. Dawson,[3] G. Fleming,[2,*] R. Mawhinney,[2] S. Ohta,[4,1] G. Siegert,[2] A. Soni,[3] P. Vranas,[5] M. Wingate,[1,*] L. Wu,[2] and Y. Zhestkov[2]

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(Received 19 July 2002; published 30 December 2003)

We report the results of a calculation of the $K \to \pi\pi$ matrix elements relevant for the $\Delta I = 1/2$ rule and ϵ'/ϵ in quenched lattice QCD using domain wall fermions at a fixed lattice spacing $a^{-1} \sim 2$ GeV. Working in the three-quark effective theory, where only the u, d, and s quarks enter and which is known perturbatively to next-to-leading order, we calculate the lattice $K \to \pi$ and $K \to |0\rangle$ matrix elements of dimension six, four-fermion operators. Through lowest order chiral perturbation theory these yield $K \to \pi\pi$ matrix elements, which we then normalize to continuum values through a nonperturbative renormalization technique. For the ratio of isospin amplitudes $|A_0|/|A_2|$ we find a value of 25.3 ± 1.8 (statistical error only) compared to the experimental value of 22.2, with individual isospin amplitudes 10%–20% below the experimental values. For ϵ'/ϵ, using known central values for standard model parameters, we calculate $(-4.0 \pm 2.3) \times 10^{-4}$ (statistical error only) compared to the current experimental average of $(17.2 \pm 1.8) \times 10^{-4}$. Because we find a large cancellation between the $I=0$ and $I=2$ contributions to ϵ'/ϵ, the result may be very sensitive to the approximations employed. Among these are the use of quenched QCD, lowest order chiral perturbation theory, and continuum perturbation theory below 1.3 GeV. We also calculate the kaon B parameter B_K and find $B_{K,\overline{\mathrm{MS}}}(2\ \mathrm{GeV}) = 0.532(11)$. Although currently unable to give a reliable systematic error, we have control over statistical errors and more simulations will yield information about the effects of the approximations on this first-principles determination of these important quantities.

$K \to 2\pi$ & ϵ'/ϵ "Flagship Project"

Now ~ 20 yrs!

Founding members Christ, Mawhinney, Blum, AS ~ '98

1st Large Scale Simulation with DWQ

RBC Collaboration

QCDSP ~ 98 → ~ '05 1 TF

RBC Colla. 98

QA ; ChPT

PRD ~ 02

DWQ
1st Large Scale simulation

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.

Quantity	Experiment	This calculation (statistical errors only)
Re A_0(GeV)	3.33×10^{-7}	$(2.96\pm0.17)\times10^{-7}$
Re A_2(GeV)	1.50×10^{-8}	$(1.172\pm0.053)\times10^{-8}$
ω^{-1}	22.2	(25.3 ± 1.8)
Re(ϵ'/ϵ)	$(15.3\pm2.6)\times10^{-4}$(NA 48)	$(-4.0\pm2.3)\times10^{-4}$
	$(20.7\pm2.8)\times10^{-4}$(KTEV)	

RBC = RBRC + BNL + Colu.

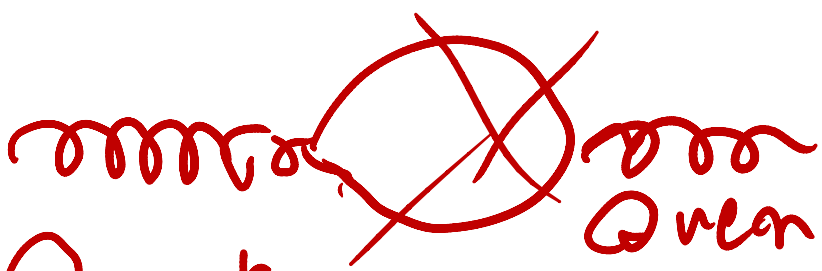
See Golterman & Pallante '01; '04; Aubin et al (RBC) '06

Extremely serious quench pathology

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

Source of problem is that H_eff for ΔS=1 has operators such as Q6 with Quark content

$(\bar{s}d)(\bar{u}u) \rightarrow$ quark loop from weak interaction



Quench approx

Q_6 gets unphysical contribution for Q_8

(8,1) (8,8)

Full QCD but ChPT a la BDSPW

Conclusion

(Sam)Shu Li, PhD thesis, Columbia '08

Quantity	This analysis	Quenched	Experiment
$\mathrm{Re}A_0$ (GeV)	$4.5(11)(53) \times 10^{-7}$	$2.96(17) \times 10^{-7}$	3.33×10^{-7}
$\mathrm{Re}A_2$ (GeV)	$8.57(99)(300) \times 10^{-9}$	$1.172(53) \times 10^{-8}$	1.50×10^{-8}
$\mathrm{Im}A_0$ (GeV)	$-6.5(18)(77) \times 10^{-11}$	$-2.35(40) \times 10^{-11}$	
$\mathrm{Im}A_2$ (GeV)	$-7.9(16)(39) \times 10^{-13}$	$-1.264(72) \times 10^{-12}$	
$1/\omega$	50(13)(62)	25.3(1.8)	22.2
$\mathrm{Re}(\epsilon'/\epsilon)$	$7.6(68)(256) \times 10^{-4}$	$-4.0(2.3) \times 10^{-4}$	1.65×10^{-3}

m_π too large for ChPT

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

LARGE SYSTEMATIC errors DUE ChPT

Lattice

N. Christ @LAT08

CMP/01.

A Breakthrough paper

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 Maiani-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

m λc l KITP

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**

DIRECT $K \to \pi\pi$ [NO ChPT]

Results for ε'

EWP

QCDP

- Using $\mathrm{Re}(A_0)$ and $\mathrm{Re}(A_2)$ from experiment and our lattice values for $\mathrm{Im}(A_0)$ and $\mathrm{Im}(A_2)$ and the phase shifts,

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

$$= \begin{array}{ll} 1.38(5.15)(4.43)\times 10^{-4}, & \text{(this work)} \\ 16.6(2.3)\times 10^{-4} & \text{(experiment)} \end{array}$$

LARGE CANCELLATION!! (80-85%)

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

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

Computed ReA2 excellent agreement with expt
Computed ReA0 good agreement with expt
Offered an "explanation" of the Delta I=1/2 enhancement

For obtaining ε’ , 6 entities must be calculated non -perturbatively

- **Re A0, ReA2, Im A0. Im A2**
- **δ_0 I=0, ππ scattering phase shift**
- **δ_2 I=2, ππ scattering phase shift**
- **Of these Re A0 and ReA2 are directly known from experiment and**

δ_0 , δ_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 δ2 agree well with expt a possible difficulty: δ0

- **The continuum and our lattice determinations of strong phase difference differs at the ~2σ level:**

not directly accessible to expt

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

Colangelo et al

RBC-UKQCD

$\phi_\varepsilon \sim 43.5 \pm 0.5^\circ$

Fortunately, due to the central value of the combination $\delta_2 - \delta_0 + \pi/2 - \phi_\varepsilon$ and to the large uncertainties in the determination of the various matrix elements, these two choices yield almost identical results; fo[illegible]

Lehner, Lunghi + AS, 1508.01801

Sensitivity of ε' to strong phase(s)

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

See also Lehner, Lunghi + AS PLB'16

$$\cos\left(\delta_2 - \delta_0 + \pi/2 - \phi_\varepsilon\right)$$

$\phi_\varepsilon \to 43.5 \pm 0.5^\circ$ "PDG"

$\phi_{\epsilon'} \sim 42.3 \pm 1.5^\circ$ [Colangelo, Gosser, Lautwyler

$\Rightarrow \cos(\;) \Rightarrow 0.99978$; $\phi_{\epsilon'} = 54.6 \pm 5.8^\circ$ RBC-UKQCD PRL'15

$\Rightarrow 0.981$

phase diff ~ 2σ BUT ε' totally insensitive!!

Diff ~ 2% on ε'

RBC-UKQCD PRL 2015

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

Description	Error	Description	Error
Finite lattice spacing	12%	Finite volume	7%
Wilson coefficients	12%	Excited states	$\leq 5\%$
Parametric errors	5%	Operator renormalization	15%
Unphysical kinematics	$\leq 3\%$	Lellouch-Lüscher factor	11%
Total (added in quadrature)			27%

perturbation Theory NLO

Buras et al

75%

15%

$Q_2 =$ 

LARGE DOUBLE cancellation

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

dominant

<1%

TABLE I. Contributions to A_0 from the ten continuum, $\overline{\text{MS}}$ operators $Q_i(\mu)$, for $\mu = 1.53$ 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 ΔI=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(~1%)…only tree operators matter**

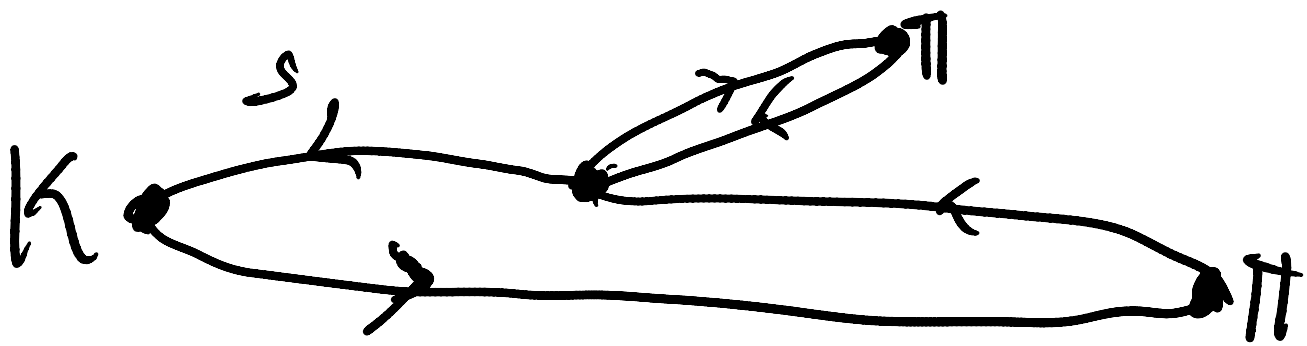
Re A0 ~ c1 Q1 + c2 Q2 to an excellent approximation!

$Q_2 \equiv$

ORIGINAL WEAK interaction

The simpler ReA2 & EWP computation much more advanced & accurate

For $\mathrm{Re}A_2$, $\Delta I = 3/2$ only a single type of quark flow diagram



No disconnected contribution) Maybe ~100 times simpler than $\mathrm{Re}A_0$!

continuum limit #s

Expt 1.48×10^{-8} GeV

$$\mathrm{Re}(A_2) = 1.50(4)_{\mathrm{stat}}(14)_{\mathrm{sys}} \times 10^{-8}\ \mathrm{GeV}$$

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

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

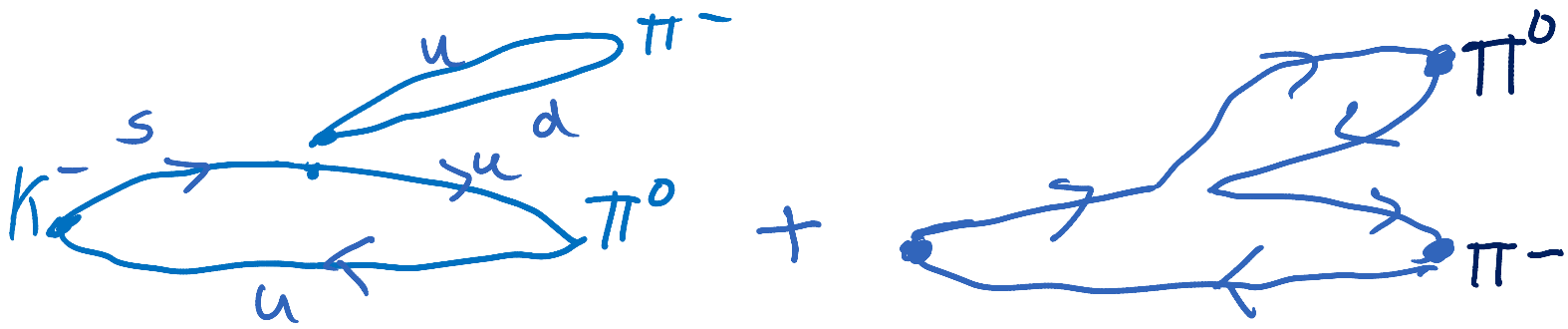
- Systematic error completely dominated by perturbative error on NPR and Wilson coefficients!!
- Future considerations:
  - Higher order PT calculation of NPR and Wilson coeffs.
  - Step-scaling NPR to higher energy scale.

Systematic errors in $\mathrm{Im}A_2/\mathrm{Re}A_2$	48^3	64^3	cont
NPR (nonperturbative)	0.1%	0.1%	0.1%
NPR (perturbative)	7.6 %	6.7 %	7.6 %
Finite volume corrections	3.5 %	3.5 %	3.5 %
Unphysical kinematics	1.8 %	4.6%	4.6%
Wilson coefficients	12.0 %	10.5 %	12.0%
Derivative of the phase shift	0	0	0
Total	14.7%	13.7%	15.3%

TABLE XIII: Systematic error breakdown for $\mathrm{Im}A_2/\mathrm{Re}A_2$.

WILSON Coeff to NLO are the limit of error NOT LATTICE Need NNLO W.C.

Dissecting 3/2 Amp on the lattice

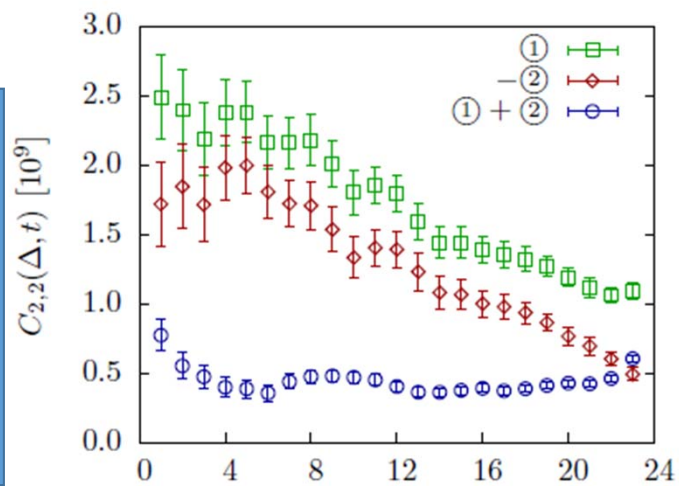


Tr X Tr

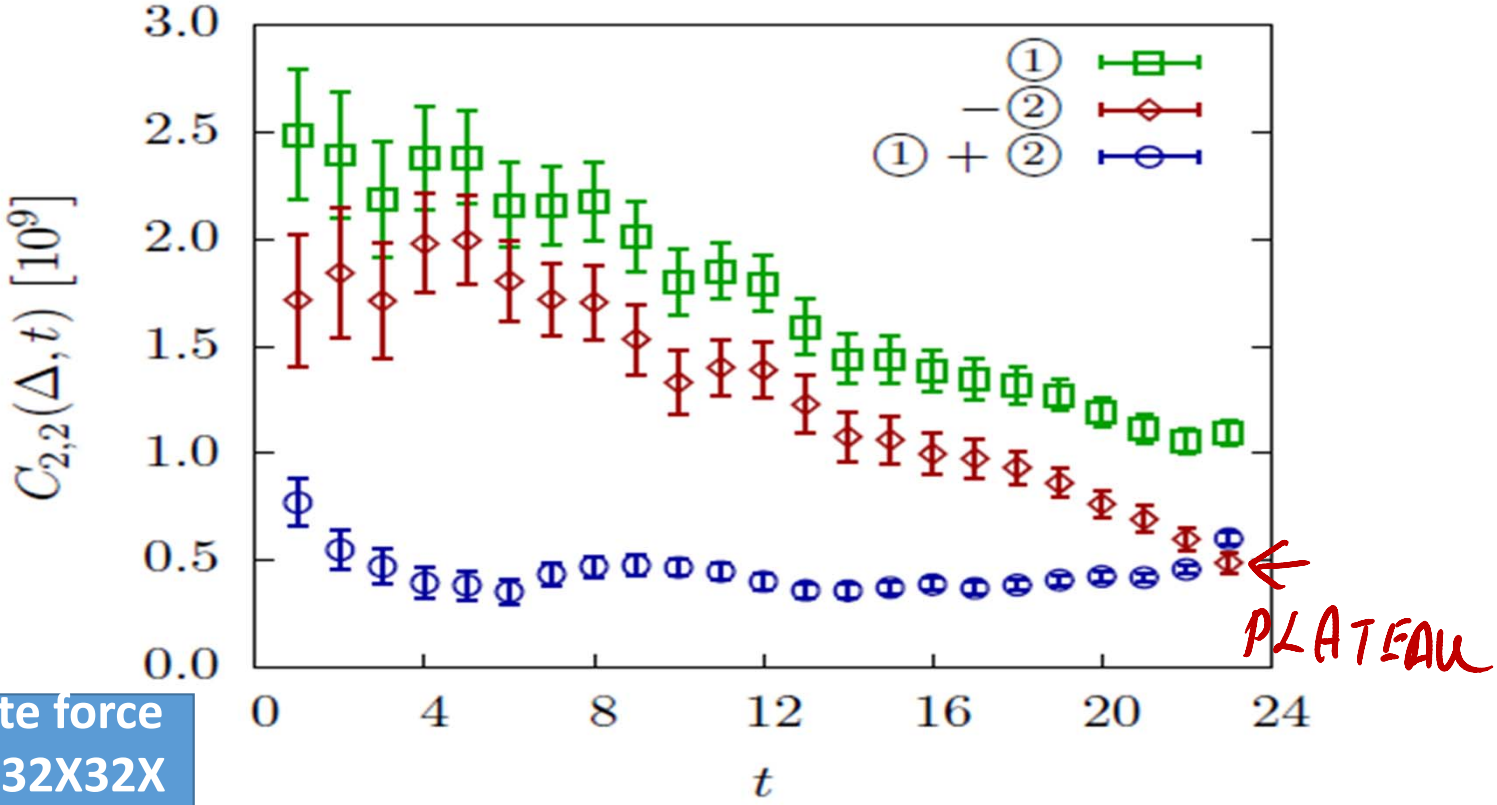
(N^2)

Tr (N)

Simplest basic step is Significantly different from phenomenological expectations



DRAMATIC CANCELLATION!

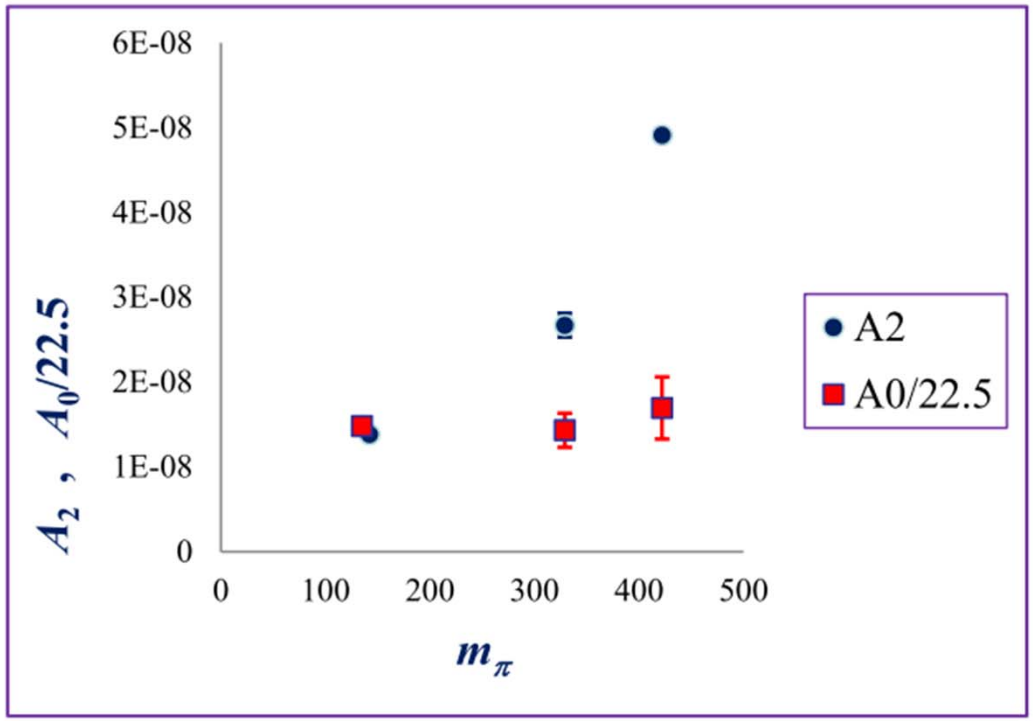


Brute force 32X32X32X 64X16

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

Compare A_2 and $A_0/22.5$

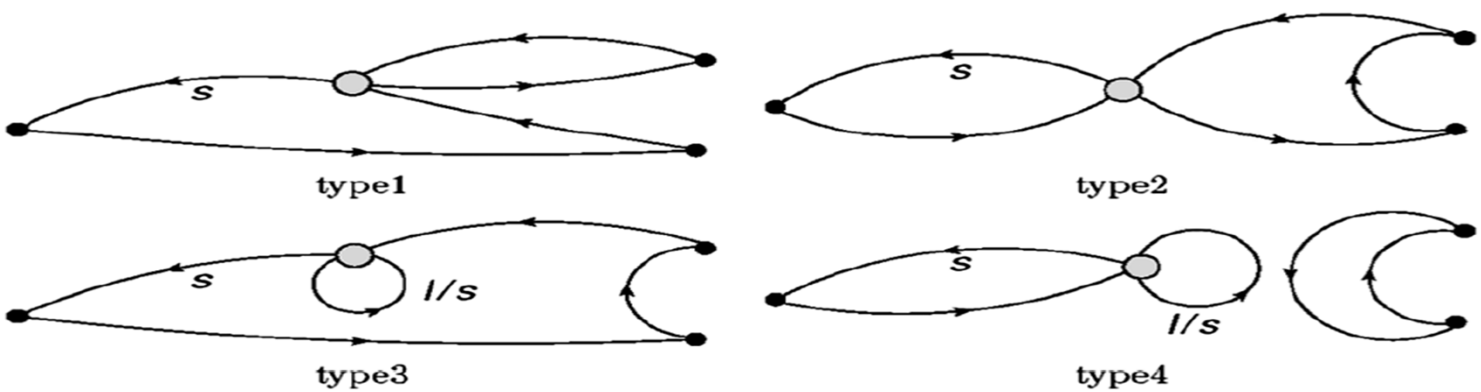


NHCC
KITP
Aug '15

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 ε' significantly enhances sensitivity to NP

- **Examination of resulting matrix elements shows that I=0 and I=2 contributions to ε' 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 ~5 TeV, there is an excellent chance that ε' will find it!

[of course requires accurate theory calculation… RBC-UKQCD plans for X5 in stat and appreciable improvements in systematic in ~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?

SUPERCOMPUTERS OVER 3 CONTINENTS!

LAT 17

Progress in the calculation of ε' on the lattice C. Kelly

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

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 ~ 1000 new configs

~ 500 new measurements

Total 700

Efforts to improve systematics

PRL '15

2nd lattice spacing underway

MATTIA BRUNO CLAT '16

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

Description	Error	Description	Error
Finite lattice spacing	12%	Finite volume	7%
Wilson coefficients	12%	Excited states	$\leq 5\%$
Parametric errors	5%	Operator renormalization	15%
Unphysical kinematics	$\leq 3\%$	Lellouch-Lüscher factor	11%
Total (added in quadrature)			27%

8% NOW

[$M = 1.53$ GeV]

2014 → $\delta[\mathrm{Im}\,A_2] \sim 3\%\,[\mathrm{stat}]\,[12\%]_{sy}$

2020 ⇒ $\delta[\mathrm{Im}\,A_2] \to 5\%$

Progress towards improved determination of A0

- **PRL 2015 with 216 measurements δ[ImA0] => ~60%(stat)**

- **Now ~around 700 measurements δ[ImA0] ~30% (stat)….**

- **Also δ(ReA0) was ~21%(stat) in the PRL 2015**
- **Now around 17%**
- **Target ~1000 measurements by end of 2017 …aim a new result**

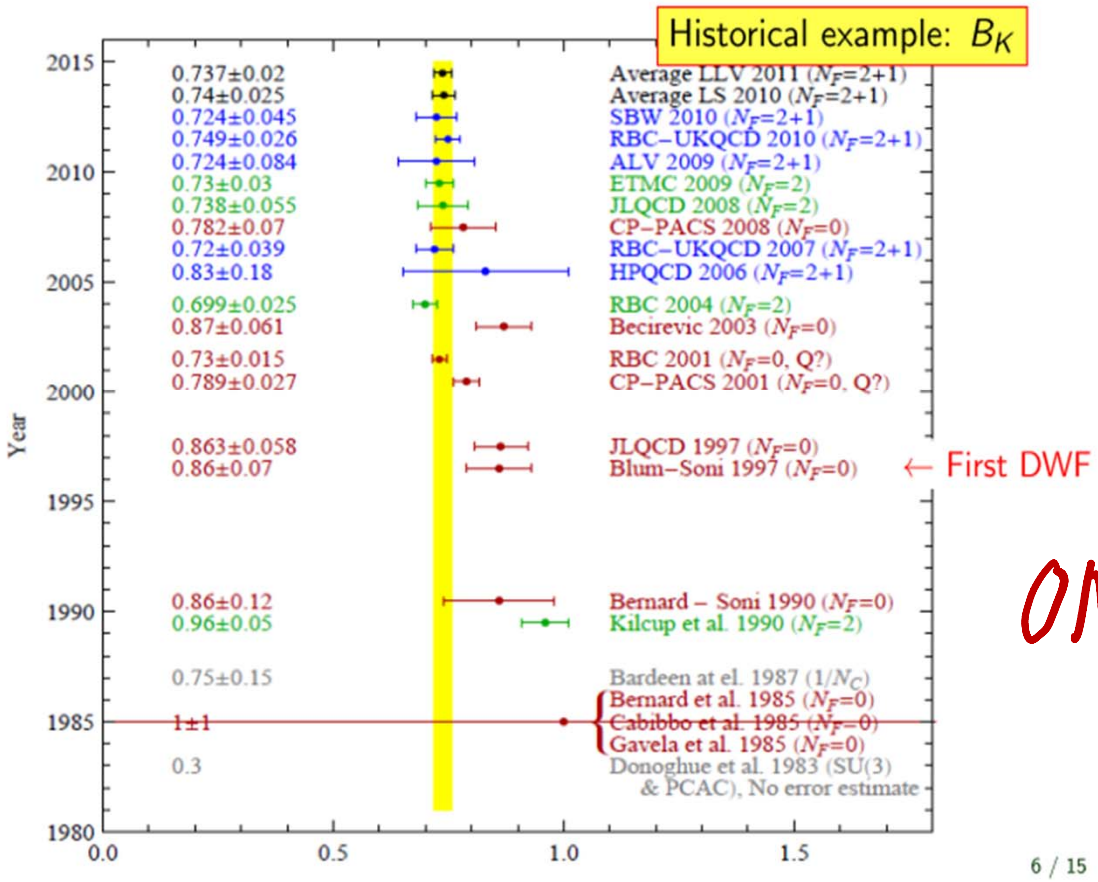
Proof of the pudding: underlying method is systematically improvable

- **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!

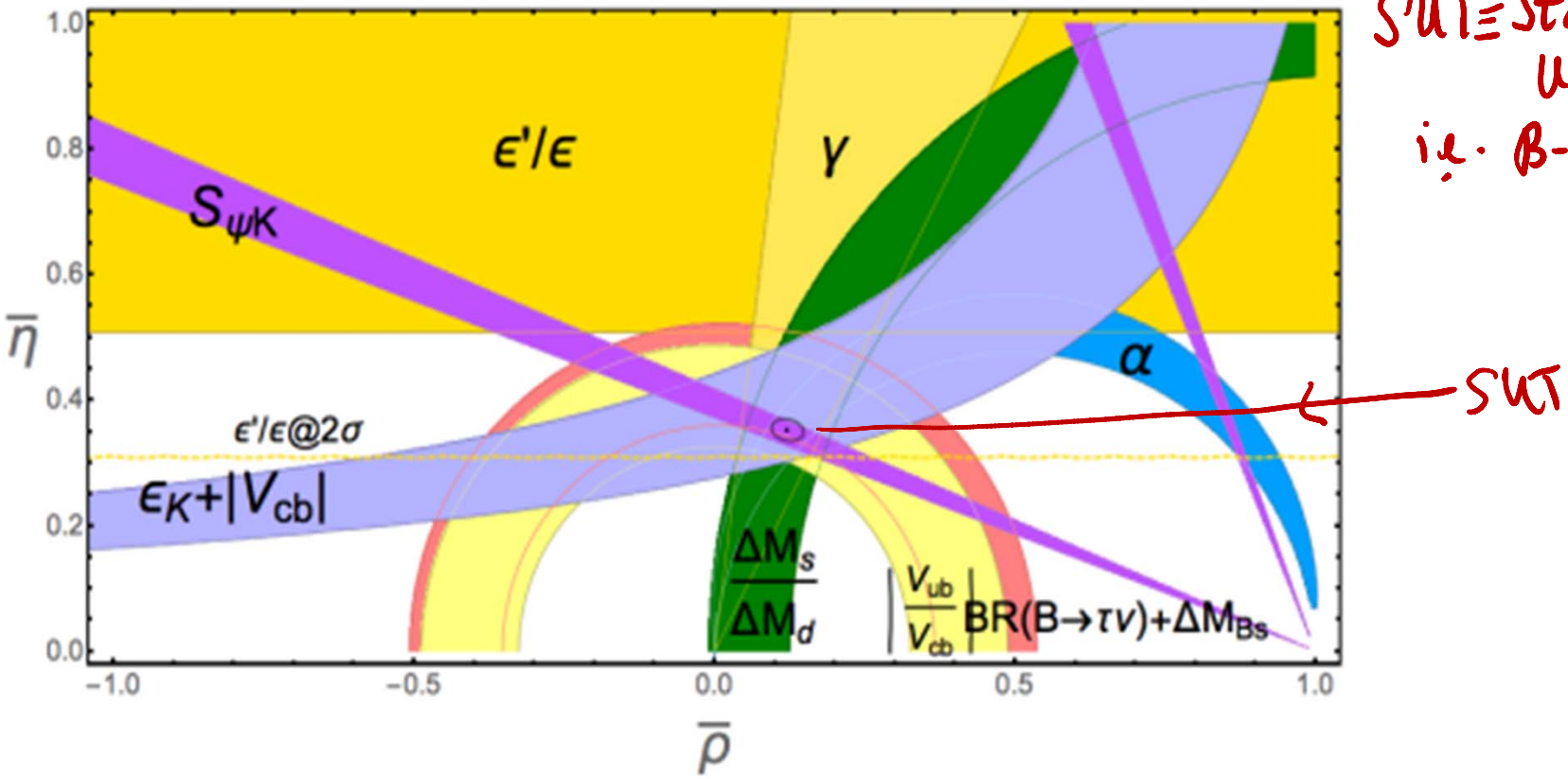


AB-initio Calculat

$$B_K = \frac{\langle K|(\bar{s}\gamma_\mu d)^2|\bar{K}\rangle}{8/3 f_K^2 m_K^2}$$

ONE ILLUSTRATION

Lattice ϵ'/ϵ & SUT : CIRCA ~ 2015



SUT ≡ Standard UT i.e. B-UT

SUT

Example one implication: K-UT

K-UT: A dream for some

Blucher, Winstein and Yamanaka '09; see also Buras

Construction of a Kaon UT

LITTENBERG PRD '89

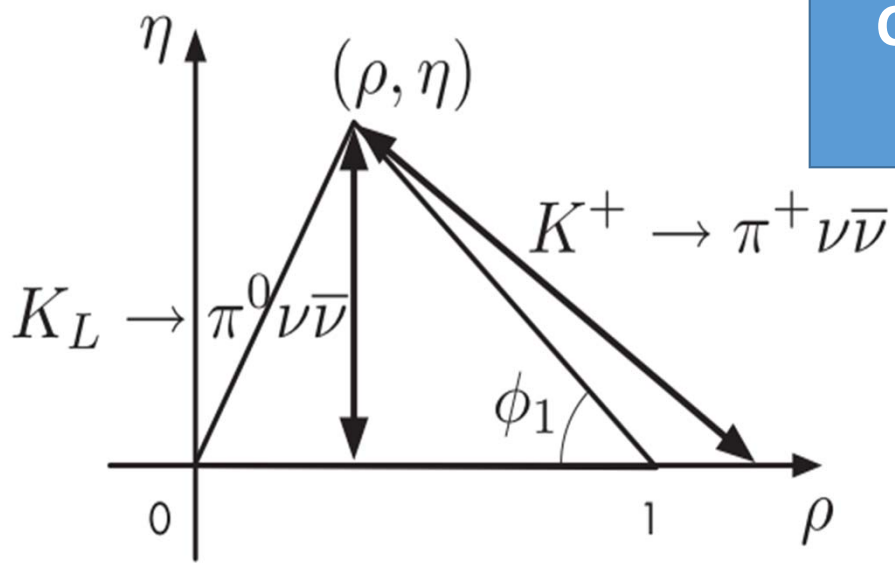


Fig. 14. Unitarity triangle.

Lehner + Luzzi + AS PLB '2016

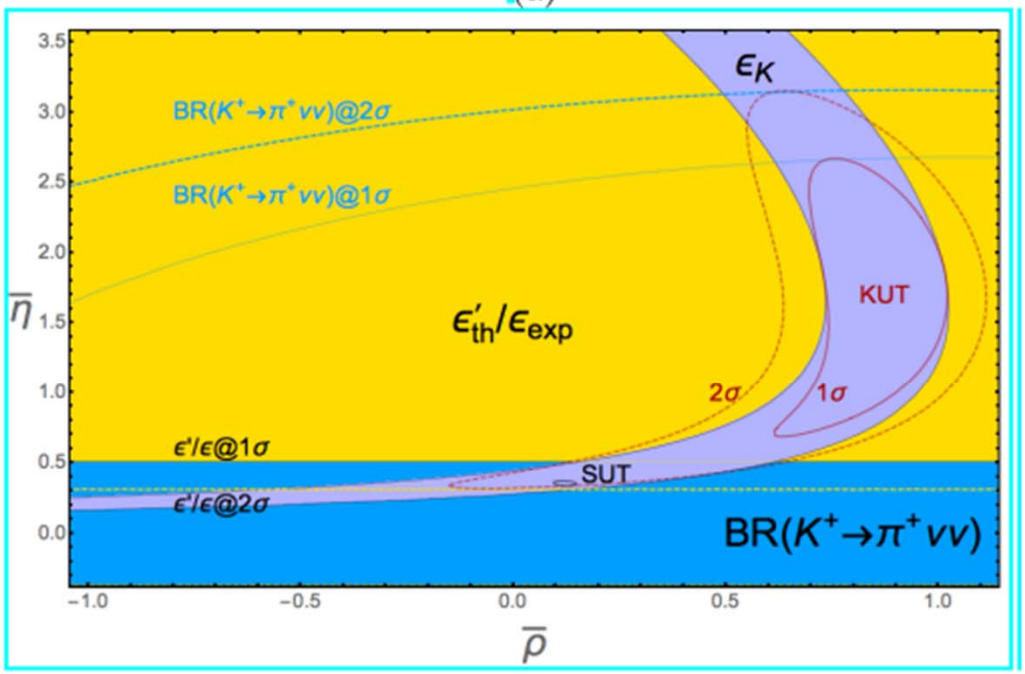
Instead of [or in addition to] $K_L \to \pi^0 \nu\bar{\nu}$ can now plan on using ϵ'/ϵ

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)

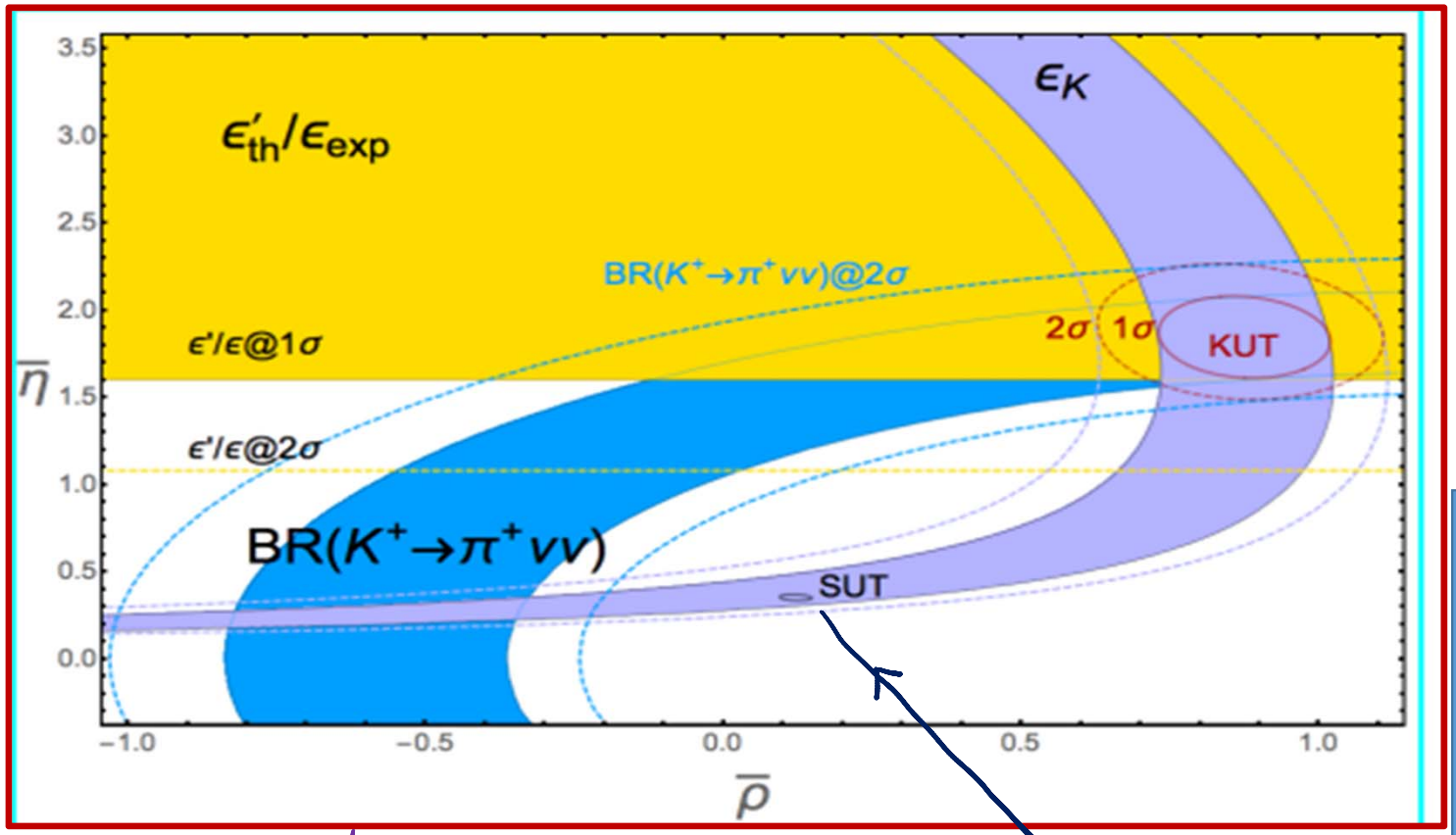


LLS '15

III $$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)_K = \begin{cases} (16.7 \pm 1.6) \times 10^{-4} & \text{PDG2015} \\ (1.36 \pm 5.21_{\text{stat}} \pm 4.49_{\text{syst}}) \times 10^{-4} & \end{cases}$$

RBC+UKQCD '15

POSSIBLE KUT CIRCA 2020: DUE NA62 + RBC-UKQCD



NO unique $\bar{\rho}, \bar{\eta}$

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

Lehner, Lunghi + AS PLB'16

"standard" (B) UT

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 ε'/ε, (and the related puzzle of the ΔI=1/2 rule)**
- **Note also, the significant progress that is anticipated in lattice calculation of ε' soon and in near future suggests that the experimental community should re-examine the determination of ε' 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 X Q1 + c2 XQ2 , holds to an excellent approx….use ReA0 expt
- **Useful op identity and its uses:** Q4 = Q3 + Q2 – Q1, to get rid of Q4

#s Based on 1st 215 measurements

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

[1/2]

0.90 ± .30

- Also Q3/Q4 is small but with largish errors → −.18 ± .36

[0]

- 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=> pi pi and eps' AT THRESHOLD……a good start

Consistent within large errors with RBC-UKQCD ε threshold done in 2012

Mass depends of ReA2, A0

PRL 2013

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

TABLE I: Summary of simulation parameters and results obtained on three DWF ensembles.

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

One measure C.K e Lat 16

	1.32 GeV 24I	1.33 GeV 32ID	1.53 GeV 32ID	2.29 GeV 24I	2.29 GeV stepscaled, no G_1	2.29 GeV stepscaled inc. G_1
(1,1)	0.06076(15)	0.063454(63)	0.05978(13)	0.036954(41)	0.03948(16)	0.03948(16)
(2,2)	0.203(19)	0.204(15)	0.300(68)	0.0795(70)	0.080(33)	0.092(35)
(2,3)	0.310(21)	0.317(16)	0.363(76)	0.1486(59)	0.153(36)	0.161(42)
(2,4)	0.0120(48)	0.0076(42)	0.030(22)	0.0033(23)	0.0083(89)	0.0086(93)
(2,5)	0.0120(42)	0.0005(31)	0.015(20)	0.0039(15)	0.0074(53)	0.0081(77)
(3,2)	0.283(22)	0.268(15)	0.264(87)	0.1547(42)	0.143(23)	0.174(26)
(3,3)	0.391(25)	0.414(17)	0.44(11)	0.2207(39)	0.238(25)	0.297(32)
(3,4)	0.0012(59)	0.0002(34)	0.019(27)	0.0077(13)	0.0057(59)	0.0017(66)
(3,5)	0.0128(62)	0.0264(43)	0.008(27)	0.0190(11)	0.0247(46)	0.0090(68)
(4,2)	0.118(70)	0.094(53)	0.24(25)	0.037(24)	0.07(10)	0.06(11)
(4,3)	0.113(76)	0.073(62)	0.26(30)	0.026(20)	0.08(11)	0.09(13)
(4,4)	0.006(20)	0.006(16)	0.076(88)	0.0318(80)	0.024(30)	0.023(31)
(4,5)	0.023(18)	0.019(12)	0.046(79)	0.0014(50)	0.033(19)	0.027(26)
(5,2)	0.239(28)	0.205(28)	0.19(17)	0.0957(84)	0.048(63)	0.033(74)
(5,3)	0.404(34)	0.347(37)	0.25(20)	0.1885(90)	0.101(77)	0.075(99)
(5,4)	0.0106(80)	0.0174(98)	0.039(62)	0.0028(26)	0.044(20)	0.031(23)
(5,5)	0.0810(100)	0.0740(93)	0.016(56)	0.0303(23)	0.012(15)	0.062(21)
(6,6)	0.00461(21)	0.005040(92)	0.006154(96)	0.001631(63)	0.00185(24)	0.00185(24)
(6,7)	0.002132(46)	0.003396(25)	0.002073(59)	0.001567(12)	0.002002(43)	0.002002(43)
(7,6)	0.02221(12)	0.024916(60)	0.024131(91)	0.018826(21)	0.02260(20)	0.02260(20)
(7,7)	0.127052(87)	0.133903(52)	0.12284(25)	0.080743(12)	0.08705(11)	0.08705(11)

Table 2: Preliminary values of Ξ 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 ΔI=3/2 continuum 2012-2015

- Original physical measurement [Phys.Rev.Lett. 108 (2012) 141601]

$$\mathrm{Re}(A_2) = 1.38(5)_{\mathrm{stat}}(26)_{\mathrm{sys}} \times 10^{-8}\ \mathrm{GeV}$$

$$\mathrm{Im}(A_2) = -6.54(46)_{\mathrm{stat}}(120)_{\mathrm{sys}} \times 10^{-13}\ \mathrm{GeV}$$

20% sys error dominated by 15% discretization error

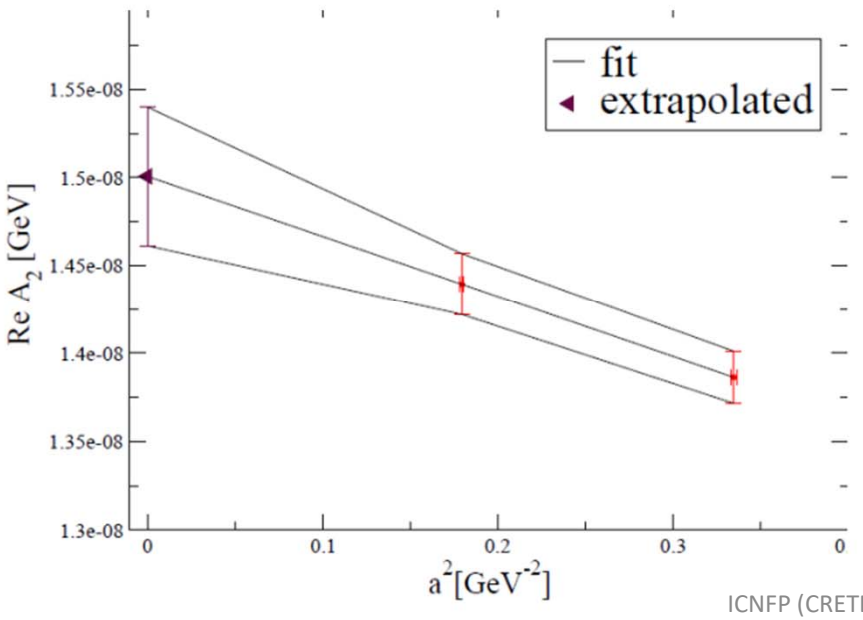
PRD '12
$32^3 \times 64 \times 16$; $a^{-1} = 1.364$ GeV
146 Configs; $m_\pi = 142.1$ MeV
$m_K = 505.5$ MeV

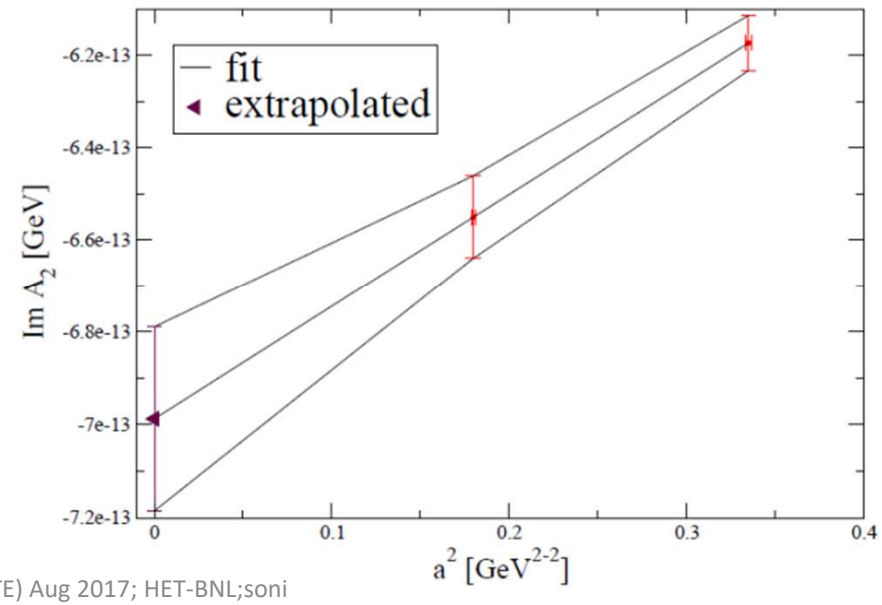
TABLE IX. Systematic error budget for $\mathrm{Re}A_2$ and $\mathrm{Im}A_2$.

	$\mathrm{Re}A_2$	$\mathrm{Im}A_2$
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%

@ the CONTINUUM

- Calculation has now been repeated on RBC & UKQCD 48^3x96 and 64^3x128 Mobius DWF ensembles with $(5\ \mathrm{fm})^3$ volumes and a=0.114 fm, a=0.084 fm.





Creely

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]

plan

- **I. DCP in B: From brown muck to standard candle**

- **II. DCP in K: From mud to a uniquely sensitive shining beacon for BSM phenomena**

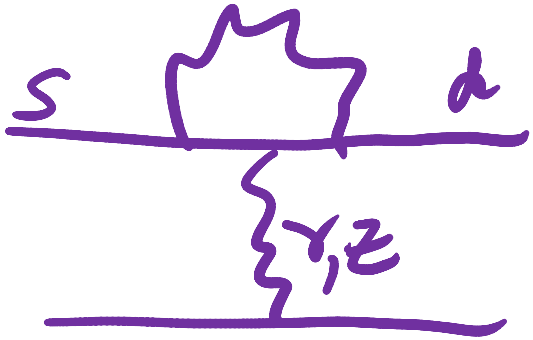
For pragmatic reasons:

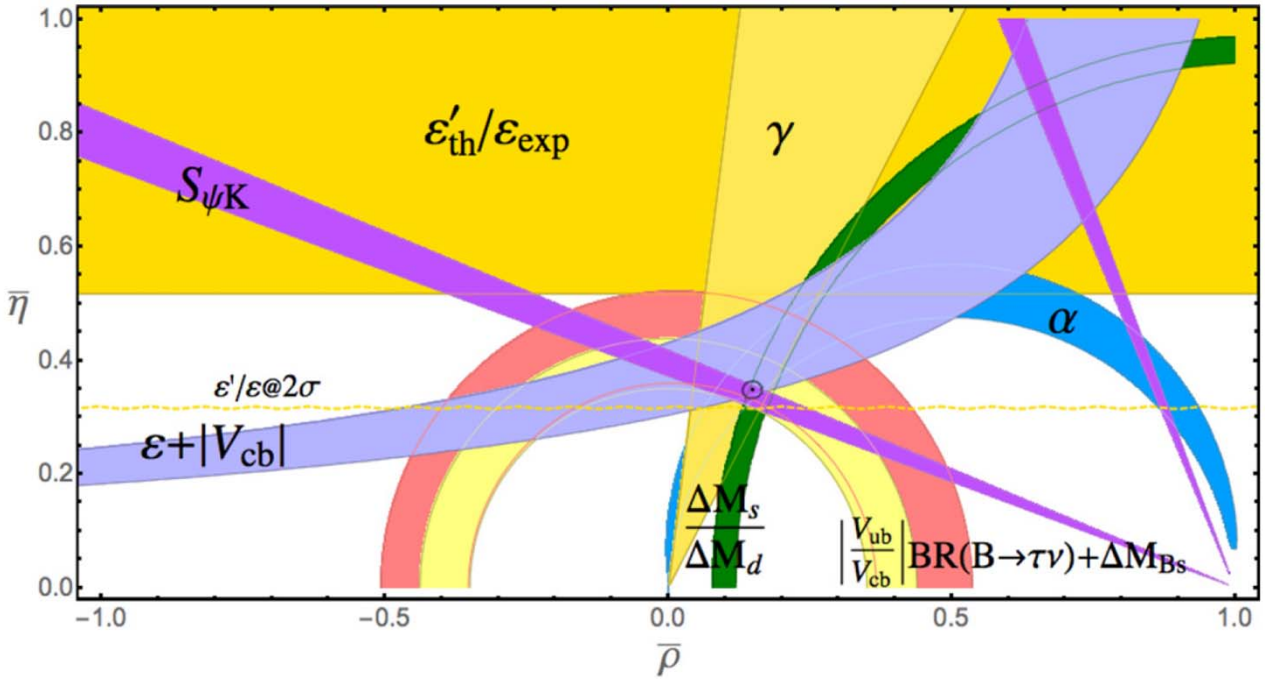
Completely diff strategies ⇒ Extremely powerful tests of SM & Search for NP

More demands on the calculation

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

$$c_8 \propto m_t^2 / M_W^2$$



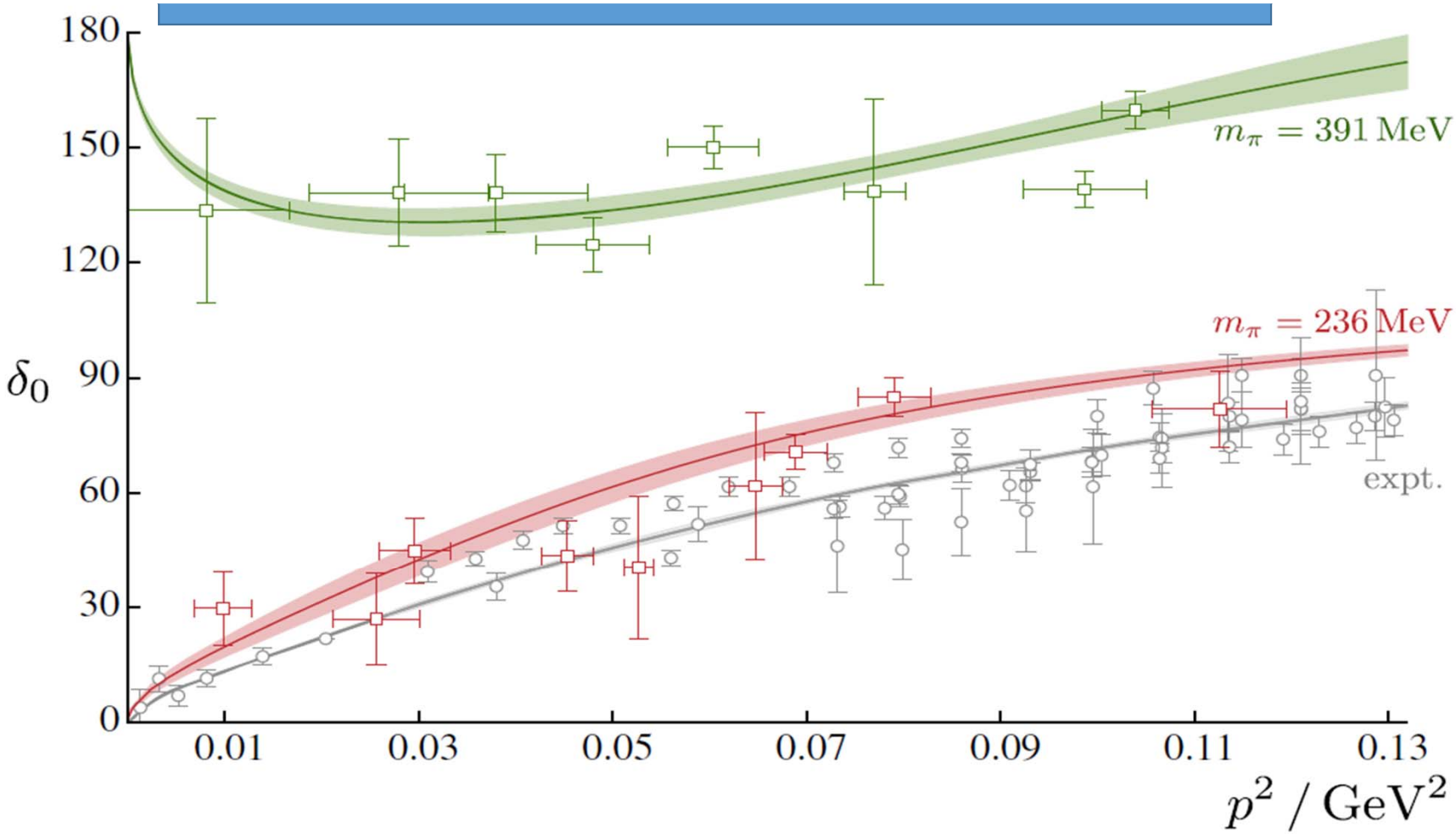

$\varepsilon'_{th}/\varepsilon_{exp}$
γ
$S_{\psi K}$
α
$\varepsilon'/\varepsilon@2\sigma$
$\varepsilon+|V_{cb}|$
$\frac{\Delta M_s}{\Delta M_d}$
$\left|\frac{V_{ub}}{V_{cb}}\right|$BR(B→τν)+$\Delta M_{Bs}$
$\bar{\eta}$
$\bar{\rho}$
1.0
0.8
0.6
0.4
0.2
0.0
−1.0
−0.5
0.0
0.5
1.0

PRL 118, 022002 (2017) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2017

Isoscalar $\pi\pi$ Scattering and the σ Meson Resonance from QCD

Raul A. Briceño,[1,*] Jozef J. Dudek,[1,2,†] Robert G. Edwards,[1,‡] and David J. Wilson[3,§]
(for the Hadron Spectrum Collaboration)

PRL'17



"Improvements in lattice ε' determination underway for past ~2 years

- **Statistics X [> ~ 5] now aiming for** [Previous result uses 216 configs]
- **Systematics.....some already done..** See below
- **EM+ isospin....** in progress. Pheno est. EMI ~ 15±8%. Cirigliano et al; Buras et al 2.16 → 2.46
- **Completely diff method(s)** → B student Dan Hoying @ Colum
- **A) excited pipi state**
- **B) Revisit ChPT** → For physical π, K masses ChPT works well D. Murphy et al RBC-UKQCD PRD 2015
  Should Revisit ChPT for K→2π & Ka BDSPW '84 Laiho + AS '04

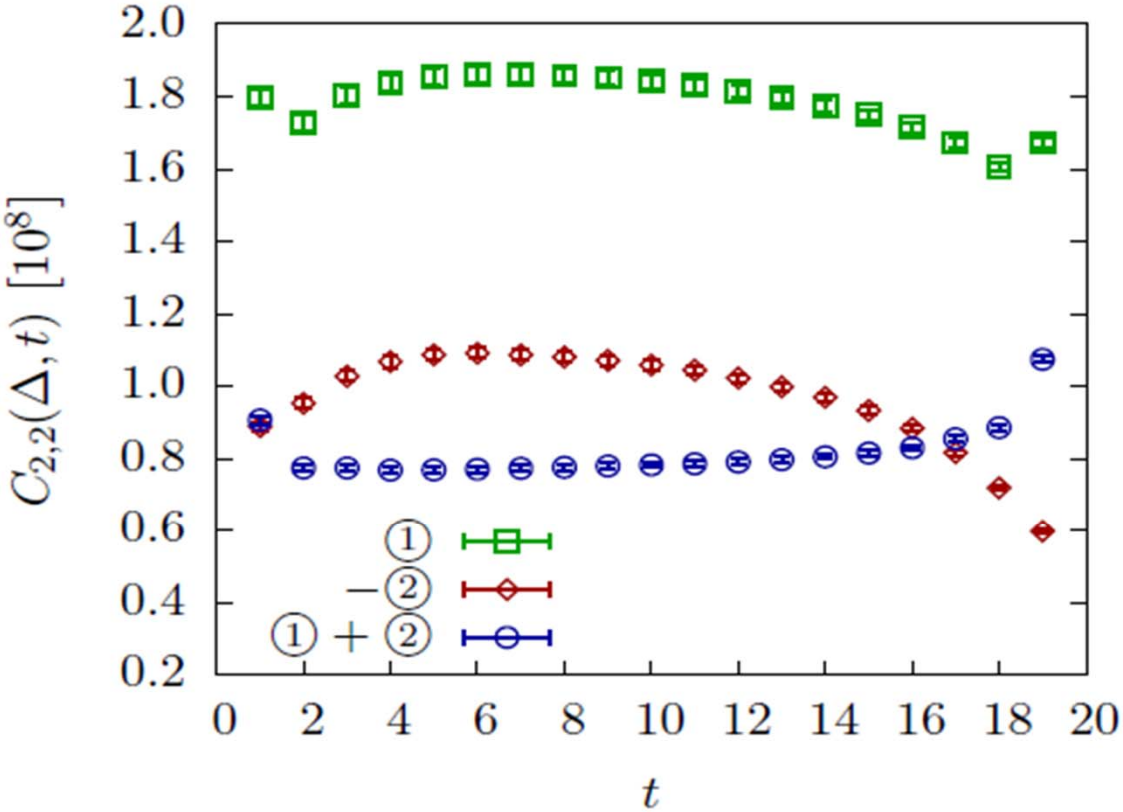


FIG. 3: Contractions ①, -② and ① + ② as functions of t from the simulation at threshold with $m_\pi \simeq 330\,\mathrm{MeV}$ and $\Delta = 20$.