Topical lectures on flavor physics & CP-violation

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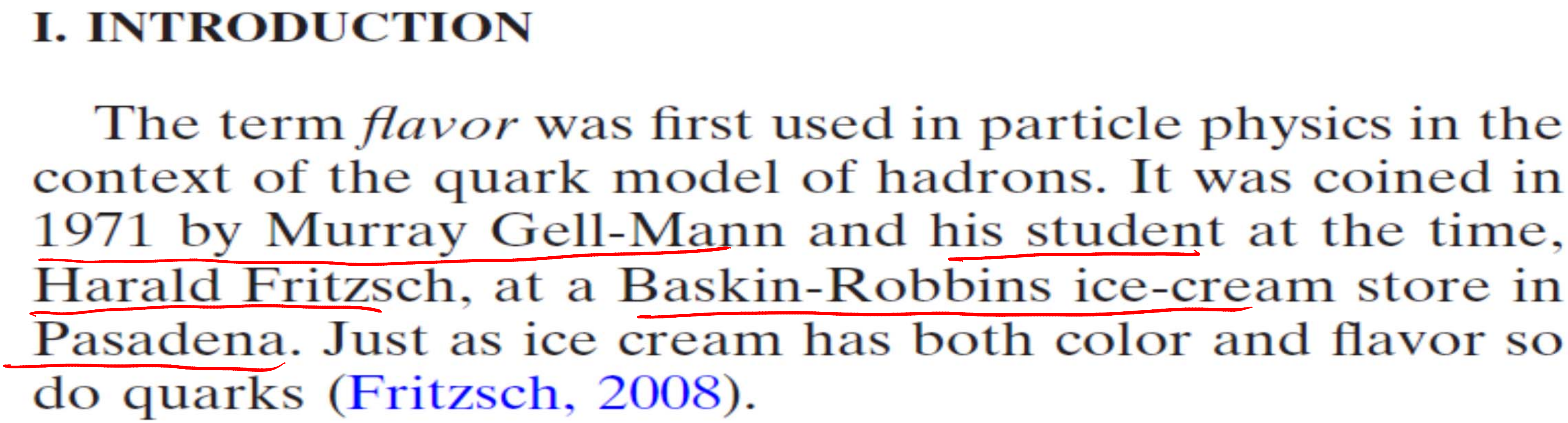
The 2018 Weihai High-Energy Physics School (WHEPS)

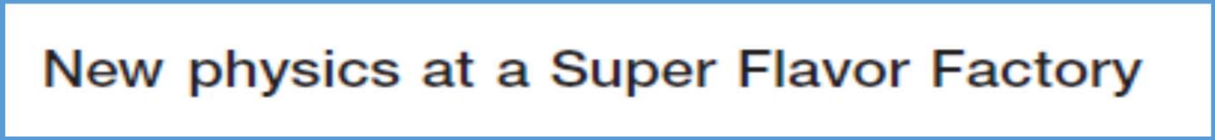
Flavor Physics: An Elementary Primer

In the very beginning



I. INTRODUCTION

The term *flavor* was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks (Fritzsch, 2008).



New physics at a Super Flavor Factory

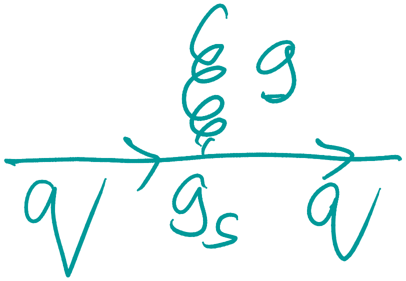
RMP '09

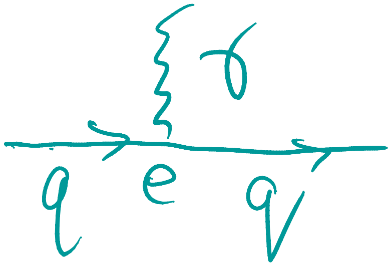
BROWDER, GERSHON, PIRJOL, ZUPAN + A.S.

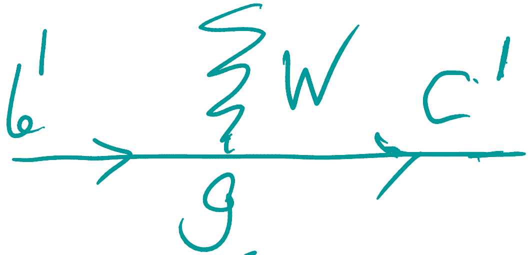
CKM –matrix and weak interactions

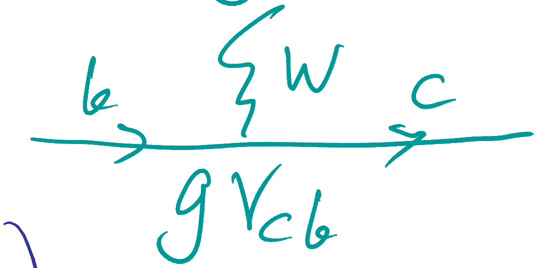
CABIBBO, PRL(63); KOBAYASHI-MASKAWA, PTP (72)

$$G_{SM} = SU(3) \times SU(2) \times U(1)$$









gauge e.s

mass e.s

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM MATRIX

Leads to profound repercussions for BSMs:
“FLAVOR PUZZLE”

Wolfenstein representation: particularly insightful

PRL '84

$\lambda \cong .22$, EXPANSION PARAMETER

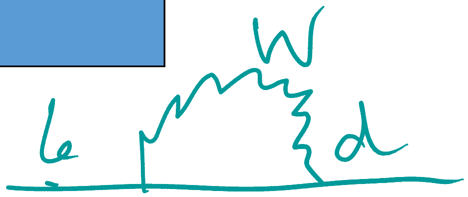
$$V_{WOLF} \equiv \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

e.g.. $V_{ii} \sim 1$, $V_{21} \sim \lambda$; $V_{23} \sim \lambda^2$; $V_{13} \sim \lambda^3$

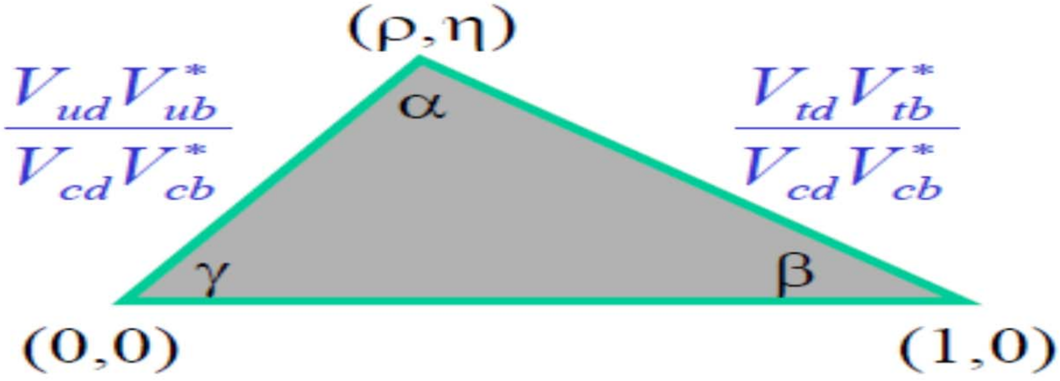
$A, \rho, \eta \sim O(1)$ η is CP-phase

Unitarity triangle(s)

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0.$$



THE UT



$\alpha, \beta, \gamma \propto \eta$

5 more UTs:
s->d (BNL)
b->s
t->c
t->u
c->u

JARLSKOG INVARIANCE

$$|J_{\rm CP}| = 2 \cdot A_\Delta ,$$

ALL MUST HAVE The Same J_{cp}

C. J. PRL'85;
See also Chau & Keung, PRL'84

C, P, T & all that

P: $\vec{x} \to -\vec{x}$; $\vec{S} \to \vec{S}$, $\vec{p} \to -\vec{p}$

C: $e^- \to e^+ \cdots$; $e^-[\vec{S},\vec{p}] \to e^+[\vec{S},\vec{p}]$

T_N: $t \to -t$

T: $t \to -t$, initial $\longleftrightarrow$ final, $e^-[\vec{S},\vec{p}] \to e^-[-\vec{S},-\vec{p}]$

CPT: $e^-[\vec{S},\vec{p}] \to e^+[-\vec{S},\vec{p}]$, initial $\longleftrightarrow$ final

QFT: Laws of physics are invariant under CPT
Thus, CPV <-> TV

Baryogenesis: Sakharov’s conditions (’68)

$$\eta = n_B / n_\gamma = (6.1^{\pm 0.3}{}_{0.2}) \times 10^{-10}$$

CPT Theorem implies 3 conditions req’d for baryogenesis

1 $\Delta B \neq 0$; 2. CPV

3. THERMAL Non Equilibrium

The measure of relevant CP Violation is given by:

$$[(m_c^2 - m_u^2)(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_s^2 - m_d^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)/m_W^{12} * J_{CP}$$

The CPV present in SM is insufficient by many orders of magnitude

Challenges of QCD

QCD & QED are relevant in SM or BSM

9.1. Basics

Quantum Chromodynamics (QCD), the gauge field theory that describes the strong interactions of colored quarks and gluons, is the SU(3) component of the SU(3)×SU(2)×U(1) Standard Model of Particle Physics.

The Lagrangian of QCD is given by

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu} \,, \tag{9.1}$$

where repeated indices are summed over. The γ^μ are the Dirac γ-matrices. The $\psi_{q,a}$ are quark-field spinors for a quark of flavor q and mass m_q, with a color-index a that runs from $a = 1$ to $N_c = 3$, *i.e.* quarks come in three "colors." Quarks are said to be in the fundamental representation of the SU(3) color group.

constant. Finally, the field tensor $F^A_{\mu\nu}$ is given by

Non-Abelian

$$F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\mu - g_s\, f_{ABC} \mathcal{A}^B_\mu \mathcal{A}^C_\nu \qquad [t^A, t^B] = i f_{ABC} t^C \,, \tag{9.2}$$

where the f_{ABC} are the structure constants of the SU(3) group.

9.1.1. ***Running coupling*** :

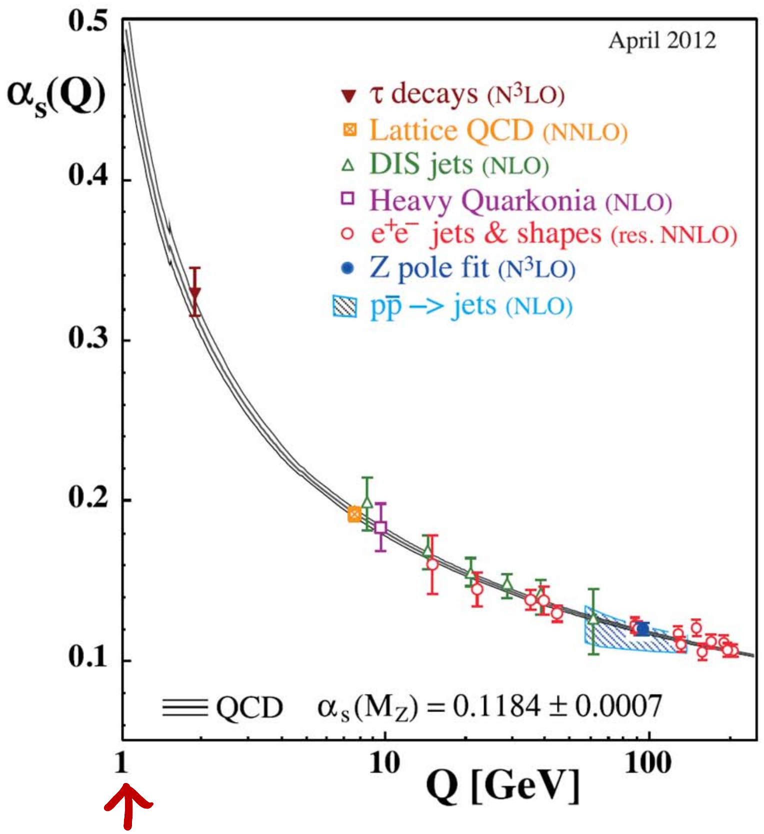
In the framework of perturbative QCD (pQCD), predictions for observables are expressed in terms of the renormalized coupling $\alpha_s(\mu_R^2)$, a function of an (unphysical) renormalization scale μ_R. When one takes μ_R close to the scale of the momentum transfer Q in a given process, then $\alpha_s(\mu_R^2 \simeq Q^2)$ is indicative of the effective strength of the strong interaction in that process.

The coupling satisfies the following renormalization group equation (RGE):

$$\mu_R^2 \frac{d\alpha_s}{d\mu_R^2} = \beta(\alpha_s) = -(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \cdots) \qquad (9.3)$$

where $b_0 = (11C_A - 4n_f T_R)/(12\pi) = (33 - 2n_f)/(12\pi)$ is referred to as the 1-loop beta-function coefficient, the 2-loop coefficient is $b_1 = (17C_A^2 - n_f T_R(10C_A + 6C_F))/(24\pi^2) = (153 - 19n_f)/(24\pi^2)$, and the 3-loop coefficient is $b_2 = (2857 - \frac{5033}{9}n_f + \frac{325}{27}n_f^2)/(128\pi^3)$. The 4-loop coefficient, b_3, is to be found in Refs. 9, 10[†]. The minus sign in Eq. (9.3) is the origin of Asymptotic Freedom, *i.e.* the fact that the strong coupling becomes weak for processes involving large momentum transfers ("hard processes"), $\alpha_s \sim 0.1$ for momentum transfers in the 100 GeV – TeV range.

$$\alpha_s(\mu_R^2) \simeq \frac{1}{b_0 t}\left(1 - \frac{b_1}{b_0^2}\frac{\ln t}{t} + \frac{b_1^2(\ln^2 t - \ln t - 1) + b_0 b_2}{b_0^4 t^2} - \frac{b_1^3(\ln^3 t - \frac{5}{2}\ln^2 t - 2\ln t + \frac{1}{2}) + 3b_0 b_1 b_2 \ln t - \frac{1}{2}b_0^2 b_3}{b_0^6 t^3}\right), \quad t \equiv \ln\frac{\mu_R^2}{\Lambda^2}, \quad (9.5)$$



$m_\pi \sim 140\text{MeV}$

$m_K \sim 500\text{MeV}$

$m_{\text{proton}} \sim 1\text{ GeV}$

Figure 9.4: Summary of measurements of α_s as a function of the respective energy scale Q. The respective degree of QCD perturbation theory used in the extraction of α_s is indicated in brackets (NLO: next-to-leading order; NNLO: next-to-next-to leading order; res. NNLO: NNLO matched with resummed next-to-leading logs; N^{3}LO: next-to-NNLO).

scope

- **1.Recent advances in direct CP violation:**

[in this i will concentrate on direct CP in B-decays and their relevance to the unitarity triangle and on recent successes in understanding long standing issues in K=>pi pi]

- **2. Flavor anomalies and possible indications of new physics**

- **3. Optimizing for new physics/CPV searches in charm and tau decays**

Summary & Outlook

“I. Recent advances in direct CP violation"

DIRECT CP: Long-standing challenge for theorists

DIRECT CP: Long-standing challenge for theorists

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:

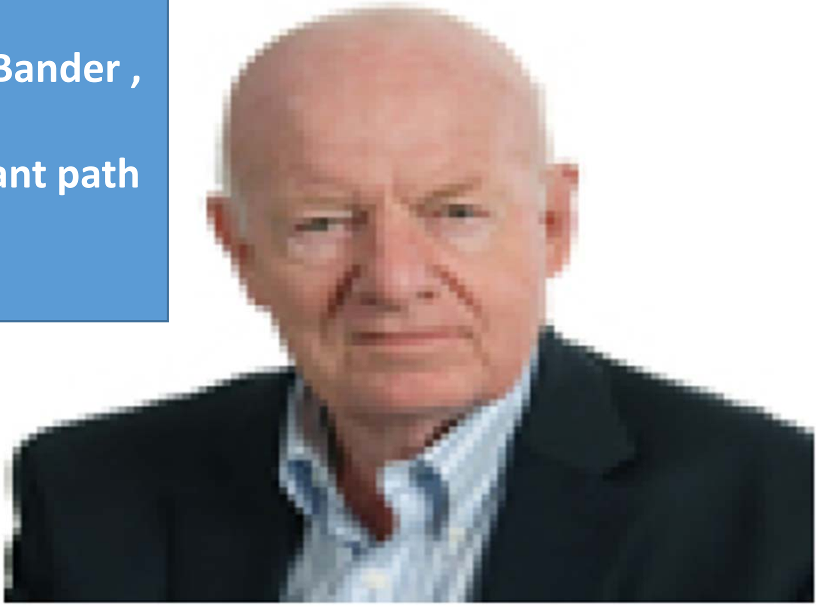
Completely diff strategies

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”**

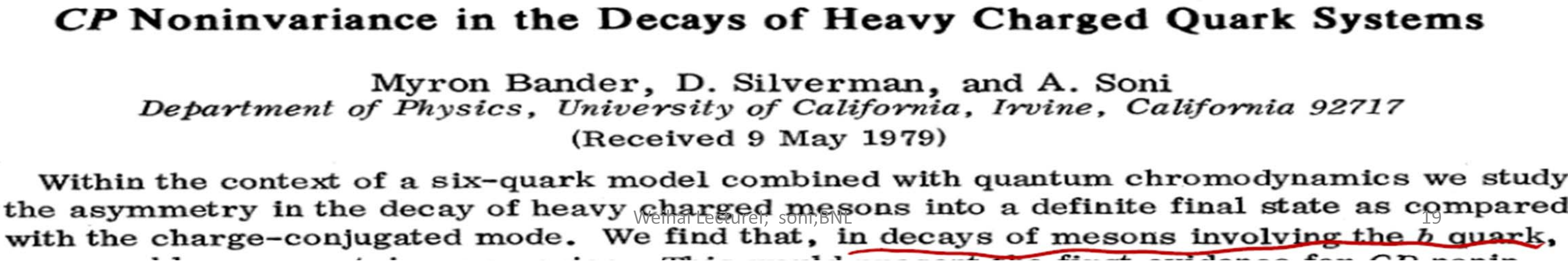
- **In K=>ππ decays, direct CP, ε’: From mud to uniquely precious beacon of new physics; primarily due to significant progress in lattice calculations after decades of relentless effort**.

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 over the years**

Different manifestations of CP

- Mixing

$K_L \to \pi\pi$

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

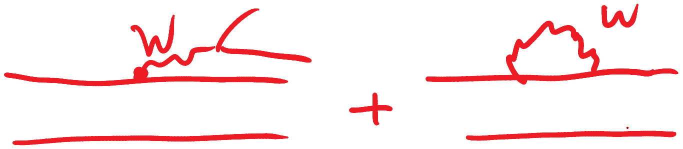
BNL '64 CRONIN + FITCH NOBEL

- Decay (direct, time-integrated)

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

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

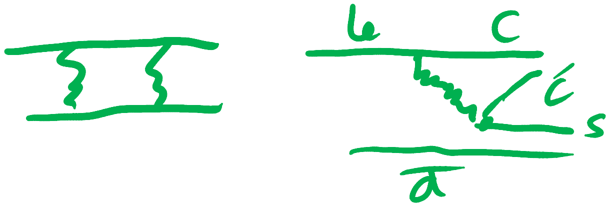
+



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

III

- Mixing and decay (time-dependent)

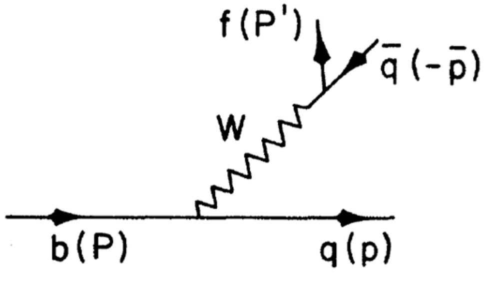


$S(B^0 \to \psi K_0) \simeq \sin 2\beta \sim 0.673$

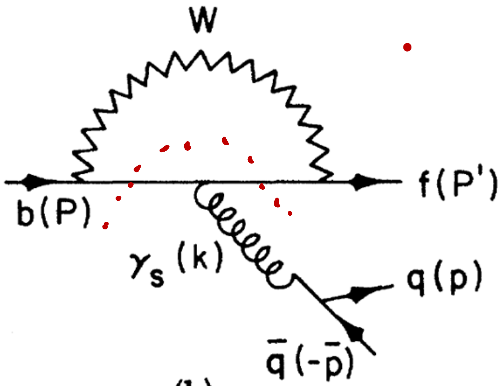
Highly instrumental in the dramatic success of the B-factories and the KM Nobel Prize

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

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



(a)



(b)

Bander, Silverman and A. S. PRL ’79

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

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

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

$$\alpha_{PRA} = \frac{\mathcal{B}(B \to f) - \mathcal{B}(\overline{B} \to \bar{f})}{\mathcal{B}(B \to f) + \mathcal{B}(\overline{B} \to \bar{f})}$$

$$= \frac{2|A_1|\,|A_2| \sin\delta \sin\phi}{|A_1|^2 + |A_2|^2 + 2|A_1|\,|A_2| \cos\delta \cos\phi} ,$$

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

Direct CP: Long^2 standing challenge for theorists

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

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

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

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

$q = u, c, t$ or
d, s, b

UNKnows 4: $|T|, |P|, \delta_{st}, \delta_{wk}$

OBSERVABLES 3 $|A|^2; |\bar{A}|^2 + a_{CP}$

DESEPERATELY NEED δ_{st}!

- **From Theory need non-perturbative framework..**
- **For K ($\varepsilon' / \varepsilon$) on going lattice efforts for ~35 years!**
- **also significant progress [by RBC-UKQCD]in related problem of the ΔI =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 $\gamma \approx 70 \pm 10^\circ$

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

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

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

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

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

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

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

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

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

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

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

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

Very large dir CP in many cases!

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

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

- ***In light of abundance of data, re-examination of theory [e.g. BBNS] is in order***

For now data driven methods

A great personal treat; thanks to LHCb

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

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

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

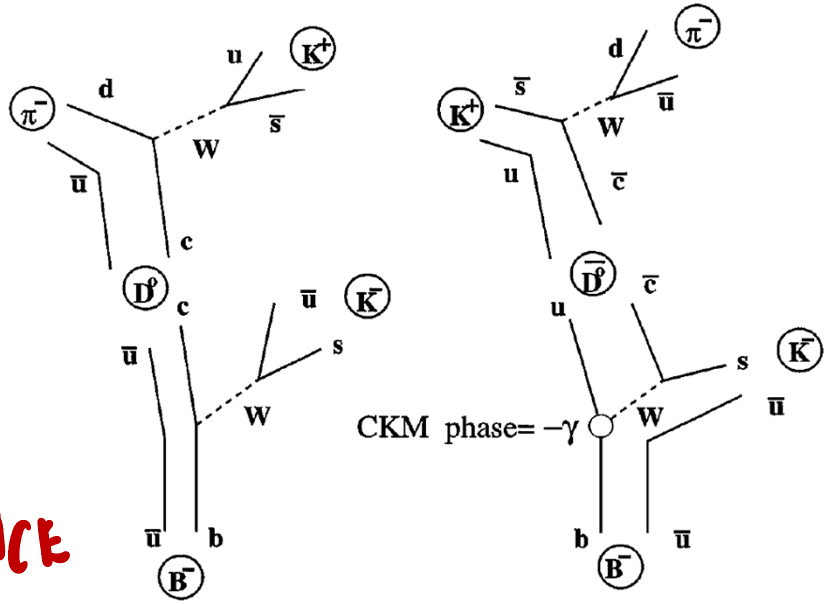


FIG. 1. Diagrams for the two interfering processes: $B^- \longrightarrow$ K^-D^0 (color-allowed) followed by $D^0 \longrightarrow K^+\pi^-$ (doubl Cabibbo suppressed) and $B^- \longrightarrow K^-\overline{D}^0$ (color-suppressed followed by $\overline{D}^0 \longrightarrow K^+\pi^-$ (Cabibbo allowed).

$$\begin{aligned} d(K, f_i) &= a(K)c(f_i) + b(K)c(\overline{f}_i) \\ &\quad + 2\sqrt{a(K)b(K)c(f_i)c(\overline{f}_i)}\cos(\xi^K_{f_i} + \gamma), \\ \overline{d}(K, f_i) &= a(K)c(f_i) + b(K)c(\overline{f}_i) \\ &\quad + 2\sqrt{a(K)b(K)c(f_i)c(\overline{f}_i)}\cos(\xi^K_{f_i} - \gamma), \end{aligned} \tag{3}$$

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

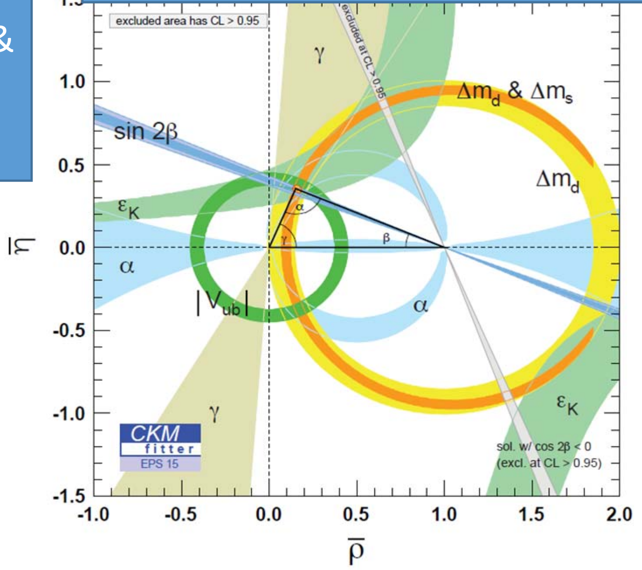
$$\{\xi^K_{f_1},\ \xi^K_{f_2},\ b(K),\ \underline{\gamma}\}$$

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

Efforts to overconstrain the CKM Matrix & UT continue

Andreas Hoecker & Malcolm John
EW Moriond '16



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

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

which improved the previous LHCb-only conclusion by 2°

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

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

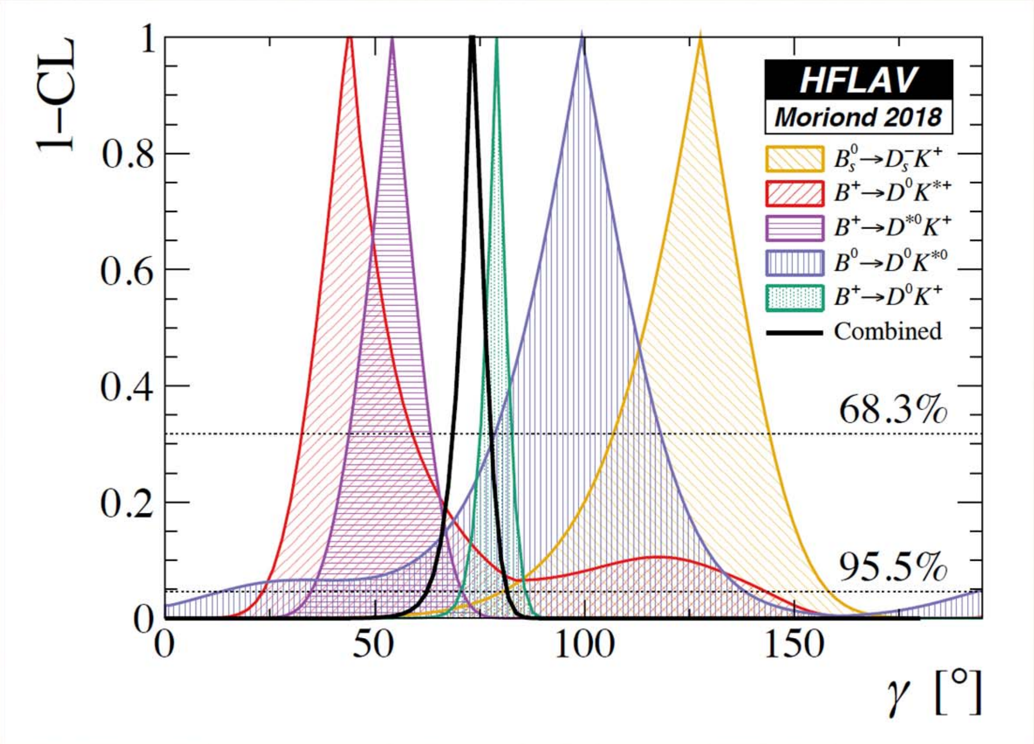
Compatible with SM-CKM to ~15% accuracy

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

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

HFlav website

World average (HFLAV)



$$\gamma = (73.5^{+4.2}_{-5.1})^\circ$$

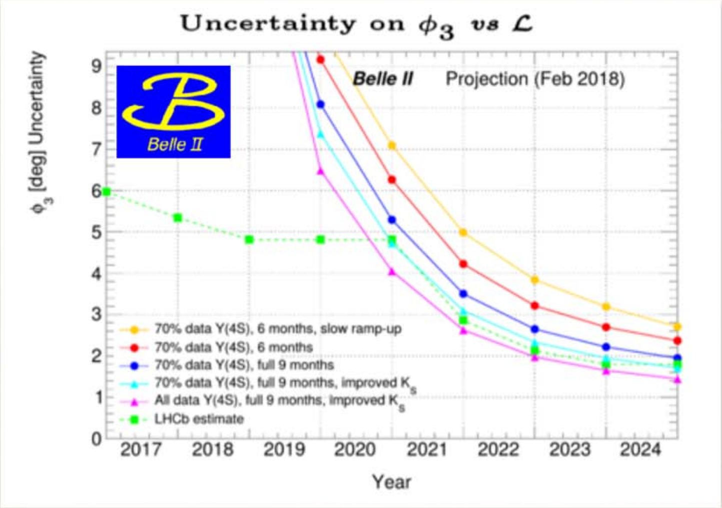
Naive 1.6σ divergence from indirect prediction

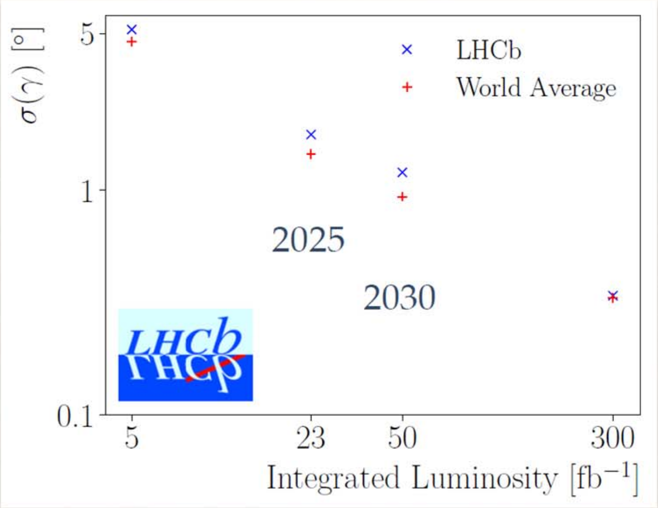
$\gamma_{\text{indirect}} = (65.3^{+1.0}_{-2.5})^\circ$ (CKMfitter)

Prospects

Expect Belle II and the LHCb upgrade to match each other's performance

- σ(γ) ~2° each by 2025





After 2025 Belle II stops but LHCb upgrade 1b and 2 aim for 300 fb^{-1}

- World average may have precision: σ(γ) ~0.3° by 2035

The ultimate theoretical error on γ from $B \to DK$ decays

Joachim Brod and Jure Zupan

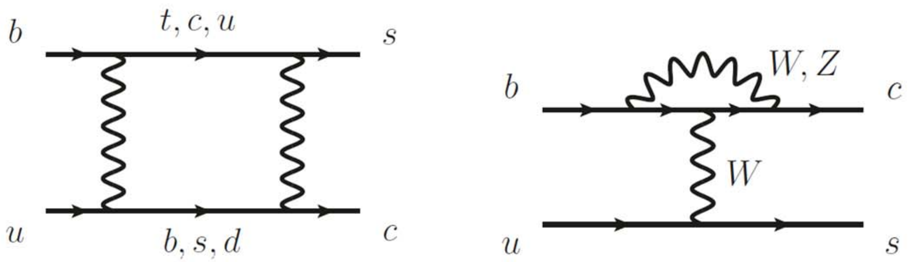
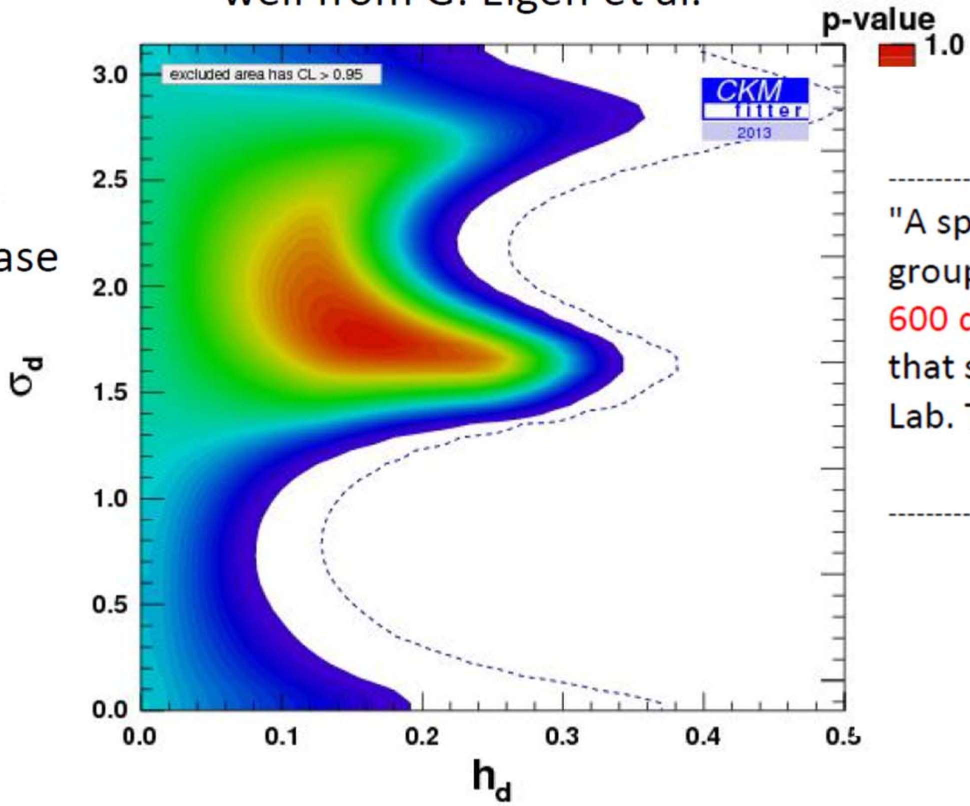


Figure 2. The electroweak corrections to $b \to c\bar{u}s$ process at order $\mathcal{O}(g^4)$, the box diagram (left) and vertex correction (right). Similar diagrams appear in $b \to u\bar{c}s$ processes.

order electroweak corrections. We study these contributions and estimate that their impact on the γ determination is to introduce a shift $|\delta\gamma| \lesssim \mathcal{O}(10^{-7})$, well below any present or planned future experiment.

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



NP Phase

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"

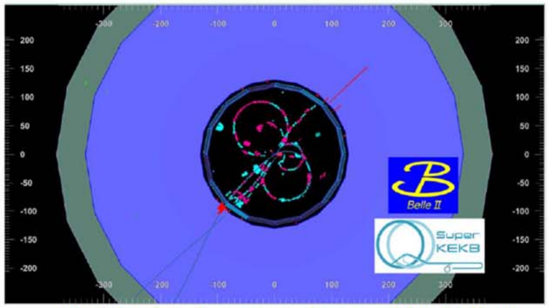
1964: BF= 2 x 10^{-3}

A failure of imagination ? Lack of patience ?

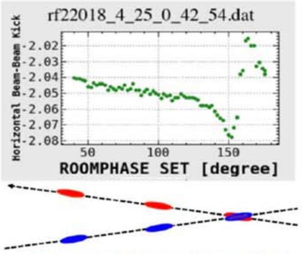
First collision

Apr. 26, 2018

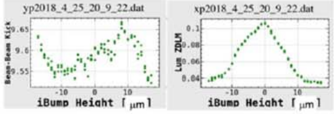
Belle II control room



First hadronic event observed by Belle II



Horizontal beam-beam kick



Vertical beam-beam kick

SuperKEKB control room

K. Akai, SuperKEKB/Belle II status, ICHEP2018, July 9, 2018

26

Toru Iijima @ SCGP May 31, 2018

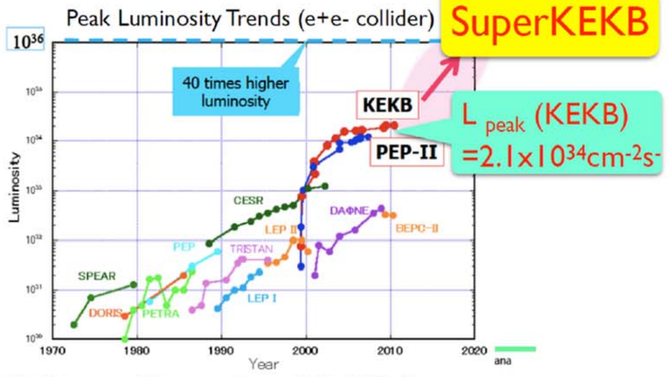
SuperKEKB/Belle II

New intensity frontier facility at KEK

- Target luminosity ; $L_{peak} = 8 \times 10^{35} cm^{-2}s^{-1}$

  $\Rightarrow \sim 10^{10}$ $B\overline{B}$, $\tau^+\tau^-$ and charms per year !

  $L_{int} > 50\ ab^{-1}$



SuperKEKB

L_{peak} (KEKB) $=2.1\times10^{34} cm^{-2}s^{-}$

The first particle collider after the LHC !

Looking forward at LHCb

7 - 8 TeV	13 TeV	14 TeV	HL-LHC →	
Run 1 2010 - 2012	Run 2 2015 - 2018	Run 3 2021 - 2023	Run 4 2026 - 2029	Run 5 2031 -
3 fb^{-1}	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}

↑ Upgrade I

↑ Upgrade II

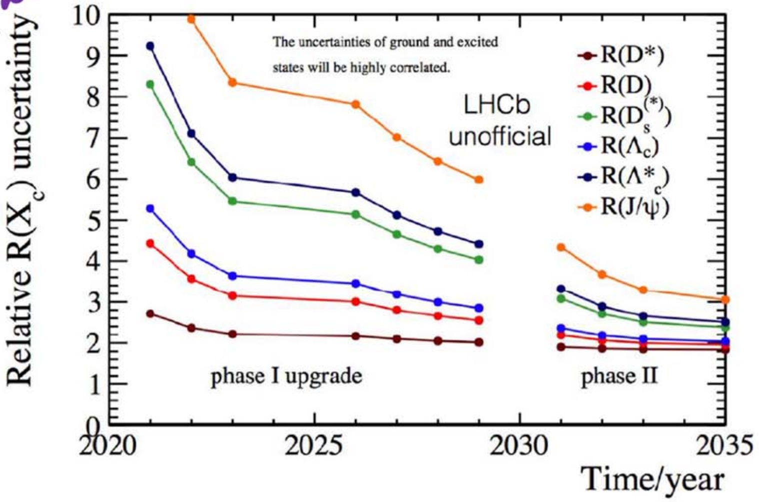
Mark Smith @
FPCP2018

C also T SZUMLAKO
FPCP 2018

Upgrade I:
CERN-LHCC-2012-007
Upgrade II:
CERN-LHCC-2017-003

Continued improvement reliant on:

- Simulation size
- Theory collaboration
- Experimental input



Data Samples / Year

Luminosity **Seconds/days** **Running time/year** **Efficiency**

$10^{35}\text{cm}^{-2}\text{s}^{-1} \times 86400\text{s} \times 180\text{days} \times 90\% = 1.4\text{ab}^{-1}$

	CLEO-C		BES-III/ year $10^{33}\text{cm}^{-2}\text{s}^{-1}$($10\text{fb}^{-1}$)	HIEPA/year $10^{35}\text{cm}^{-2}\text{s}^{-1}$ (1ab^{-1})
J/ψ	–	–	10×10^{9}	10×10^{11}
ψ(2S)	54 pb^{-1}	27×10^{6}	3×10^{9}	3×10^{11}
ψ(3770)	818 pb^{-1}	5×10^{6} D-pair	4×10^{7}	4×10^{9}
4.17 GeV	586 pb^{-1}	7×10^{5} D_s-pair	1×10^{6}	1×10^{8}
$\tau^+\tau^-$ (4.25)		4×10^{6}	3×10^{7}	3×10^{9}

High Intensity Electron Positron Accelerator (HIEPA)

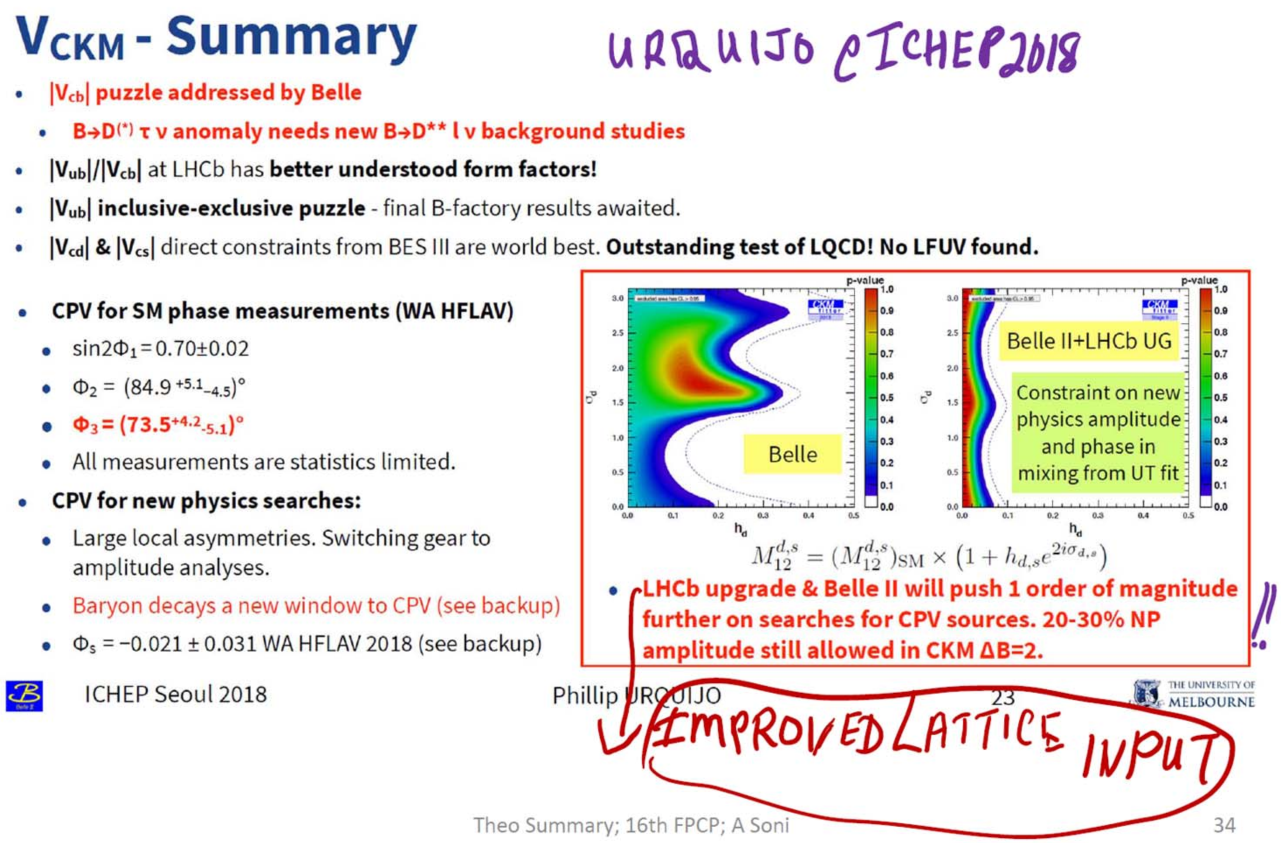
Super Tau Charm Facility (STCF)

Outline

- **Introduction - Why**
- **HIEPA - What**
- **Status and future plan - How**

Zhengguo Zhao

University of Science and Technology of China



V_{CKM} - Summary

URQUIJO @ICHEP2018

- **$|V_{cb}|$ puzzle addressed by Belle**
  - **B→D$^{(*)}$ τ ν anomaly needs new B→D** l ν background studies**
- **$|V_{ub}|/|V_{cb}|$** at LHCb has **better understood form factors!**
- **$|V_{ub}|$ inclusive-exclusive puzzle** - final B-factory results awaited.
- **$|V_{cd}|$ & $|V_{cs}|$** direct constraints from BES III are world best. **Outstanding test of LQCD! No LFUV found.**

- **CPV for SM phase measurements (WA HFLAV)**
  - $\sin 2\Phi_1 = 0.70 \pm 0.02$
  - $\Phi_2 = (84.9^{+5.1}_{-4.5})°$
  - **$\Phi_3 = (73.5^{+4.2}_{-5.1})°$**
  - All measurements are statistics limited.
- **CPV for new physics searches:**
  - Large local asymmetries. Switching gear to amplitude analyses.
  - Baryon decays a new window to CPV (see backup)
  - $\Phi_s = -0.021 \pm 0.031$ WA HFLAV 2018 (see backup)

$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times (1 + h_{d,s} e^{2i\sigma_{d,s}})$$

- **LHCb upgrade & Belle II will push 1 order of magnitude further on searches for CPV sources. 20-30% NP amplitude still allowed in CKM ΔB=2.**

!!

IMPROVED LATTICE INPUT

ICHEP Seoul 2018 Phillip URQUIJO 23 THE UNIVERSITY OF MELBOURNE

II. Dir CP in K=> ππ, i.e. ε’/ε; *From mud to a uniquely sensitive shining beacon for BSM phenomena*

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

outline

- **In K=>ππ decays, direct CP, ε': From extreme example of brown muck (i.e non-perturbative mud)to uniquely precious beacon of new physics; primarily due to significant progress in lattice calculations that took decades of relentless effort**. ***Led to clarifying some LONG STANDING (~60 Years) text book problems and extreme sensitivity to new physics…..major focus of this talk***
- ***After ~35 years of effort & over coming huge number of obstacles a calculational framework based on lattice techniques & built on preserving important***

symmetries of the continuum theory and direct K=>ππ [i.e w/o using

ChPT] enabled by the Lellouch-Lucsher method is used at physical

kinematics with 1st results ~2015

- ***Improvements in process for past over 2 years;X6.5 stat + syst , results anticipated ~ early 2018***
- ***Potential implications for BSMs***
- ***Summary + Outlook***

Plan

- **Introduction: motivation & Recapitulation**
- **Early attempts**
- **Obstacles galore=> overcoming each leads to imp. applications**
- **Direct K=> ππ**
- **Underlying framework**
- **1st results**
- **Improvements underway**
- **Few implications**
- **Interests from new physics perspective**
- **Summary & Outlook**

BSM-CP: Theoretical motivation

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

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

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

MORE LATER

Recapitulate: Many fascinating aspects of kaons=> led to several profoundly important discoveries in Particle Physics

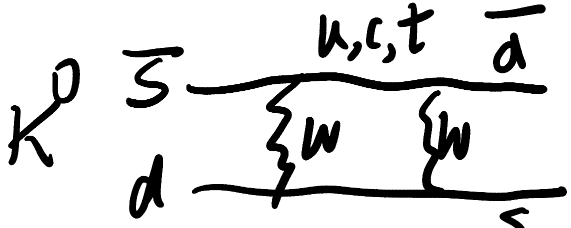
- I: $\Delta I = 1/2$ Rule / Puzzle

$K^+ \;\; \frac{\bar{s}}{u} \qquad\qquad \frac{\bar{s}}{d} \;\; K^0 < \begin{matrix} K_S \\ K_L \end{matrix} \qquad I = 1/2$

$\rightarrow 2\pi\,(I=2, \Delta I = 3/2$ only$) \qquad\qquad \rightarrow 2\pi\,(I=0, 2; \Delta I = 1/2, 3/2)$

$\tau_{K^+} / \tau_{K_S} \sim 450! \quad >> 1 \;\Rightarrow\; \Delta I =$ Dominance/Rule/Puzzle

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



QM mixing

$\Delta S = 2$

$O(G_F^2)$

2 States K_L, K_S If CP is exact

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

CP−

$\rightarrow 3\pi$

$\not\rightarrow 2\pi$

CP+

$\rightarrow 2\pi$

$\not\rightarrow 3\pi$

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

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

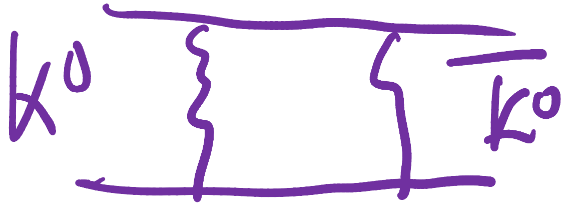
III Indirect CP violation

BNL 1964 Fitch, Cronin, Christensen + Turlay

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

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

NOBEL PRIZE
Cronin + Fitch



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

IV: ε' / ε: Direct CPV

EXPERIMENTAL ROUTE

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

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

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

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

$$\Rightarrow 10^{-6}$$

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

$K \to 2\pi$

FROM THEORY

I=2 amp

I=0 amp

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

Indirect $\not{CP}$

BNL '64
CRONIN + FITCH N.P.

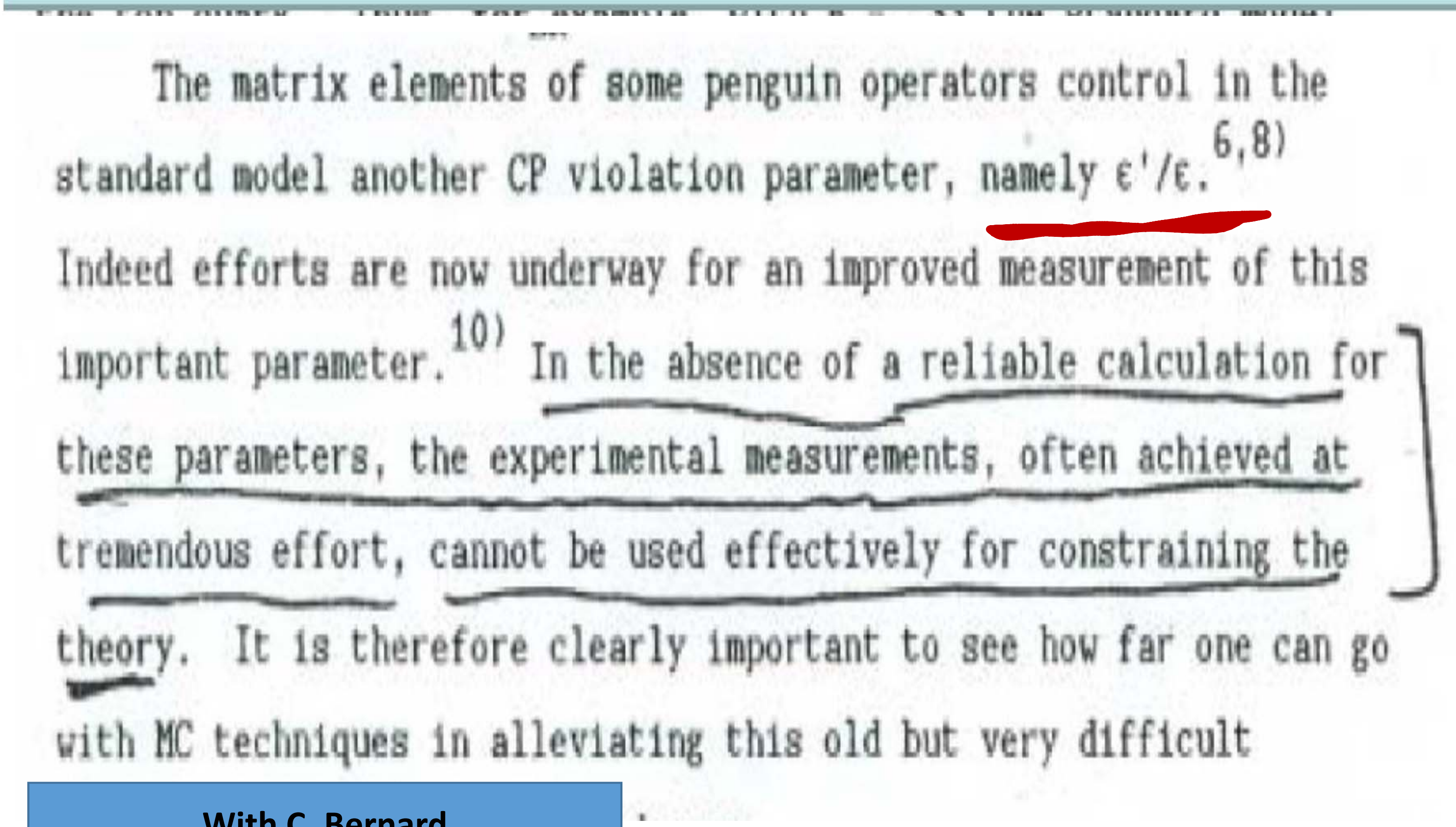
$$|\epsilon| = 2.228(11) \times 10^{-3},$$

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

DIRECT $\not{CP}$

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

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



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

With C. Bernard
[UCLA]

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 $\Delta S=1$ 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 HAD to be overcome

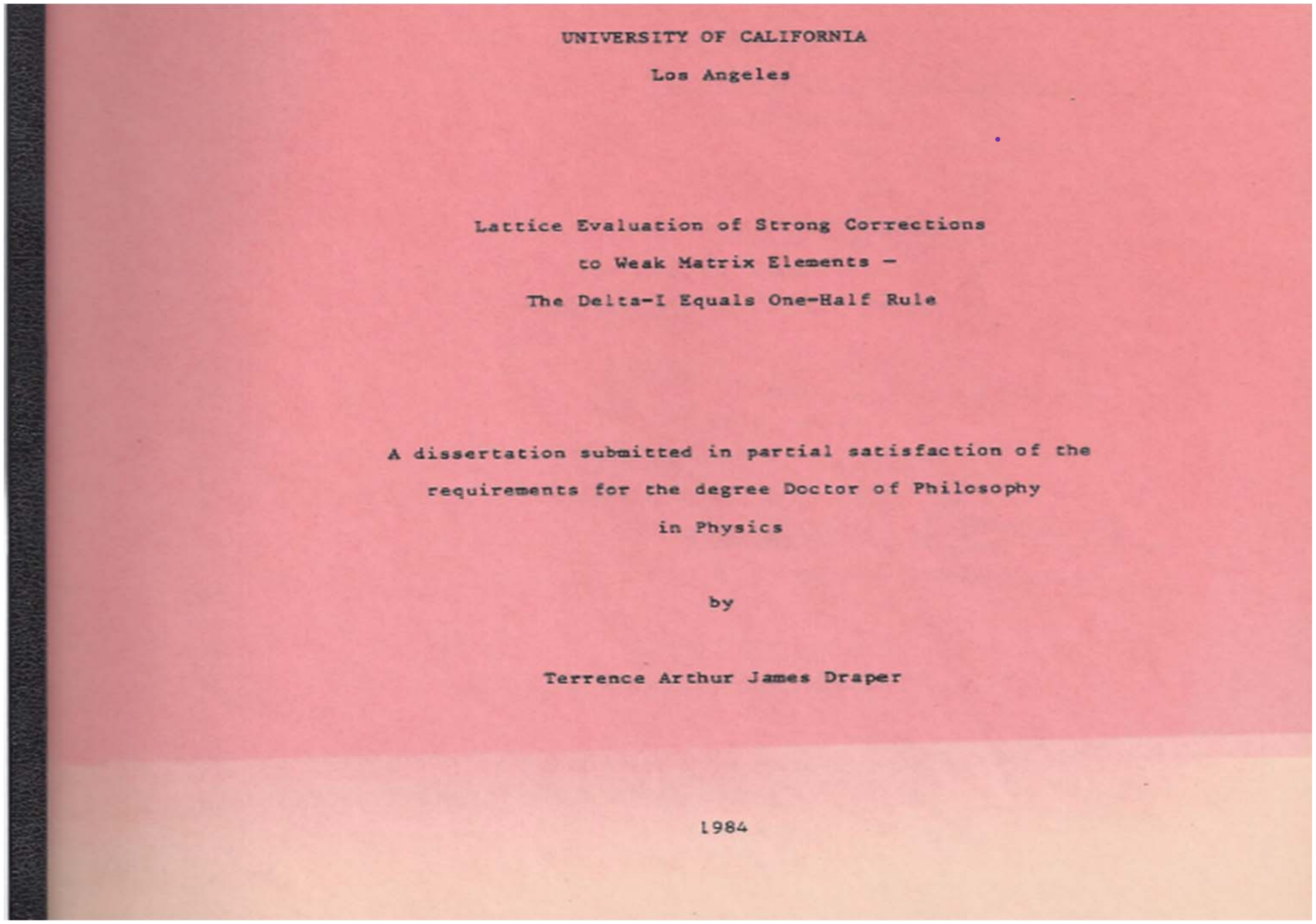
~2006

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 + (3 new) PhD thesis*: Terry Draper (UCLA'84), George Hockney(UCLA'86), Cristian Calin (Columbia=CU'01), Jack Laiho(Princeton'04), Sam Li(CU'06), Matthew Lightman(CU'09), Elaine Goode(Southampton'10), Qi Liu(CU'12), Daiqian Zhang(CU'15)+ [new ones starting from CU, U Conn and Southampton] + many PD's & junior facs.. obstacles & challenges (and of course "mistakes"!) ad infinitum.....

Tianle WAng,
Dan Hoying

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
Fri Beer Party
~ June 20, 1982 !!

WHY FOCUS with SUCH intense DETERMINATION

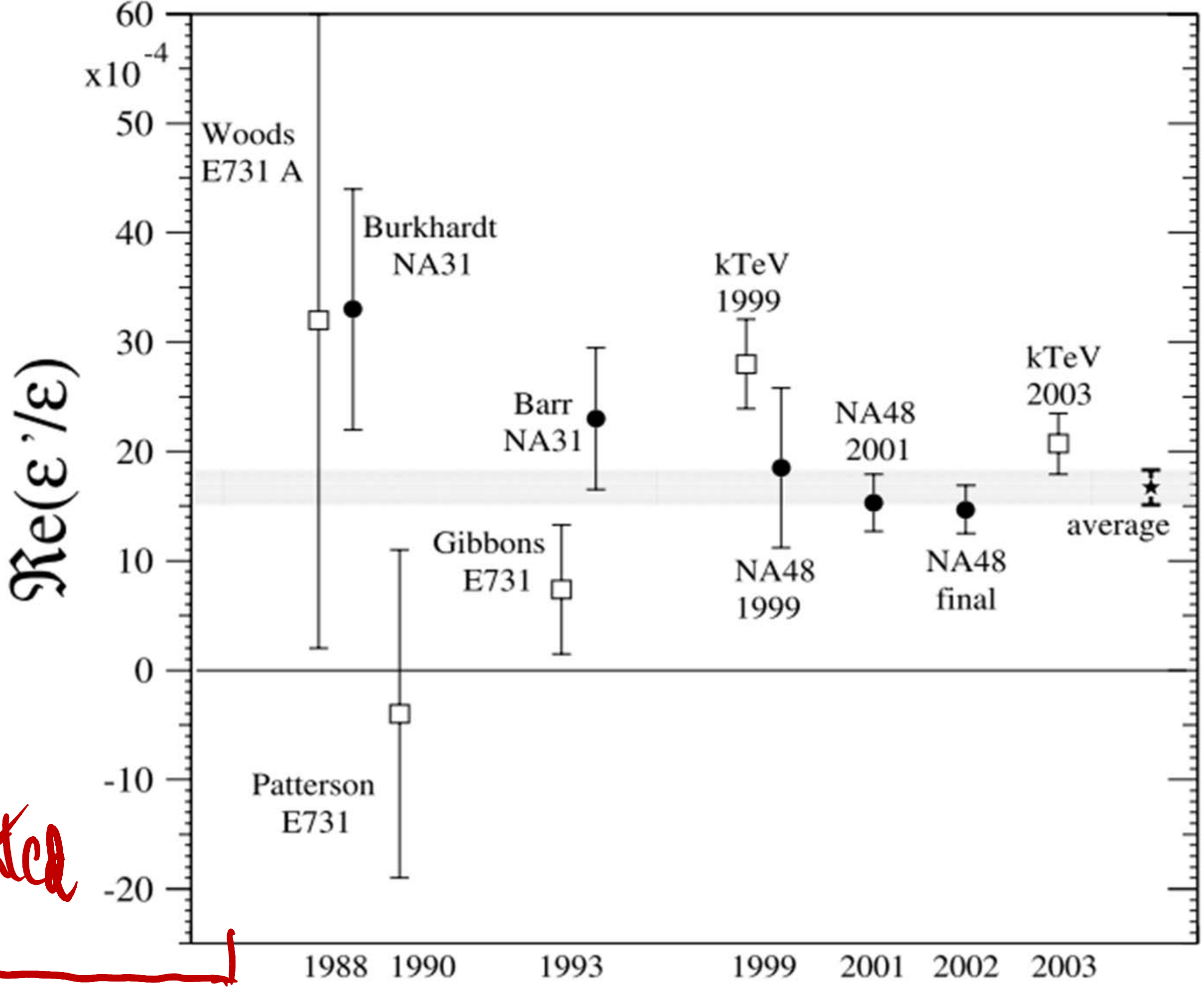
Underlying Realization

ε’: a possible 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**
- **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**

A monumental experimental achievement!



LATTICE work started

Konrad Kleinknecht "Uncovering CPV"

16.6(2.3) x10^{-4}
PDG 2014

Basic calculational framework

Δ S=1 H_W

WC to NLO

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

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

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

$m_i = \langle K | Q_i | \pi\pi \rangle$ 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

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

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

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

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

I=0 ⇒

→ 0

$m_q \to 0$

EWP

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

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

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

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

I=2

→ const

$m \to 0$

EWP

Why EWK cannot be neglected : 3 Reasons

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

$$\left[\frac{\overset{\text{EWP}}{\mathrm{Im}A_2}}{\underset{\text{small}}{\mathrm{Re}A_2}} - \frac{\overset{\text{QCDP}}{\mathrm{Im}A_0}}{\underset{\text{large}}{\mathrm{Re}A_0}}\right]$$

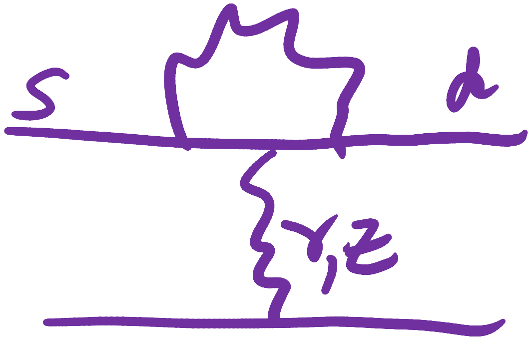
$$\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} \sim 22$$

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

More demands on the calculation

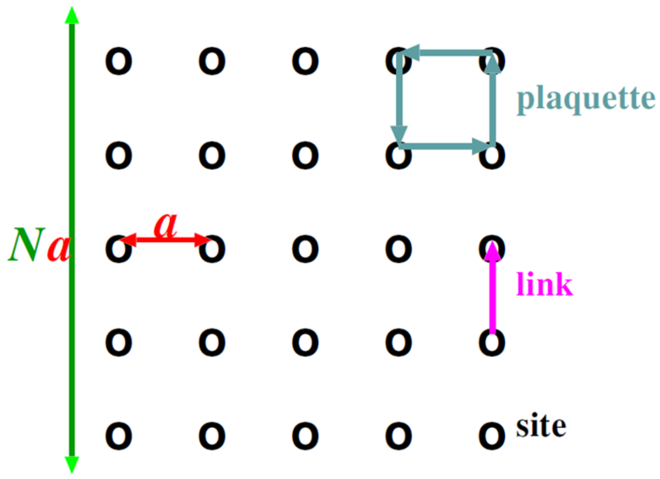
- **~ The 1995 discovery of the huge top mass accentuated the cancellation of I=0 and I=2 contributions to ε' significantly, putting additional demands on the calculation but also enhancing the potential for discovery of new physics**

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



What the hell is lattice QCD?

Gunnar Bali



typical values:

$a^{-1} = 2\text{–}5$ GeV, $Na = 2\text{–}7$ fm

continuum limit: $a \to 0$, Na fixed

infinite volume: $Na \to \infty$

$$\langle O \rangle = \frac{1}{Z} \int [dU]\,[d\psi][d\bar{\psi}]\, O[U] e^{-S[U,\psi,\bar{\psi}]}.$$

Trick: Euclidian time $\tau = -it$.

"Measurement": average over a <u>representative</u> ensemble of gluon configurations $\{U_i\}$ with probability $P(U_i) \propto \int [d\psi][d\bar{\psi}] e^{-S[U,\psi,\bar{\psi}]}$

$$\langle O \rangle = \frac{1}{n} \sum_{i=1}^{n} O(U_i) + \Delta O \qquad \Delta O \propto \frac{1}{\sqrt{n}} \xrightarrow{n\to\infty} 0$$

Input: discretized $\mathscr{L}_{QCD} = \frac{1}{16\pi\alpha_s(a)} FF + \sum_f \bar{q}_f(\not{D} + m_f(a))q_f$

Gunnar Bali

$$\begin{aligned} m_{\Xi}^{\text{latt}} &= m_{\Xi}^{\text{phys}} & \longrightarrow & \quad a \\ M_{\pi}^{\text{latt}}/m_{\Xi}^{\text{latt}} &= M_{\pi}^{\text{phys}}/m_{\Xi}^{\text{phys}} & \longrightarrow & \quad m_u(a) \approx m_d(a) \\ & \cdots \end{aligned}$$

Output: hadron masses, matrix elements, decay constants, etc...

Required:

1. $L = Na \to \infty$: FSE suppressed with $\exp(-LM_\pi) \Rightarrow LM_\pi \gtrsim 4$.
2. $m_q^{\text{latt}} \to m_q^{\text{phys}}$: chiral perturbation theory (χPT) helps for m_{ud} but m_{ud}^{latt} must be sufficiently small to start with ($M_\pi \lesssim 200\,\text{MeV}$?).
3. $a \to 0$: functional form known: $\mathcal{O}(a^2), \mathcal{O}(\alpha_s a) \Rightarrow \approx 4$ lattice spacings.

Only in very few calculations (almost) all of the above is done as yet, e.g., light hadron spectrum, meson decay constants, α_s, $m_{u,d,s,c}$.

Computational challenges

Gunnar Bali

Cost of simulation is proportional to

- number of points: $\sim N^4 = (L/a)^4$
- condition number of linear system: $1/M_\pi^2$
- $L^{1/2}/M_\pi$ in (Omelyan) time integration within hybrid Monte Carlo
- $1/a^{\geq 2}$ critical slowing down (autocorrelations)

Adjusting $L \propto 1/M_\pi$ this means:

$$\text{cost} \propto \frac{1}{a^{\geq 6}\, M_\pi^{7.5}}$$

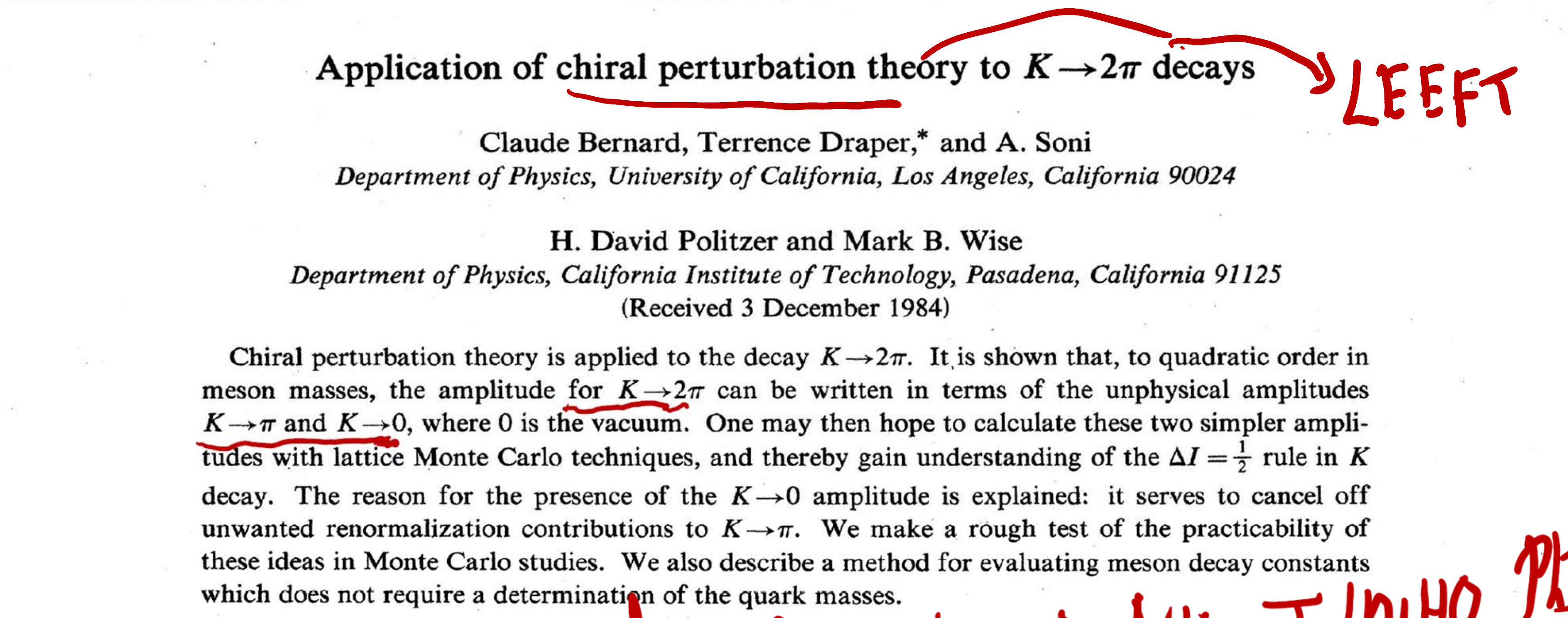
For many observables at small M_π $\exists$ additional noise/signal problems.

State of the art: 192×96^3 sites, corresponding to $\approx (2 \times 10^{10})^2$ (sparse) complex matrices.

Tremendous progress in Hybrid Monte Carlo, solver, noise reduction.

Less improvement recently in compute power.

For simplicity: 1st strategy via ChPT



PHYSICAL REVIEW D VOLUME 32, NUMBER 9 1 NOVEMBER 1985

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

LEEFT

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.

USED extensively on lattice for ∼ 20 years ⇒ NLO

J. LAIHO PhD Thesis ∼ '03

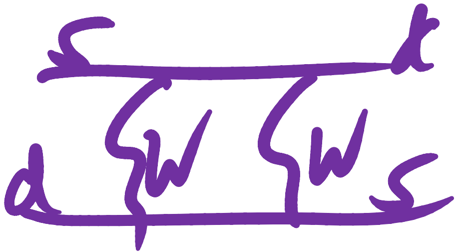
Acknowledge many significant contributions

- **While focus is on lattice calculations of K=>ππ primarily by our RBC-UKQCD Collab**

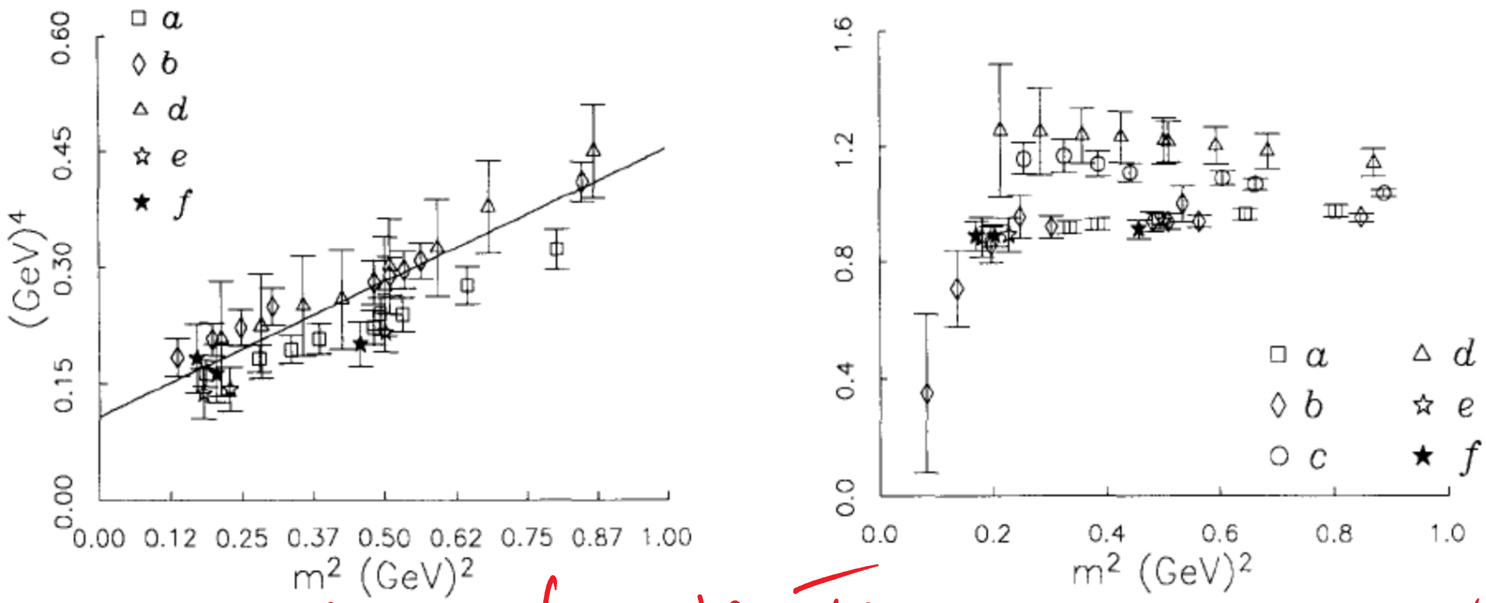
- **Over the years many important contributors, in particular:**

- **(Mary)Gaillard, (Ben) Lee; Altarelli, Maiani; Shifman, Vainshtein, Zhakrov; Buras & Co; Martinelli & Co; (Claude) Bernard; de Rafael; Pich Bijnens……**

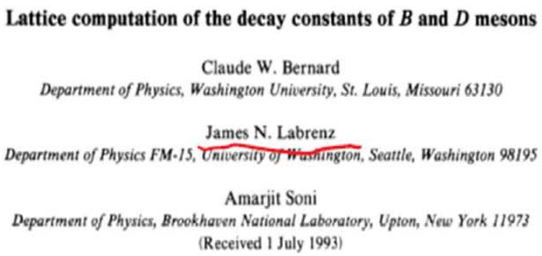
$\langle K|(\bar{s}\gamma_{\mu L} d)^2|\bar{K}\rangle$



'88



χS Violation by K-K̄ ⇒ FINE TUNING PROBLEM



Lattice computation of the decay constants of B and D mesons

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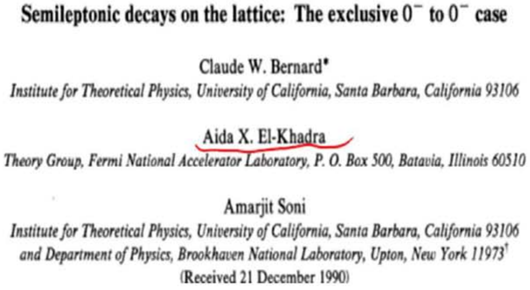
(Received 1 July 1993)



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

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Theory Group, Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510

Amarjit Soni
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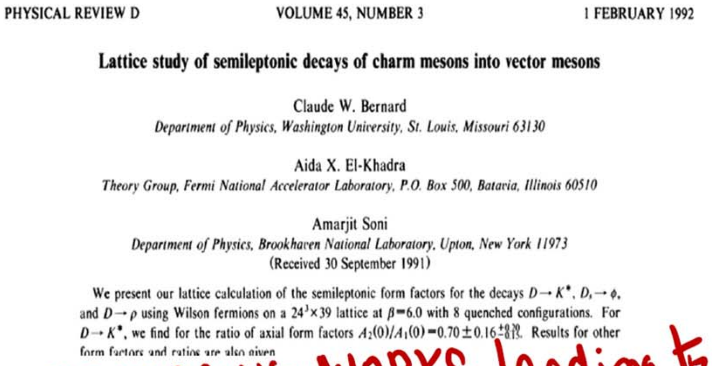
and Department of Physics, Brookhaven National Laboratory, Upton, New York 11973†
(Received 21 December 1990)



PHYSICAL REVIEW D VOLUME 45, NUMBER 3 1 FEBRUARY 1992

Lattice study of semileptonic decays of charm mesons into vector mesons

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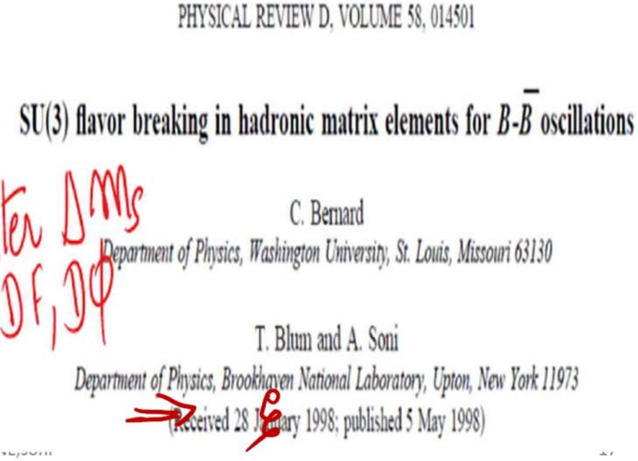
(Received 30 September 1991)

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

PIONEERING WORKS Leading to Modern Day UT ?



PHYSICAL REVIEW D, VOLUME 58, 014501

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

Later Δm_s CDF, DØ

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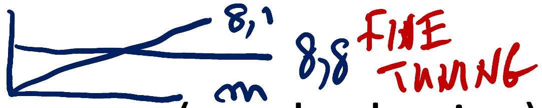
(Received 28 January 1998; published 5 May 1998)

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; Lahnenz.... 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: 32^3X64X16X50X10X5/6^3 X17 ~10^8

A chance (crucial) meeting: Yigal Shamir visits me in Haifa ~94 summer

- **For K=> pi pi project, way to overcome the fine-tuning problem of Wilson Fermions is to use a new formulation of**

fermions on the lattice=> DOMAIN WALL FERMIONS [computationally much harder but are continuum -like possessing chiral symmetry]

- **Furman + Shamir: hep-lat/9405004**
- **See also Yigal Shamir, hep-lat 9303005**

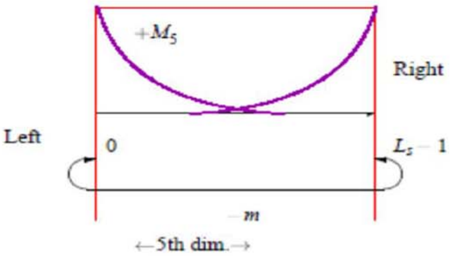
WAY FORWARD: Adopt DWF for $K \to \pi\pi$ & ϵ'? 95-96?.

EXACT CHIRAL SYMMETRY ON THE LATTICE

→ ∞ 5th Dim

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

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



Shamir & Furman, NPB 439, 54,1995

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

PHYSICAL REVIEW D VOLUME 56, NUMBER 1 1 JULY 1997

QCD with domain wall quarks

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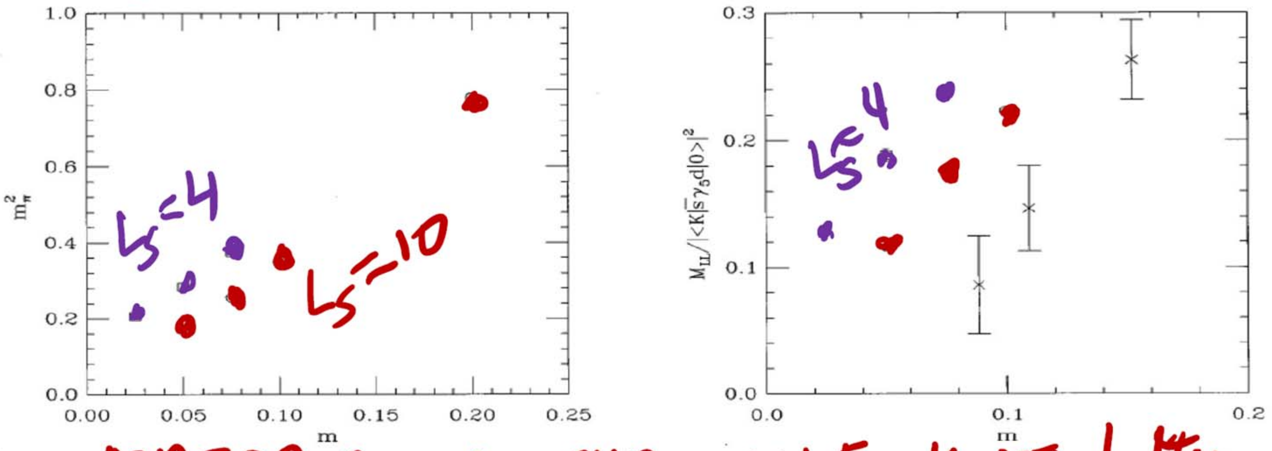
(Received 27 November 1996)

We present lattice calculations in QCD using Shamir's variant of Kaplan fermions which retain the continuum $SU(N)_L \times SU(N)_R$ 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.

MAJOR BREAKTHROUGH FOR K→ππ Lattice Calculations

$K \to 2\pi$ ChPT

With DWQ in Quench Approx

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.

1st application of BDSPW'84 with DWQ

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

$K \to 2\pi$ & ϵ'/ϵ "Flagship Project" Now ~ 20 yrs!

1st Large Scale Simulation with DWQ

RBC Collaboration

QCDSP ~98→~'05 1TF

RBC Collab'98

QA ; ChPT

PRD ~ 02

DWQ
1st Large Scale simulation

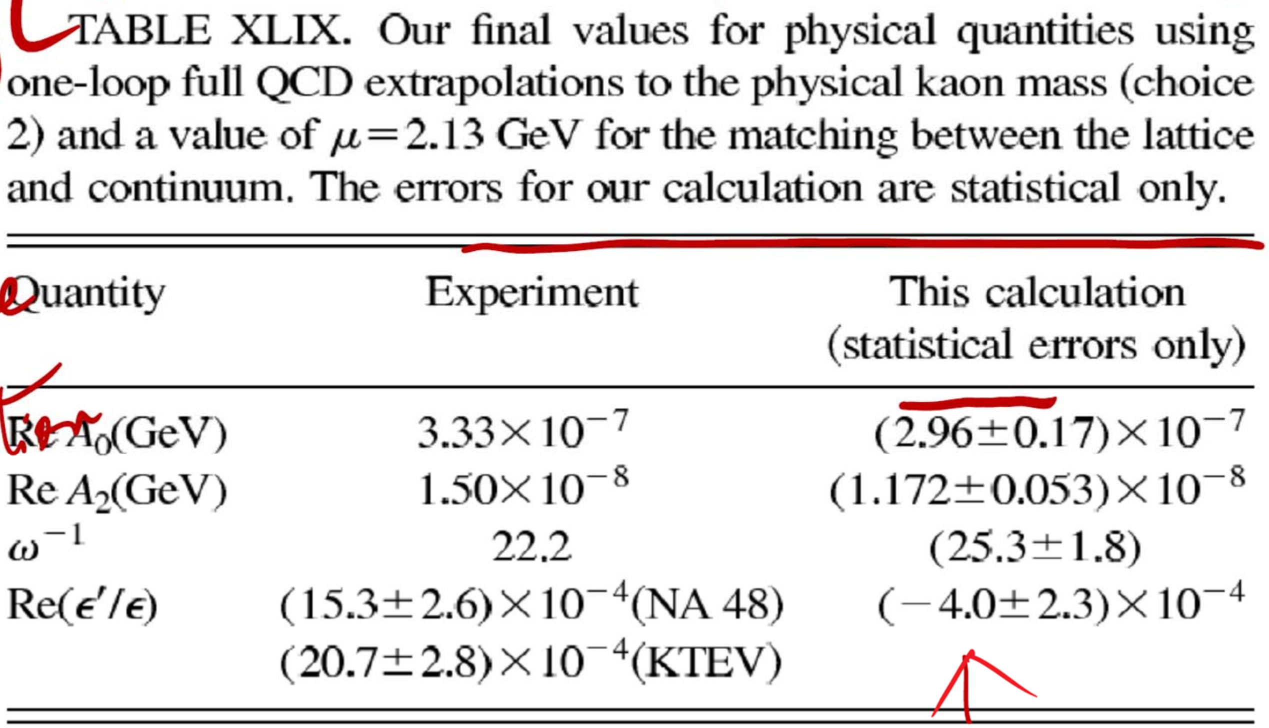


TABLE XLIX. Our final values for physical quantities using one-loop full QCD extrapolations to the physical kaon mass (choice 2) and a value of $\mu = 2.13$ GeV for the matching between the lattice and continuum. The errors for our calculation are statistical only. ←

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) $(20.7\pm2.8)\times10^{-4}$(KTEV)	$(-4.0\pm2.3)\times10^{-4}$

RBC ≡ RBRC + BNL + Col

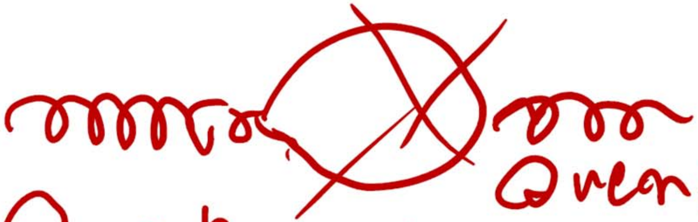
See Golterman & Pallante '01; '04; Aubin et al (RBC) '06

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

For the ΔS=1 Hamiltonian, DWF not enough, full QCD is also essential….



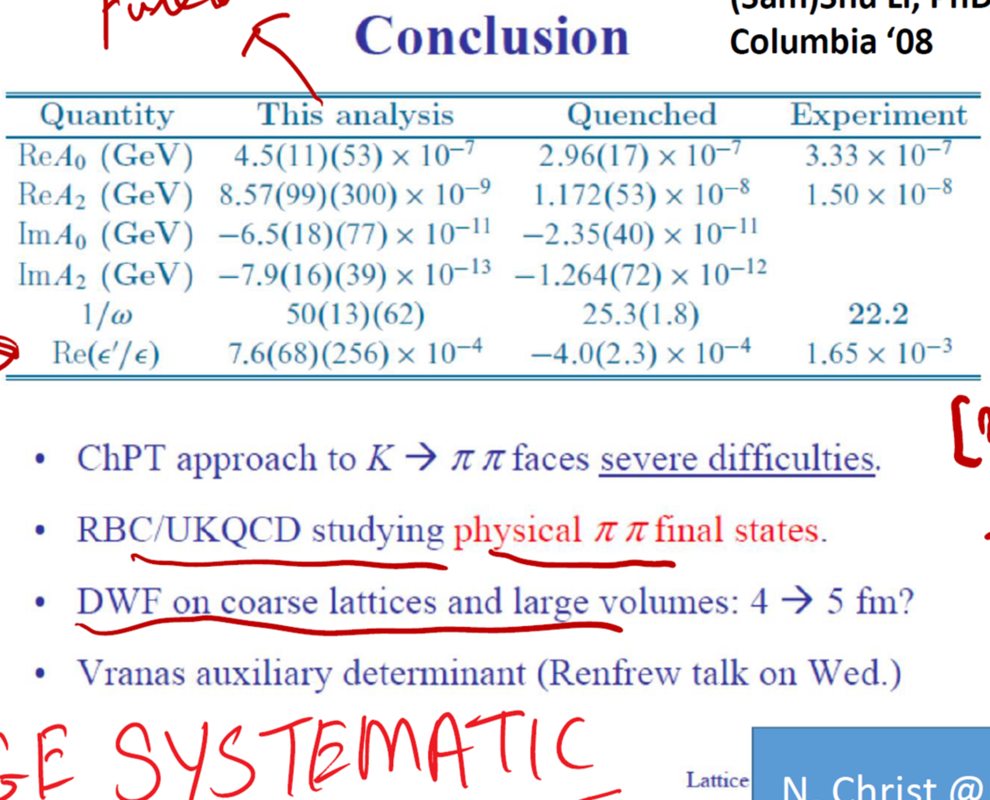
Quench approx

Q_6 gets unphysical contribution fr Q_8

(8,1) (8,8)

FullQCD But ChPT a la BDSPW

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



Conclusion

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}

- 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 → 5 fm?
- Vranas auxiliary determinant (Renfrew talk on Wed.)

Lattice

[m_M too large for ChPT.... HINDSIGHT]

LARGE SYSTEMATIC errors DUE ChPT

N. Christ @LAT08

CMP/01.

a new method

another key development for light meson physics from lattice

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

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

* **Allows to bypass Maini-Testa theorem**

COMMON interest: use of DWQ for simulations

;

?

Relating lattice ME to physical amplitudes

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

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

→ Phase shift

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

A/M is LL factor F

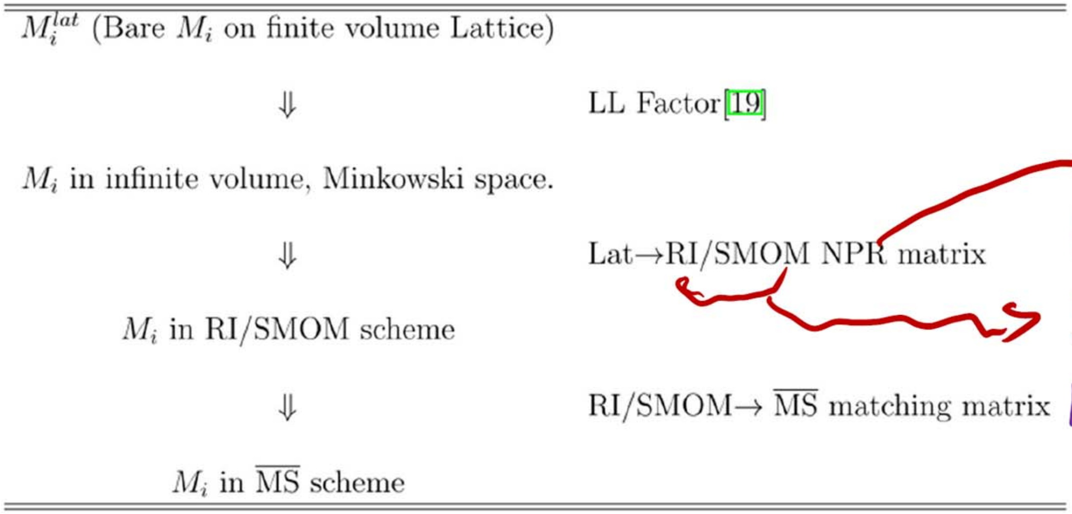
$q = \frac{pL}{2\pi}$;

↳ $\sim \frac{\delta}{q}$ for small p

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

Relating bare LME => MS-bar ME

D. Zhang
PhD Thesis
[CU]



M_i^{lat} (Bare M_i on finite volume Lattice)	
$\Downarrow$	LL Factor[19]
M_i in infinite volume, Minkowski space.	
$\Downarrow$	Lat→RI/SMOM NPR matrix
M_i in RI/SMOM scheme	
$\Downarrow$	RI/SMOM→ $\overline{\text{MS}}$ matching matrix
M_i in $\overline{\text{MS}}$ scheme	

Table 3.2: Work flow from bare lattice matrix elements to $\overline{\text{MS}}$ decay matrix elements.

Rome-Southampton
MARTINELLI et al
'94

Sturm et al '09

1-loop pert matchg
Lehner+Sturm
PRD'11

Ensemble

USED for A_0

- 32^3x64 Mobius DWF ensemble with IDSDR gauge action at β=1.75. Coarse lattice spacing (a^{-1}=1.378(7) GeV) but large, (4.6 fm)^3 box.
- Using Mobius params (b+c)=32/12 and L_s=12 obtain same explicit χSB as the L_s=32 Shamir DWF + IDSDR ens. used for ΔI=3/2 but at reduced cost.
- Utilized USQCD 512-node BG/Q machine at BNL, the DOE "Mira" BG/Q machines at ANL and the STFC BG/Q "DiRAC" machines at Edinburgh, UK.
- Performed 216 independent measurements (4 MDTU sep.).
- Cost is ~1 BG/Q rack-day per complete measurement (4 configs generated + 1 set of contractions).
- G-parity BCs in 3 spatial directions results in close matching of kaon and $\pi\pi$ energies:

$32^3 \times 64 \times 12$

$m_{res} = .0018$

$m_s = .045$

m_K=490.6(2.4) MeV

$E_{\pi\pi}$(I=0) = 498(11) MeV

$E_{\pi\pi}$(I=2) = 573.0(2.9) MeV

E_π=274.6(1.4) MeV (m_π = 143.1(2.0) MeV)

PHYSICAL MASSES of Kinematics!

Results for ε'

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

EWP

QCDP

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

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

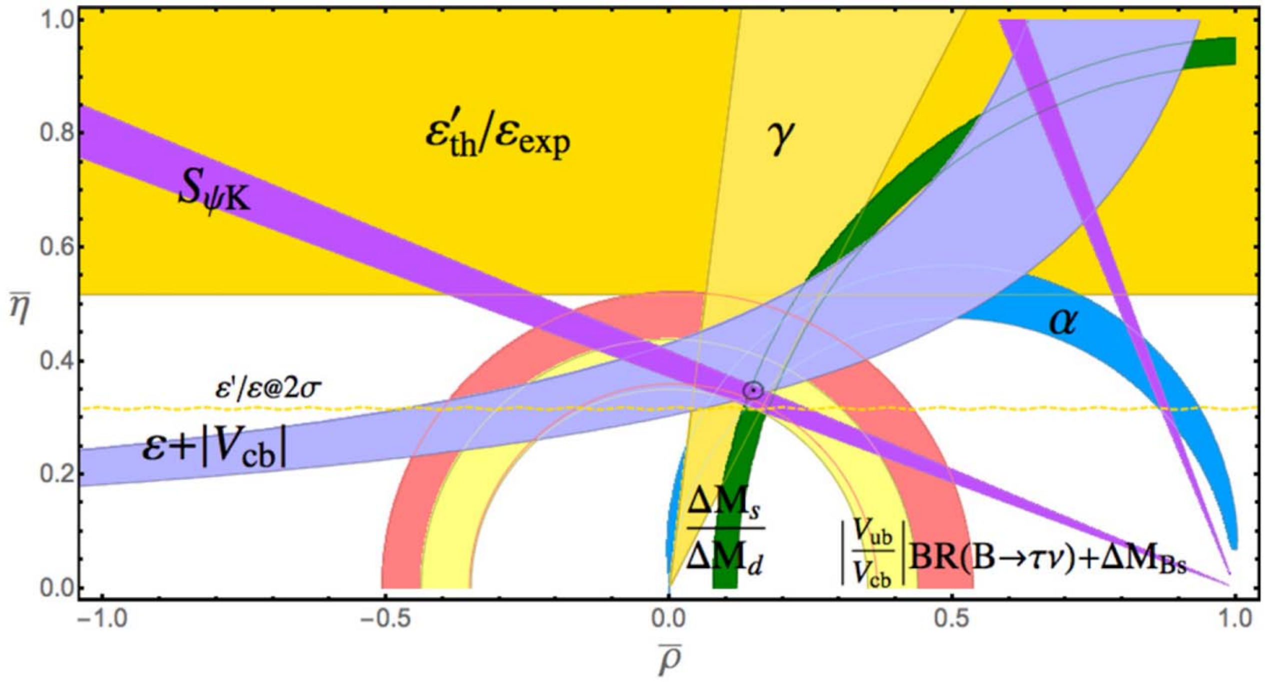
LARGE CANCELLATION!!

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

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

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


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

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**

Details of key important aspects of the calculation

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

$m \lambda c$ (KITP

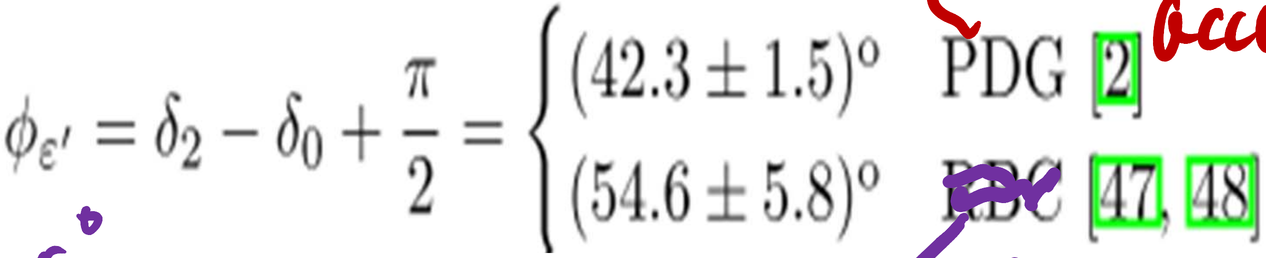
RBC Collaboration

- 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**

A possible difficulty: strong phases

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

-

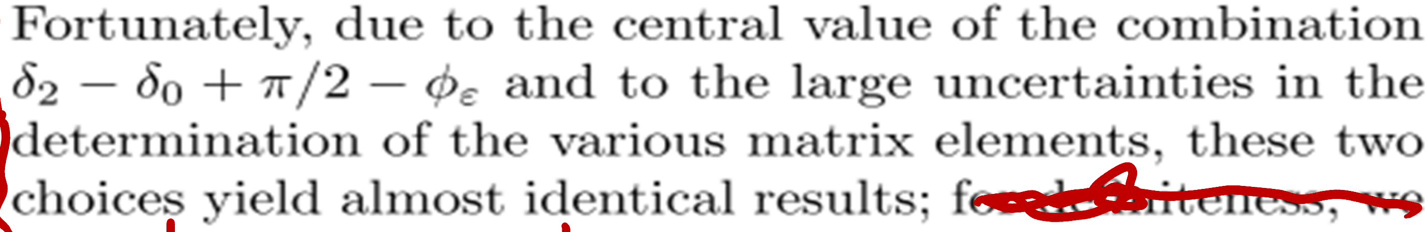


$$\phi_{\varepsilon'} = \delta_2 - \delta_0 + \frac{\pi}{2} = \begin{cases} (42.3 \pm 1.5)^{\circ} & \text{PDG [2]} \\ (54.6 \pm 5.8)^{\circ} & \cancel{\text{RBC}}\ [47, 48] \end{cases} .$$

→ Not directly accessible to expt

→ RBC-UKQCD

$\phi_{\epsilon} \sim 43.5 \pm 0.5^{\circ}$



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; ~~for definiteness, we~~

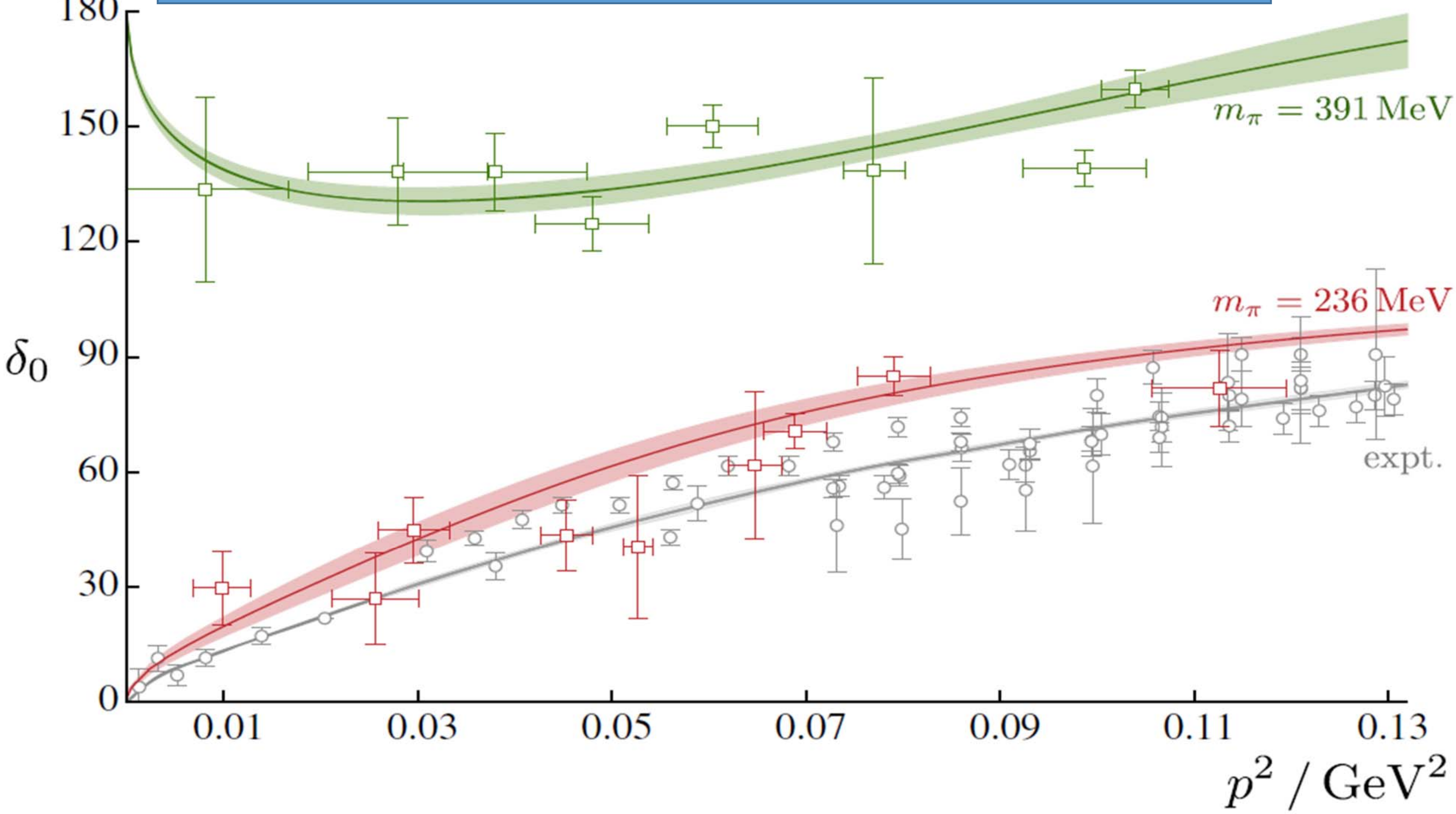
→ Lehner, Lunghi + AS, 1508.01801

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



RBC-UKQCD PRL 2015

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

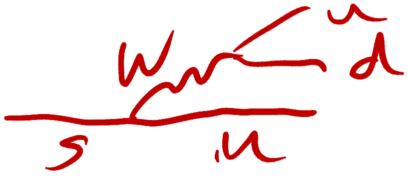
Description	Error	Description	Error
Finite lattice spacing	12%	Finite volume	7%
Wilson coefficients	12%	Excited states	$\leq 5\%$
Parametric errors	5%	Operator renormalization	15%
Unphysical kinematics	$\leq 3\%$	Lellouch-Lüscher factor	11%
Total (added in quadrature)			27%

Lattice
* 2018

75%

15%

$Q_2 =$



large cancellation

dominant

<1%

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	$4.66(0.96)(0.27) \times 10^{-7}$	$-1.90(1.19)(0.32) \times 10^{-11}$

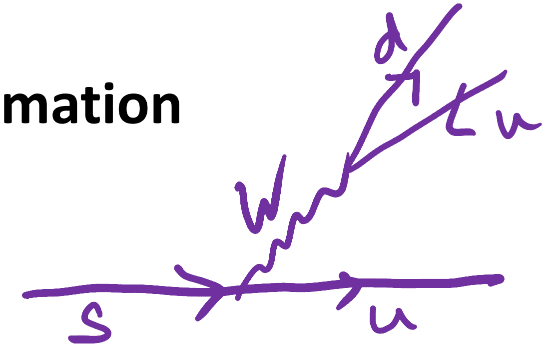
TABLE I. Contributions to A_0 from the ten continuum, $\overline{\text{MS}}$ operators $Q_i(\mu)$, for $\mu = 1.53$ GeV. Two statistical errors are shown: one from the lattice matrix element (left) and one from the lattice to $\overline{\text{MS}}$ conversion (right).

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

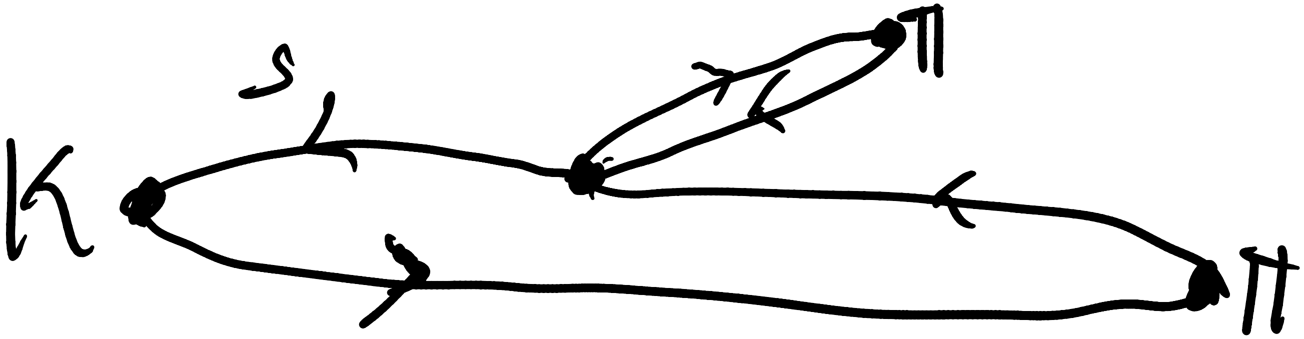
$Q_2 \equiv$



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 $\mathrm{Re}A_0$!

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

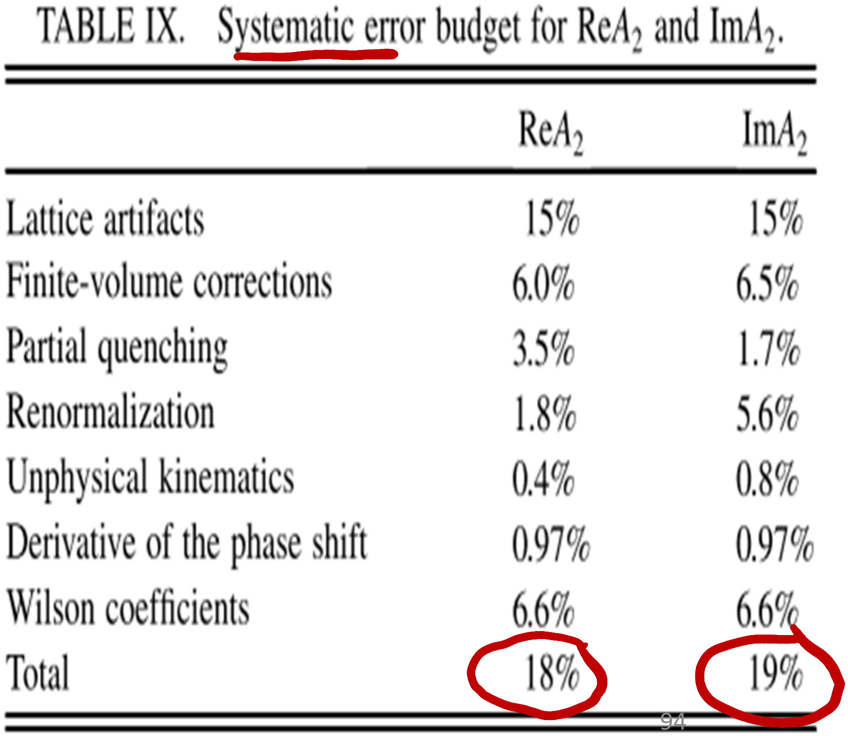
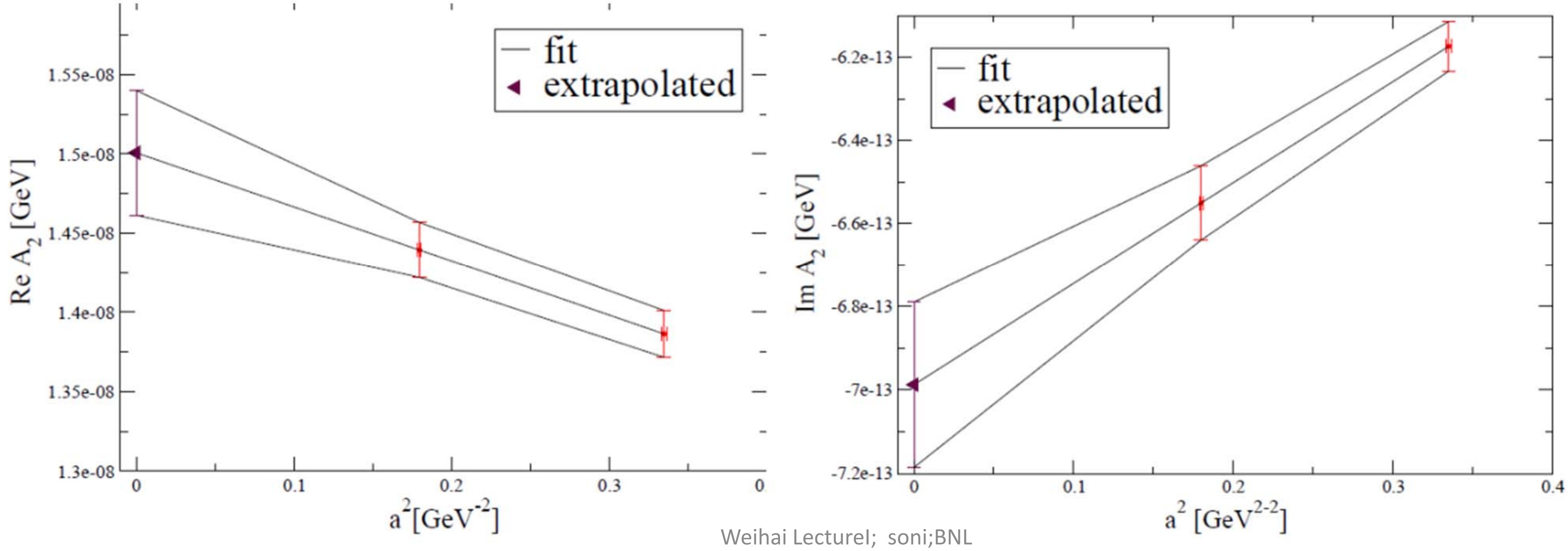


TABLE IX. Systematic error budget for $\mathrm{Re}A_2$ and $\mathrm{Im}A_2$.

	$\mathrm{Re}A_2$	$\mathrm{Im}A_2$
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 fm)^3 volumes and a=0.114 fm, a=0.084 fm.



C Kelly

continuum limit #5

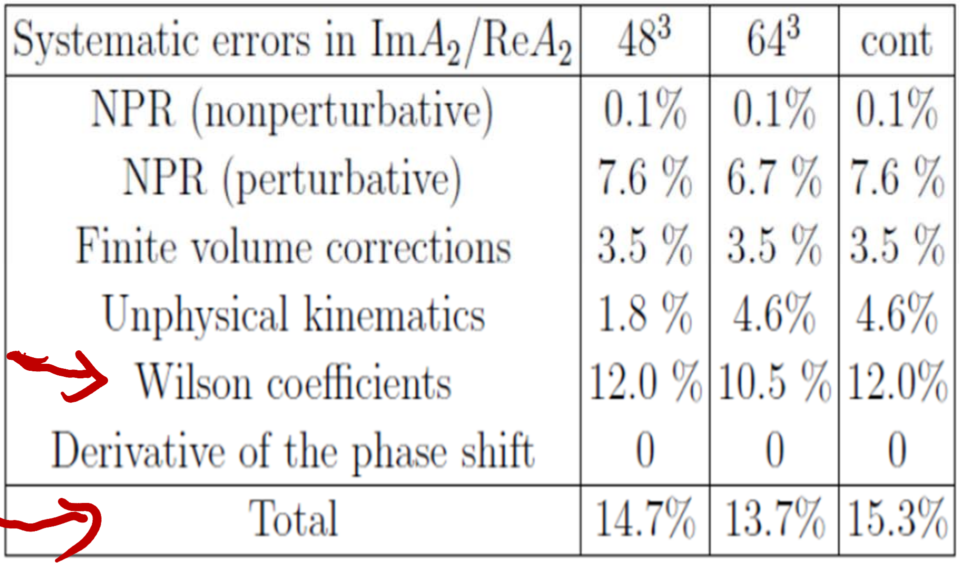
Expt 1.48×10^{-8} GeV

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

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

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.

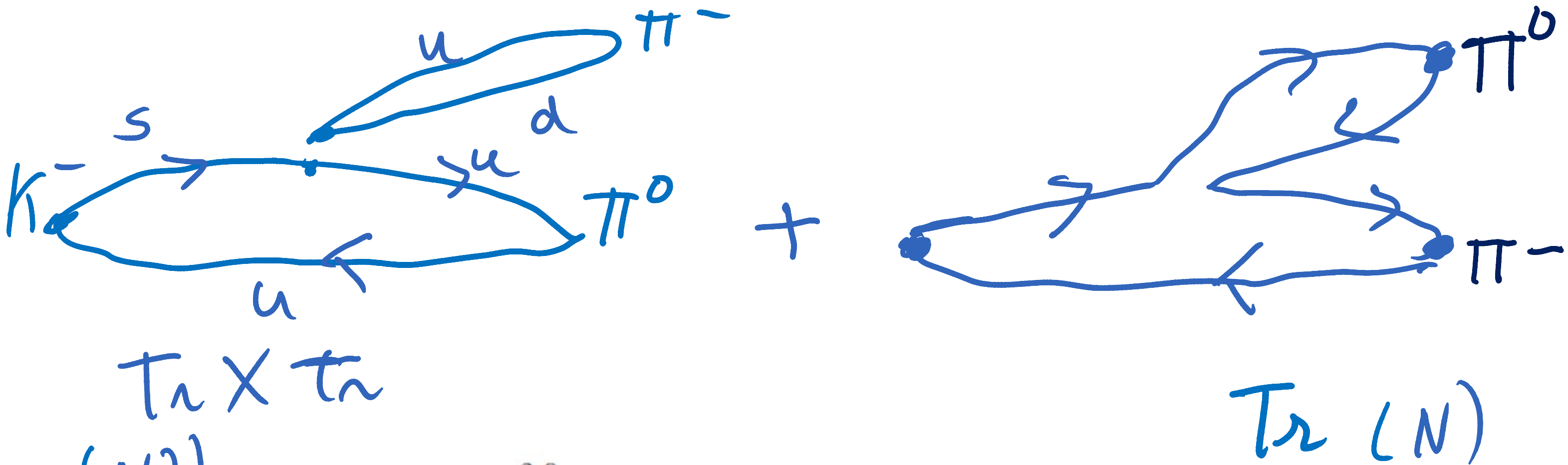


Systematic errors in $\mathrm{Im}A_2/\mathrm{Re}A_2$	48^3	64^3	cont
NPR (nonperturbative)	0.1%	0.1%	0.1%
NPR (perturbative)	7.6 %	6.7 %	7.6 %
Finite volume corrections	3.5 %	3.5 %	3.5 %
Unphysical kinematics	1.8 %	4.6%	4.6%
Wilson coefficients	12.0 %	10.5 %	12.0%
Derivative of the phase shift	0	0	0
Total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

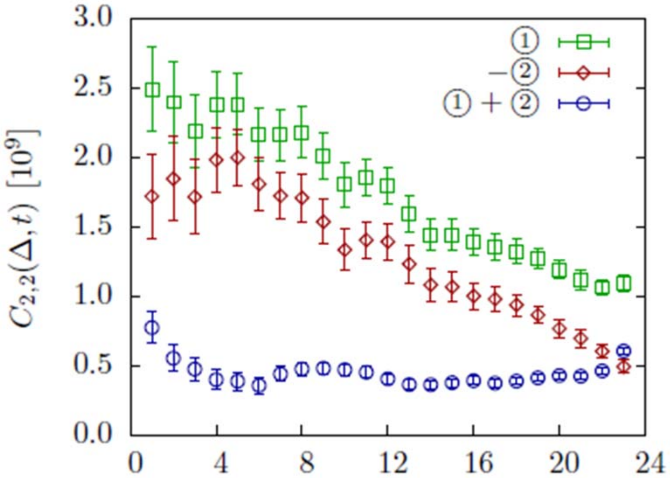
TABLE XIII: Systematic error breakdown for $\mathrm{Im}A_2/\mathrm{Re}A_2$.

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

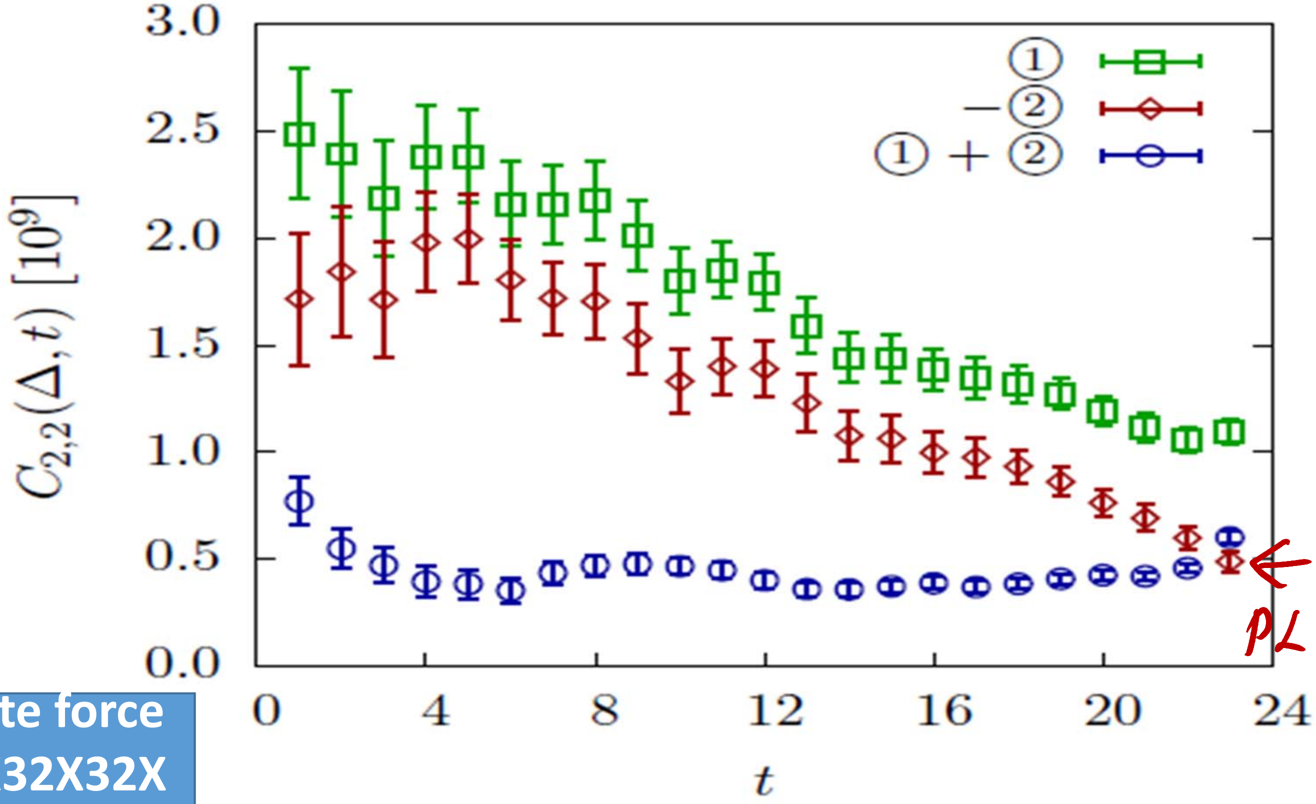
Dissecting 3/2 Amp on the lattice



Simplest basic step is Significantly different from phenomenological expectations



DRAMATIC CANCELLATION!



PLATEAU

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

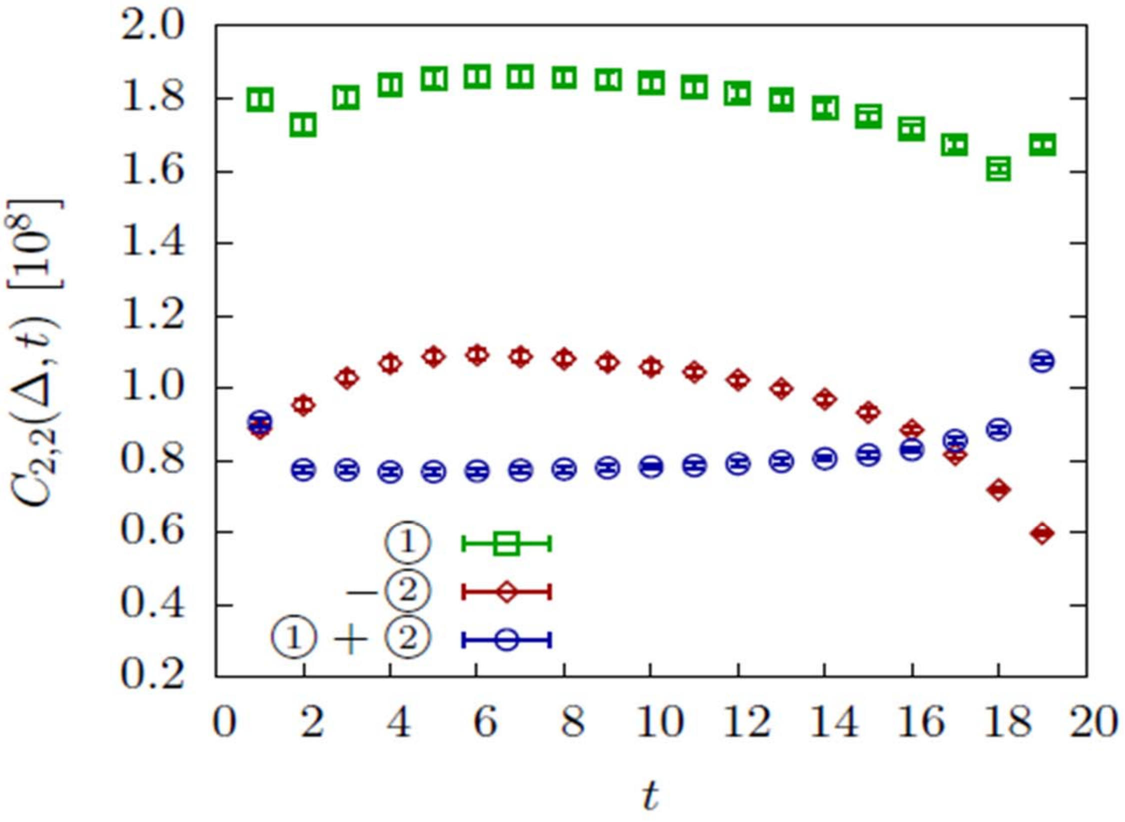
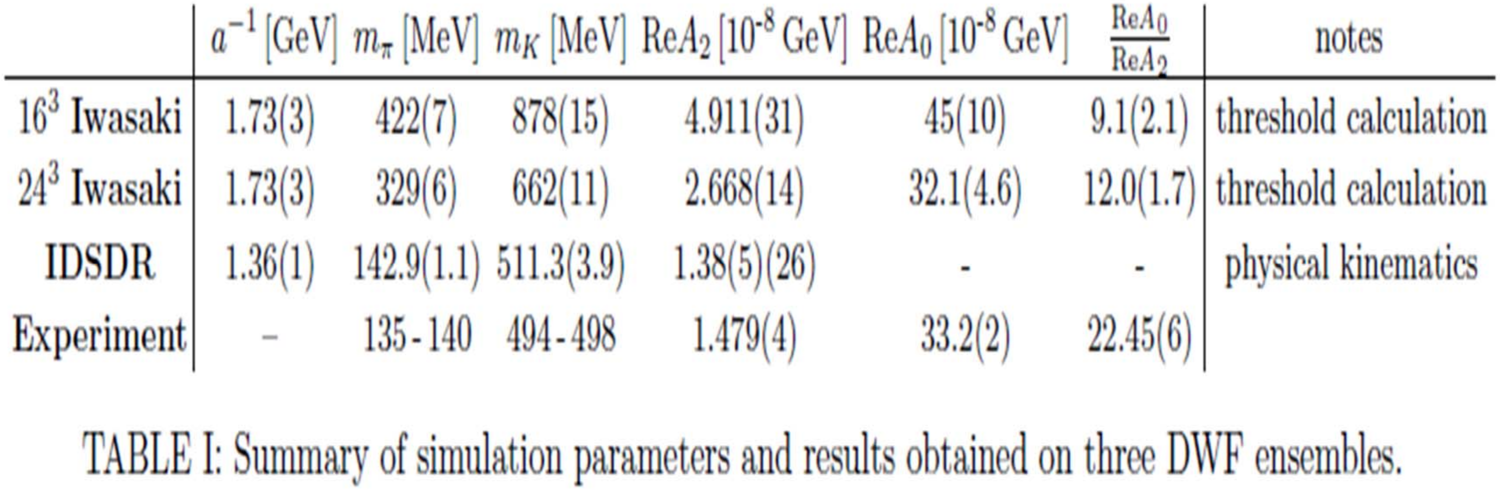


FIG. 3: Contractions ①, -② and ① + ② as functions of t from the simulation at threshold with $m_\pi \simeq 330\,\text{MeV}$ and $\Delta = 20$.

Mass depends of ReA2, A0

PRL
2013

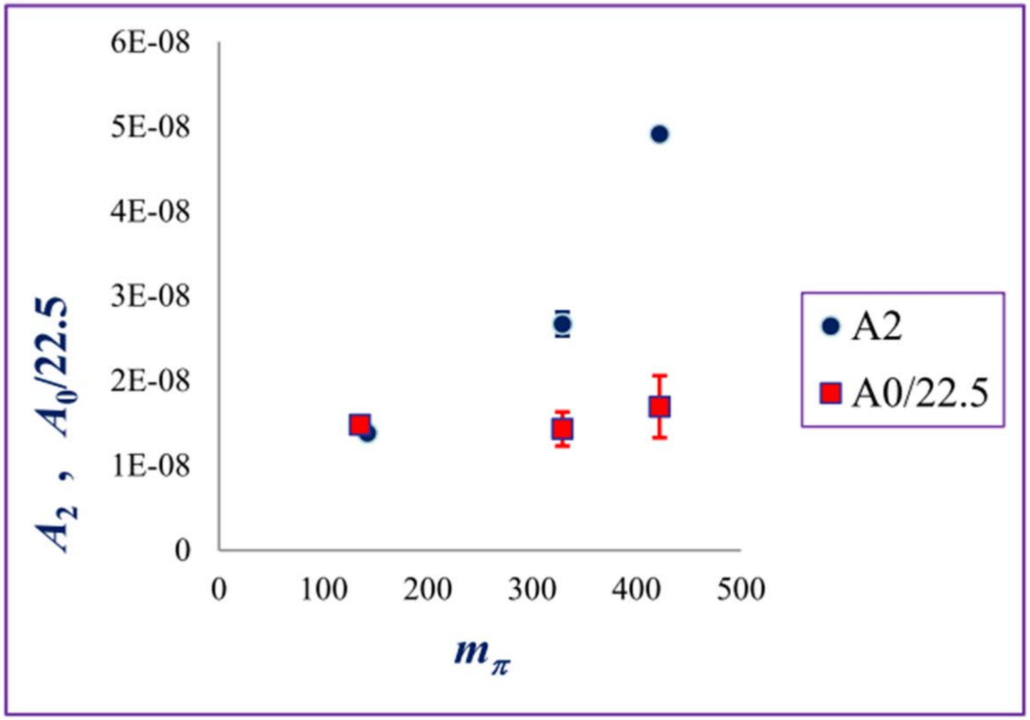


	a^{-1} [GeV]	m_π [MeV]	m_K [MeV]	$\mathrm{Re}A_2$ [10^{-8} GeV]	$\mathrm{Re}A_0$ [10^{-8} GeV]	$\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}$	notes
16^3 Iwasaki	1.73(3)	422(7)	878(15)	4.911(31)	45(10)	9.1(2.1)	threshold calculation
24^3 Iwasaki	1.73(3)	329(6)	662(11)	2.668(14)	32.1(4.6)	12.0(1.7)	threshold 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

Compare A_2 and $A_0/22.5$



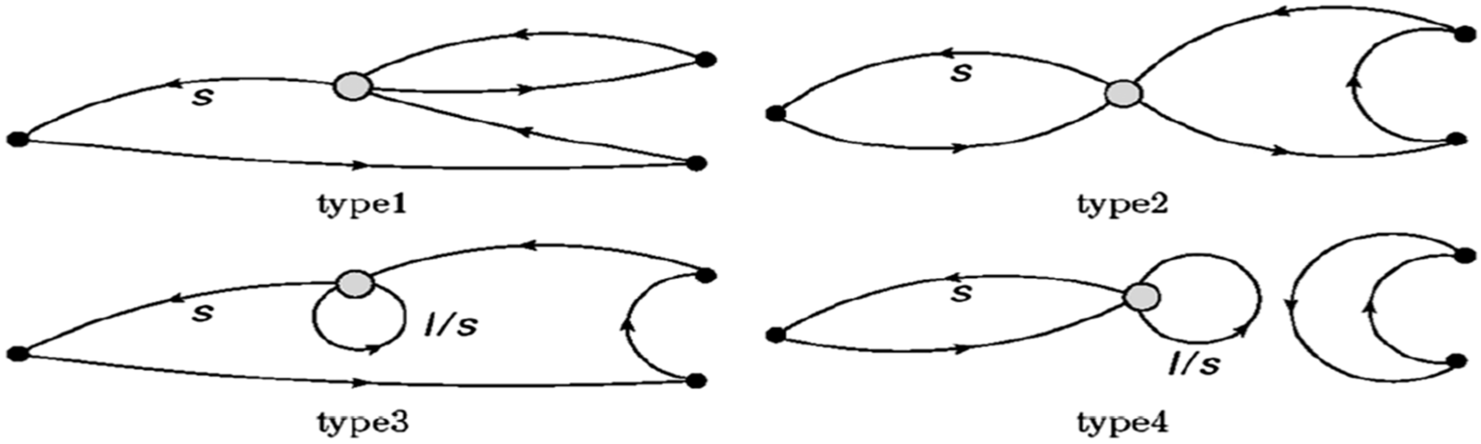
NHCe
KITP
Aug '15

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
- **Factor of around 2 to 3 in the matrix elements for**

I=1/2 versus 3/2



Large cancellation significantly enhances senstivity to NP

- **Examination of resulting matrix elements shows that I=0 and I=2 contributions to epsilon’ suffer large cancellation!**

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 3 years vigorous pursuit for improvement in statistics as well as in systematics

Where are we now with respect to this plan?

"Improvements in" lattice Ɛ' determination underway for past ~3 years

[Previous result uses 215 configs]

- Statistics X [> ~ 5] now aiming for
- Systematics…..some already done.. EMI
- EM+ isospin….

$\delta[\mathrm{Im}\,A_0] \sim (15 \pm 8)\%$

Cirigliano et al '04

- Completely diff method(s)
- A) excited pipi state

TB student

- B) Revisit ChPT

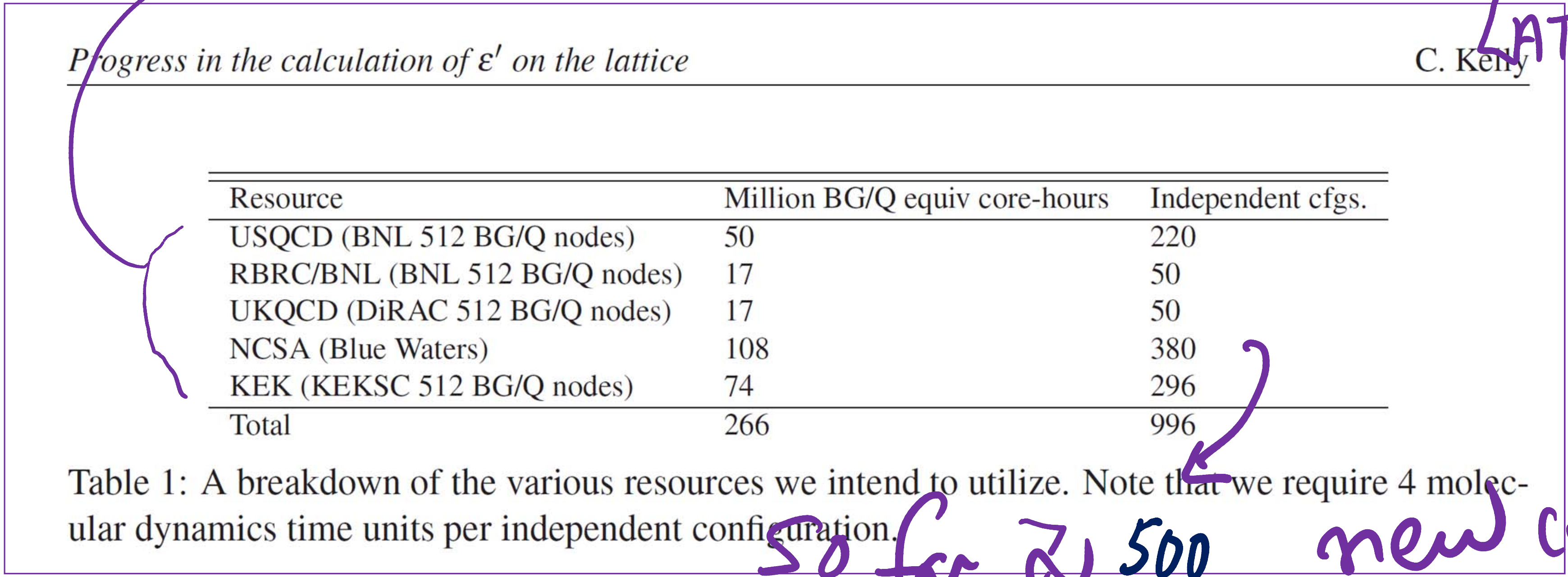
→ BDSPW '84; LAIHO + AS ~'04

LOχPT NLO

RBC-UKQCD, D. Murphy et al [1511.01950]

↓ D. HOYING

SUPERCOMPUTERS OVER 3 CONTINENTS!



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.

LAT'16

so far $\gtrsim$ 500 new configs

$\gtrsim$ 250 new measurement

Total ~ 1440 configs now being used

Efforts to improve systematics

→ PRL '15

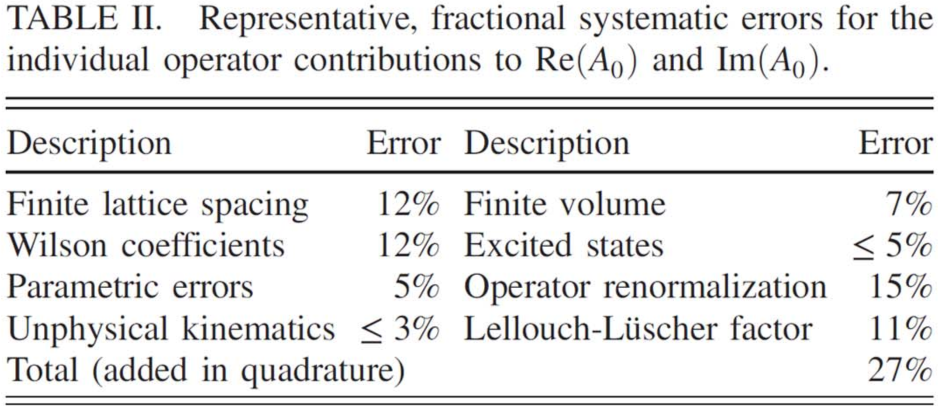


TABLE II. Representative, fractional systematic errors for the individual operator contributions to $\mathrm{Re}(A_0)$ and $\mathrm{Im}(A_0)$.

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%

2nd lattice spacing underway

MATTIA BRUNO @LAT'16

→ 8% NOW

[M = 1.53 GeV]

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

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

Expectations for improved determination of ImA0 in another ~3 years……δ[ImA0] ~10%(st);15%(sy)=> 18% (total)

Best guesses

2015 60% 27%

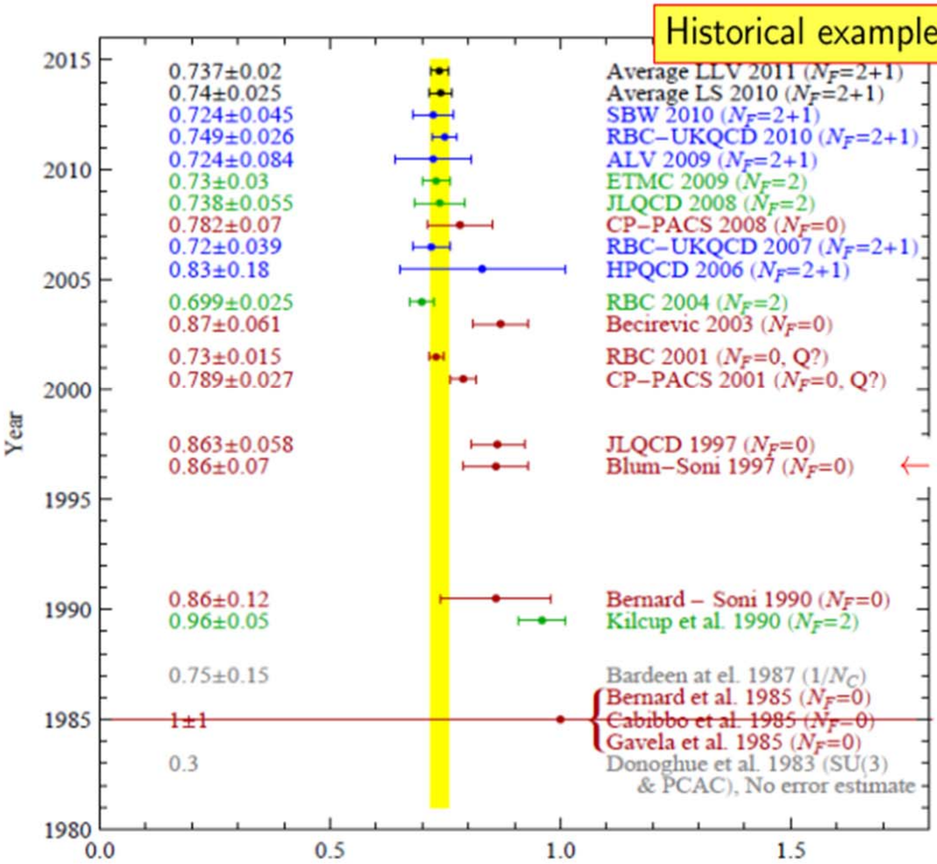
Proof of the pudding: underlying method is systematically improvable

- **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

← First DWF

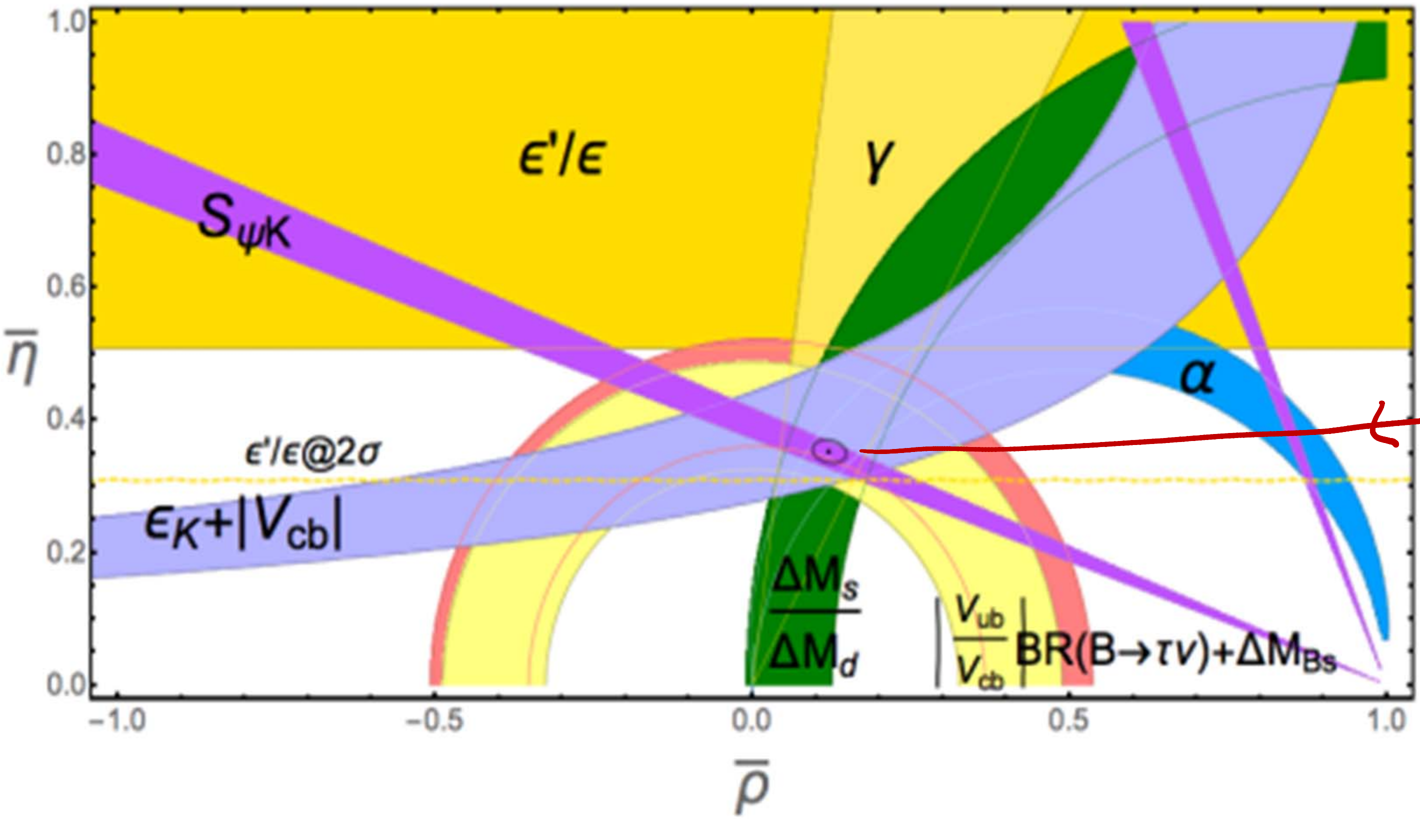
6 / 15

AB-initio Calculat

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

ONE ILLUSTRATION

Lattice ϵ'/ϵ & SUT : CIRCA ~ 2015



SUT ≡ Standard UT i.e. B-UT

SUT

K-UT: A dream for some

Blucher, Winstein and Yamanaka ’09; see also Buras

Construction of a Kaon UT

LITTENBERG
PRD '89

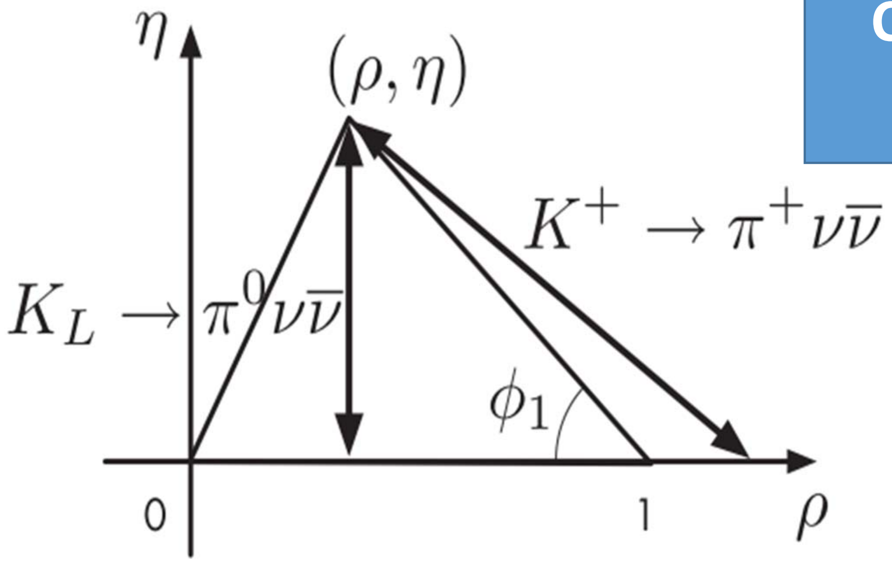


Fig. 14. Unitarity triangle.

Lehner+Lunghi+AS
PLB '2016

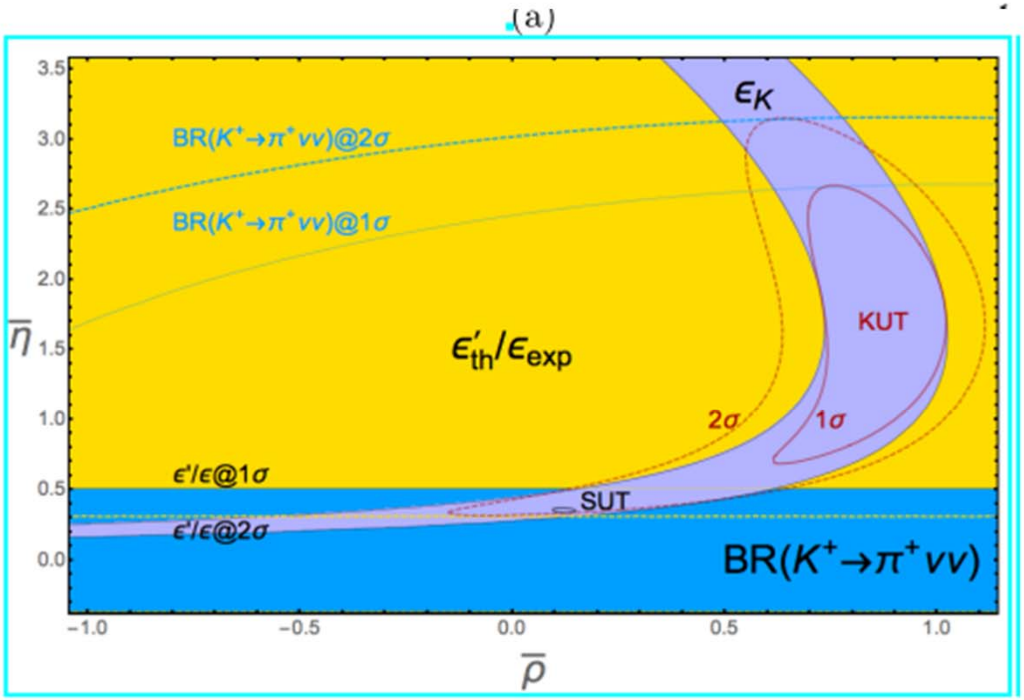
Instead of [or in addition to] $K_L \to \pi^0 \nu\bar{\nu}$ can now plan on using ϵ'/ϵ

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

I ϵ_K Indirect CP

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

(a)



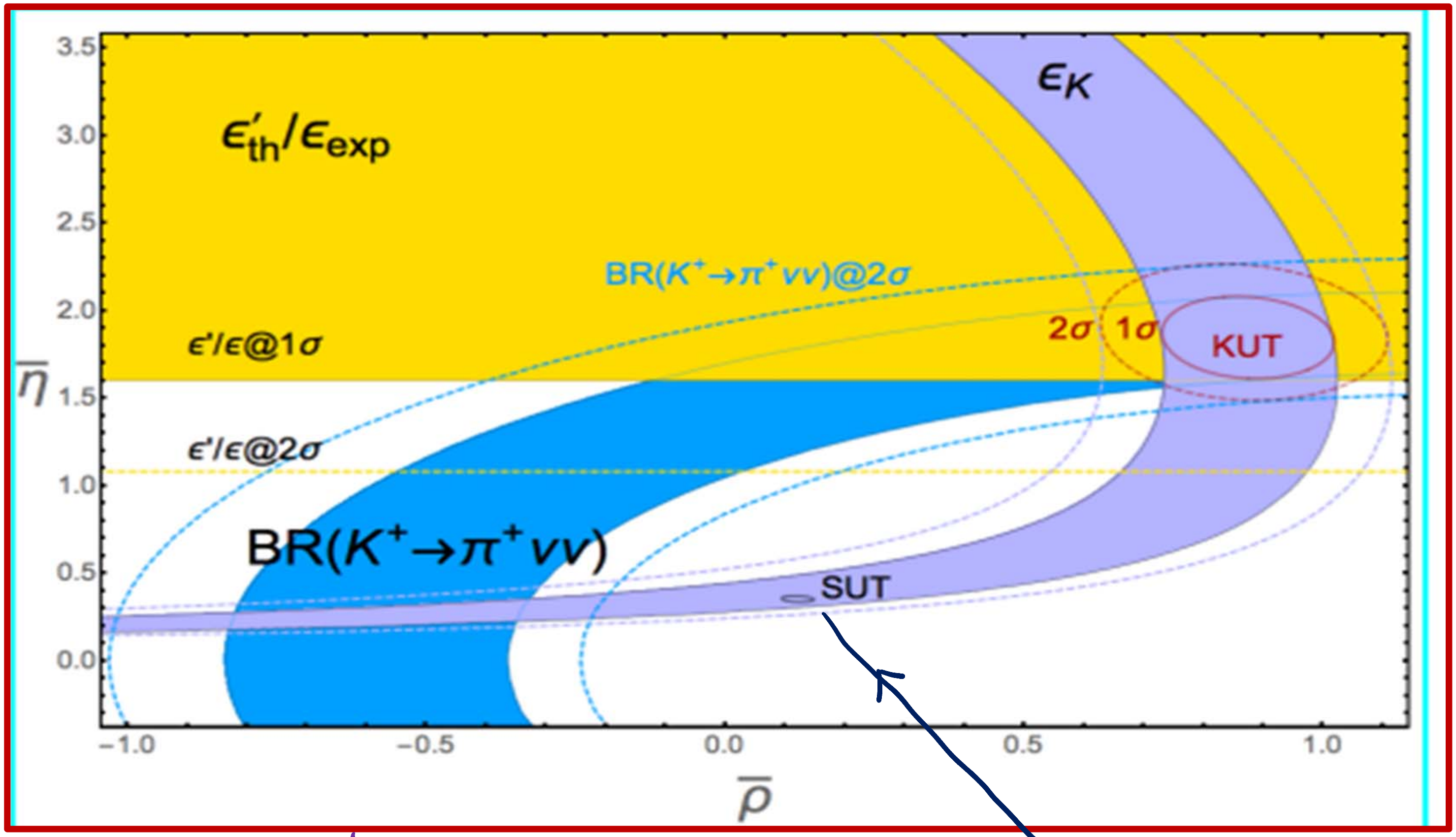
LLS '15

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

PDG 2015

RBC+UKQCD '15

POSSIBLE KUT CIRCA 2020: DUE NA62 + RBC-UKQCD



NO unique ρ, η

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

Lehner, Lunghi + AS PLB'16

"Standard" (B) UT

Summary & Outlook

- **In the past ~2 decades, B expts + lattice => SM-CKM paradigm of CP violation works to about an accuracy of ~ 15% through the SUT; now need to forge ahead in search for NP via precision experimental and theoretical studies**
- **Traditional challenges of direct CP persist though significant progress was attained in phenomenological methods via data driven ways for deducing very precise value for the CKM-phase-ν which should serve as a "STANDARD" candle for testing new phenomena**
- **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, ΔI=1/2 rule, LD non-local contributions to ΔmK, εK, K+ >π+νν, ….**
- **In conjunction with existing expt info and with anticipated improvements in key Kaon experiments, a unitarity triangle based primarily on K-decays will become available in a few years.**
- **Note also, the significant progress that has been made and is anticipated in lattice calculation of ε' in the next few years 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 ought to significantly improve precision due vast amount of anticipated relevant data**
- ***All these efforts should lead to more stringent tests of the SM and much better clues to onset 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 measmts

- But, current lattice cal show rather largish central value for [- Q1/Q2] with appreciable errors compared to expectation from large N 0.90 ± .30 [1/2]
- 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