"Recent advances in lattice weak matrix elements for searching new physics"

Amarjit Soni

BNL-HET

KAVLI-IPMU-Tokyo

02/13/19

outline

- K=> pi pi, ε' status with X6.5 more stat than 1st , 2015 result
- non-local matrix elements[NLME]… [in progress] Delta m_K, epsilon_K^LD, K^+ => pi^+ nu nu…….
- Experimental developments on the horizon

  + lattice developments…..Bearing both of these in mind…
- simplest new application in B-decays → A.S LAT'18
- Other possible applications…
- Tau decays → A.S. WEH'18; τ'18
- summary

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 sectoras well as charged sector can have new phases; SUSY or WEXD [see e.g Agashe, Perez & AS, PRD '04 : 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***

c More later

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

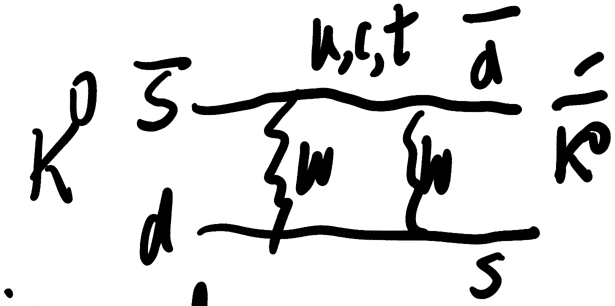
- I: $\Delta I = 1/2$ Rule / Puzzle

K^+: $\bar{s}$, u $\qquad$ K^0: $\bar{s}$, d $\qquad K^0 \to K_S, K_L$ $\qquad I = 1/2$

$\to 2\pi\,(I=2,\ \Delta I = 3/2 \text{ only})$ $\qquad \to 2\pi\,(I = 0, 2;\ \Delta I = 1/2, 3/2)$

$\tau_{K^+}/\tau_{K_S} \sim 450! \gg 1 \Rightarrow \Delta I$: Dominance/Rule/Puzzle

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



QM mixing

$\Delta S = 2$

$O(G_F^2)$

2 States K_L, K_S If CP is exact

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

CP− CP+

$\rightarrow 3\pi$ $\rightarrow 2\pi$

$\not\rightarrow 2\pi$ $\not\rightarrow 3\pi$

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 $\tau_{K_L} / \tau_{K_S} \sim O(500) \gg 1$

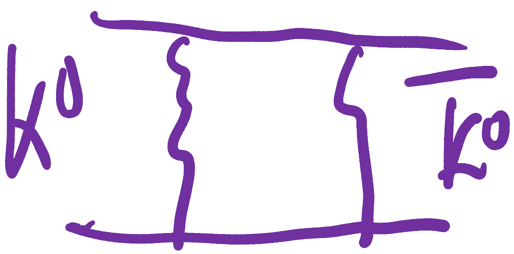
III Indirect CP violation

BNL 1964 Fitch, Cronin, Christensen + Turlay

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

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

NOBEL PRIZE
Cronin + Fitch



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

IV: ε' / ε: Direct CPV

EXPERIMENTAL ROUTE

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

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

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

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

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

Conf on NP@LHC 02/29/16; A. Soni 10

K→2π

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

($\mathrm{Im}A_2$: I=2; $\mathrm{Im}A_0$: I=0)

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

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

Indirect CP

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

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

DIRECT CP

$\epsilon' \ll \epsilon$

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

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

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

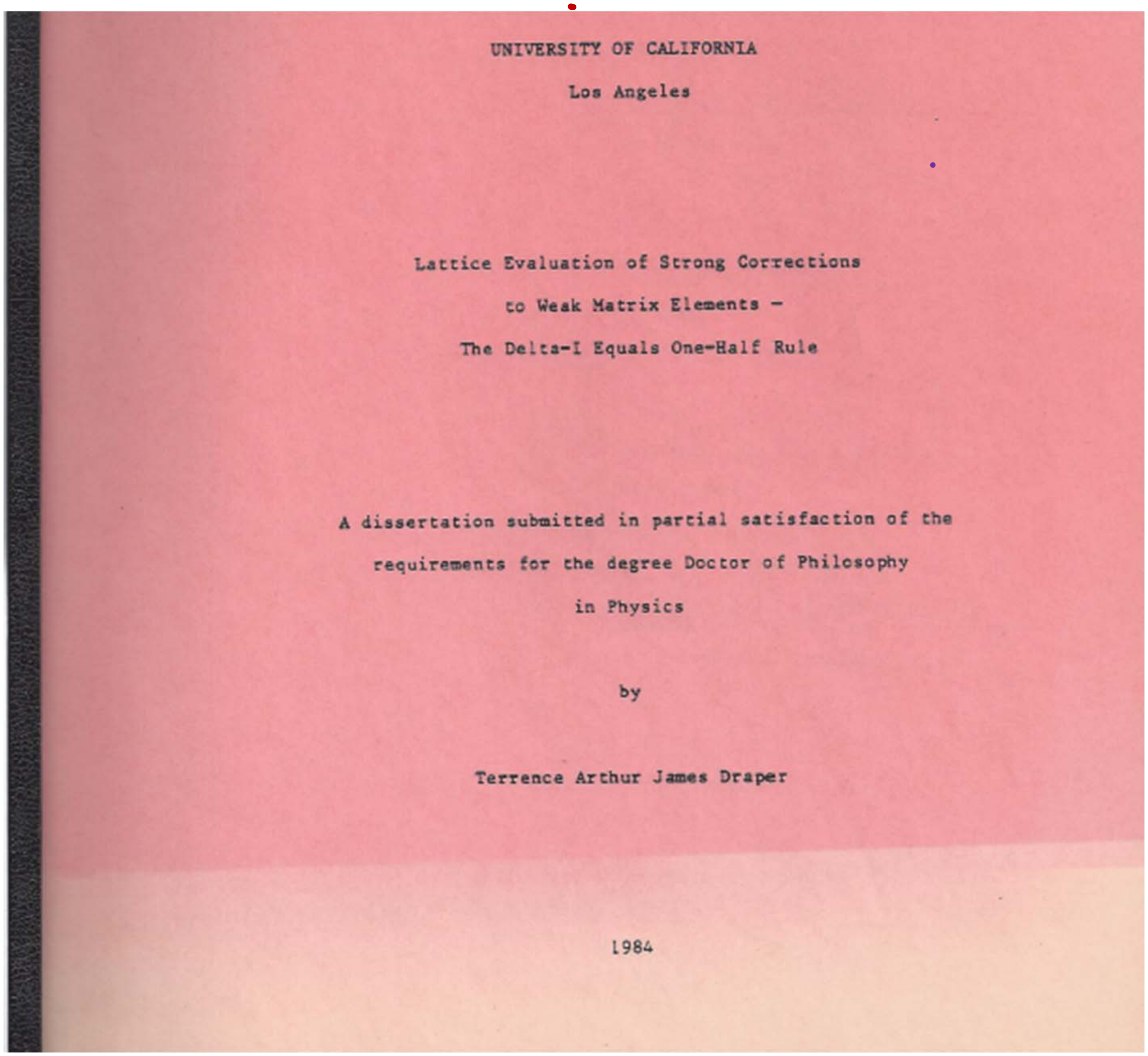
With C. Bernard [UCLA]

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 Beer Party ~ June 20, 1982!!

[UCLA]

Beware of End of year Beer Parties!

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**

BASIC CALCULATIONAL FRAMEWORK

Δ S=1 H_W

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

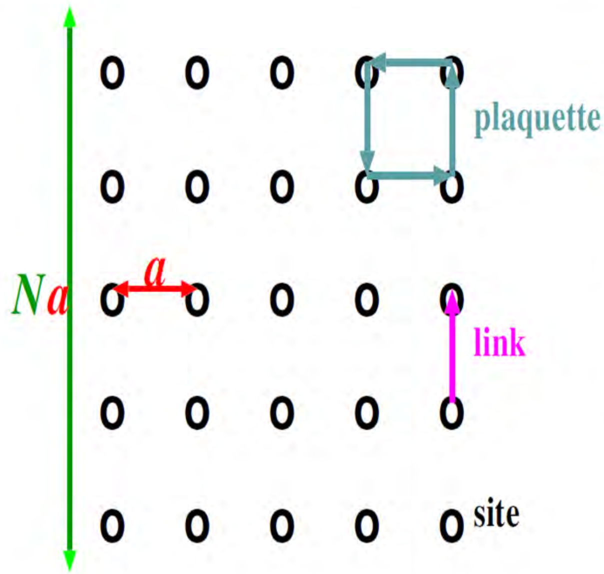
$$H_W = \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \sum_{i=1}^{10} [z_i(\mu) + \tau y_i(\mu)] Q_i(\mu).$$

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

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

What the hell is lattice QCD?

Gunnar Bali



typical values:

$a^{-1} = 2$–5 GeV, $Na = 2$–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 representative ensemble of gluon configurations $\{U_i\}$ with probability $P(U_i) \propto \int [d\psi][d\bar{\psi}] e^{-S[U,\psi,\bar{\psi}]}$

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

K→ππ quark flow diagrams [gluons not shown]

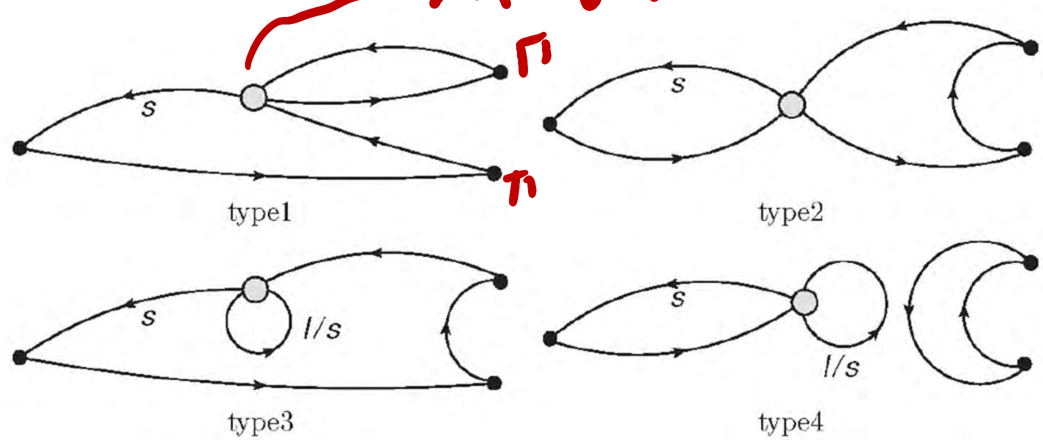


FIG. 1. Examples of the four types of diagram contributing to th[illegible] $K \to \pi\pi$ decay. Lines labeled ℓ or s represent light or strange quarks. Unlabeled lines are light quarks.

type 4 only in I=0

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 ⇒

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

→ 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

→ const

$m \to 0$

QCDP

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 ε' they enter as** $$\left[\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]$$

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

small ← $\mathrm{Re}A_2$; $\mathrm{Re}A_0$ → large

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

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

$\varepsilon_8 \propto m_t^2/M_W^2$

- ***As a result, the large accidental cancellations significantly enhances sensitivity of ε' to NP***

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

→ LEFT

BDSPW-85

Claude Bernard, Terrence Draper,* and A. Soni
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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


REFRIGERATION & AIR CONDITIONI
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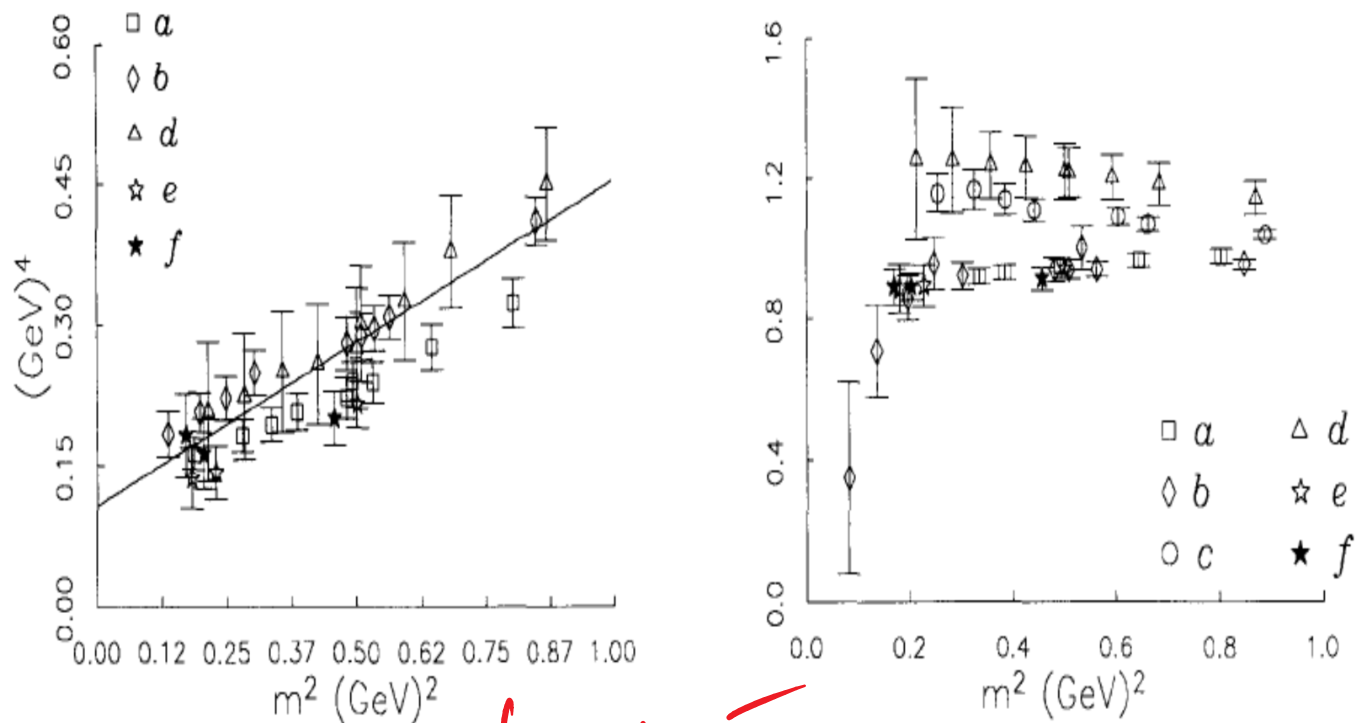
GMC

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

K ⊗⊗ K̄ ↑ op '88

s W W d



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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(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 $A_2(0)/A_1(0) = 0.70 \pm 0.16^{+0.20}_{-0.15}$. 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

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Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 28 January 1998; published 5 May 1998)

PIONEERING WORKS Leading to Modern Day UT

Later ΔM_s CDF, D0

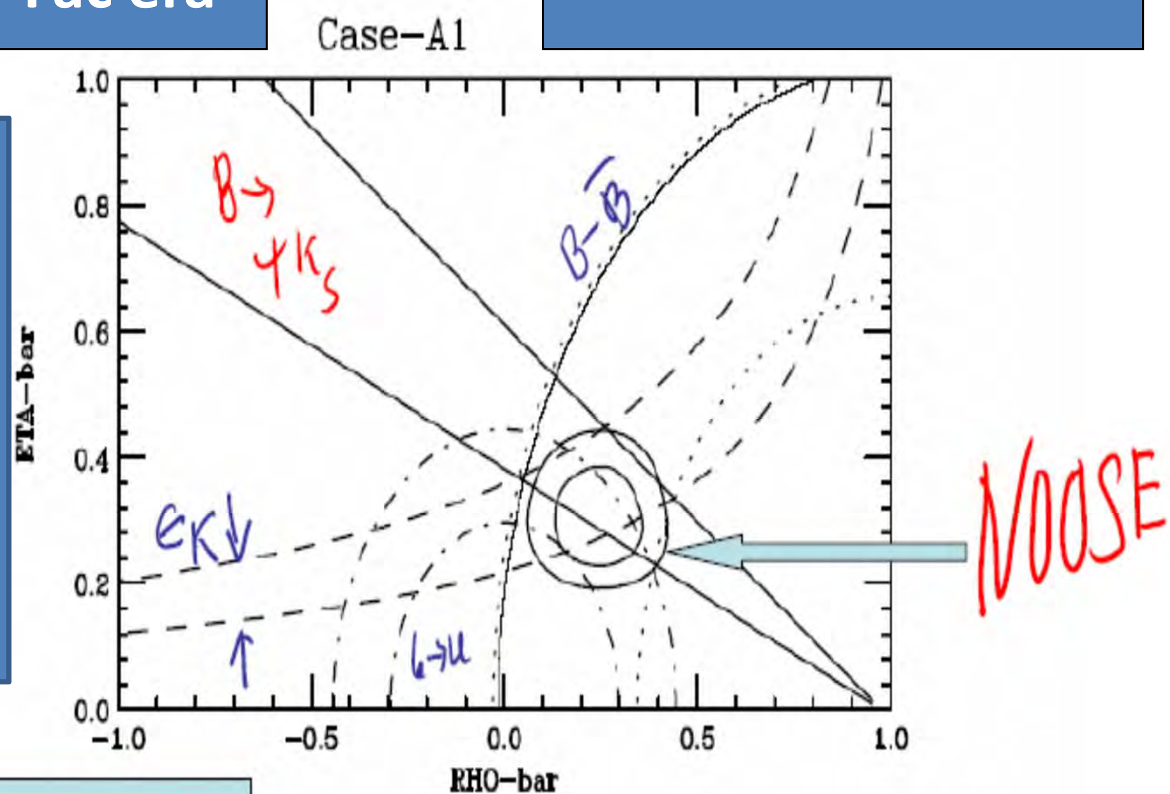
the “beginning” “Dawn “

the asymmetric B-Fac era

ood &AS, hepph/0103

Japan

1st Hint of
confirmation of
CKM
CP description



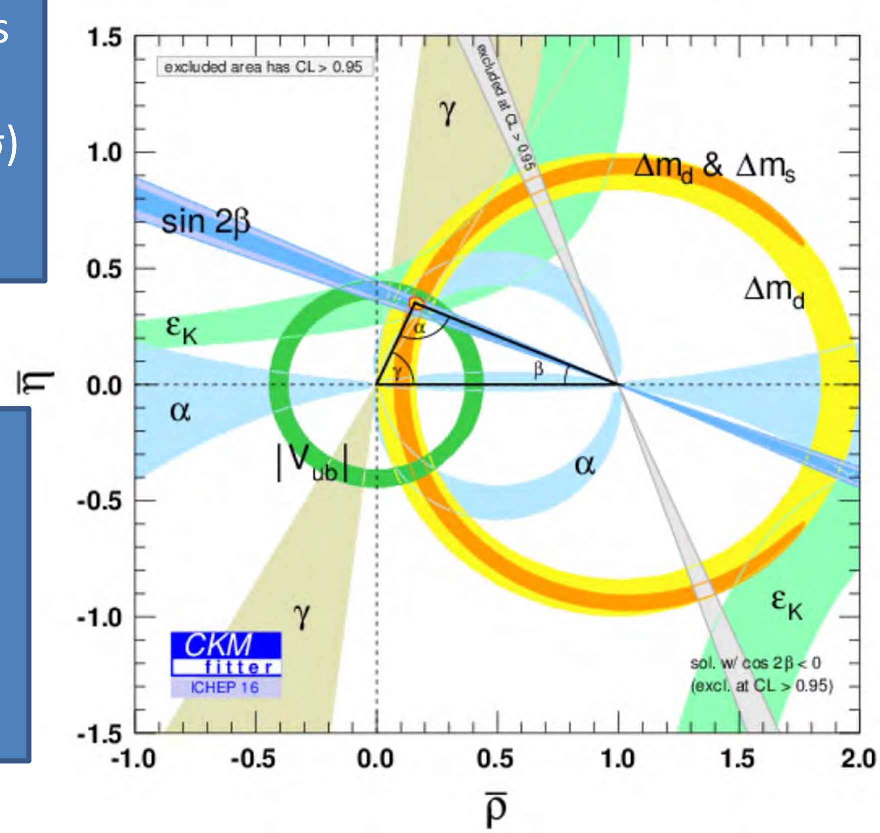
Most bands due
To theory errors

New physics will be a perturbation, impo
to use clean theory and lots of statisti .

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

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

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



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

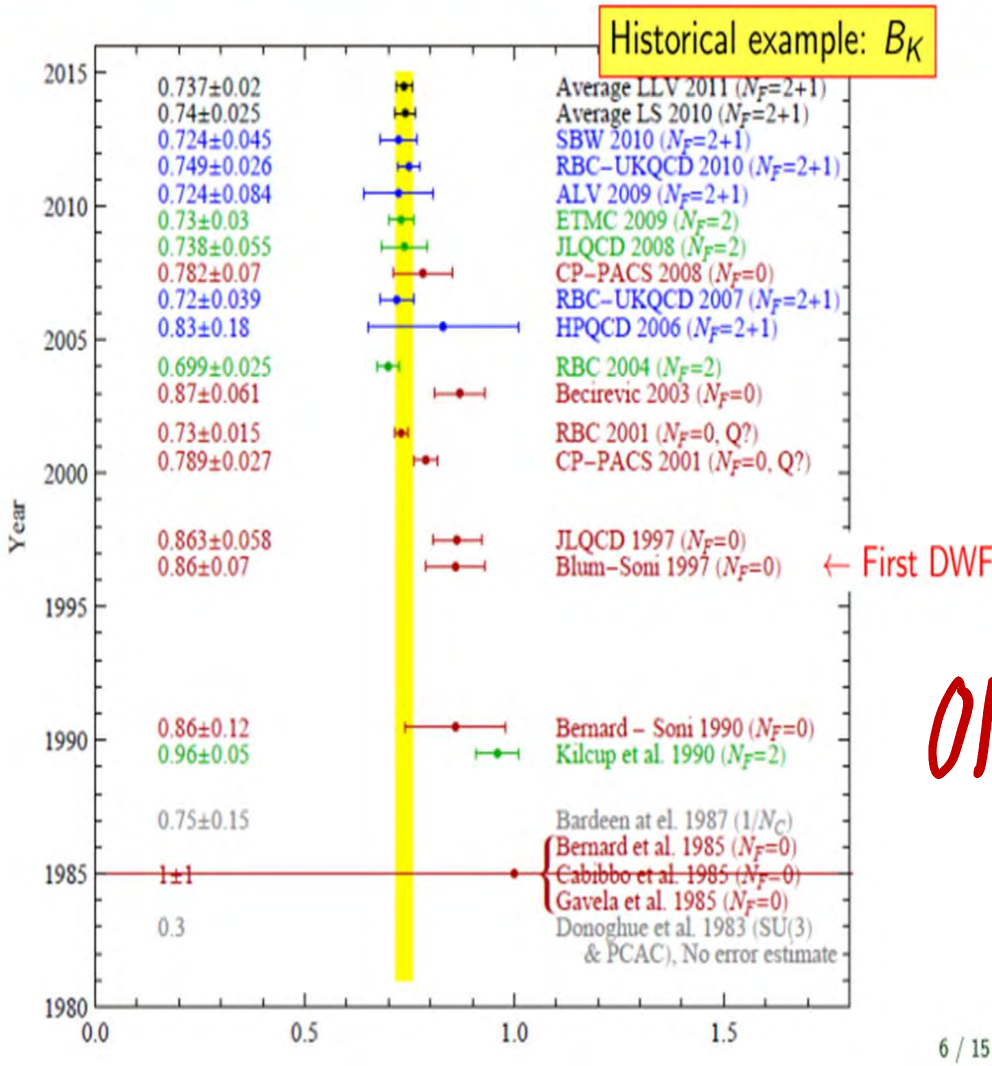
Courtesy: Tom Browder

Critical Role of the B factories in the verification of the KM hypothesis was recognized and cited by the Nobel Foundation

A single irreducible phase in the weak interaction matrix accounts for most of the CPV observed in kaons and B's

CP violating effects in the B sector are O(1) rather than O(10^{-3}) as in the kaon system

Power of the lattice: Only method to systematically reduce the NP error!

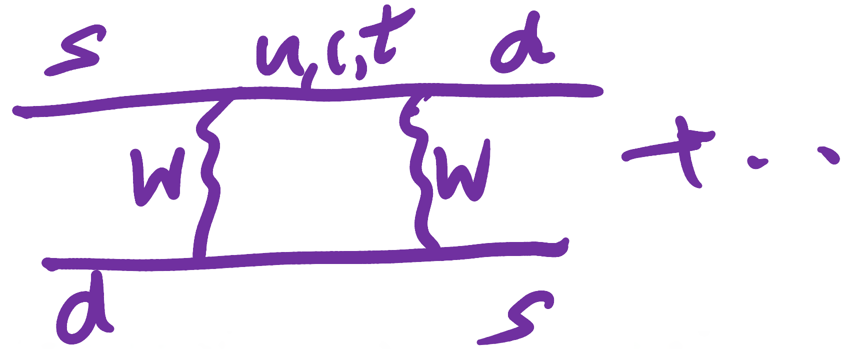


AB-initio Calculat

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

ONE ILLUSTRATION

Why B_K is needed?



$$|\varepsilon_K| = \frac{G_F^2 m_W^2 f_K^2 m_K}{12\sqrt{2}\pi^2 \Delta m_K^{\exp}} \hat{B}_K \kappa_\varepsilon \, \mathrm{Im}\Big(\eta_1 S_0(x_c)\,(V_{cs}V_{cd}^*)^2 + 2\eta_3 S_0(x_c,x_t) V_{cs}V_{cd}^* V_{ts}V_{td}^* + \eta_2 S_0(x_t)\,(V_{ts}V_{td}^*)^2\Big) . \quad (2.3)$$

η_i = QCD Corrections

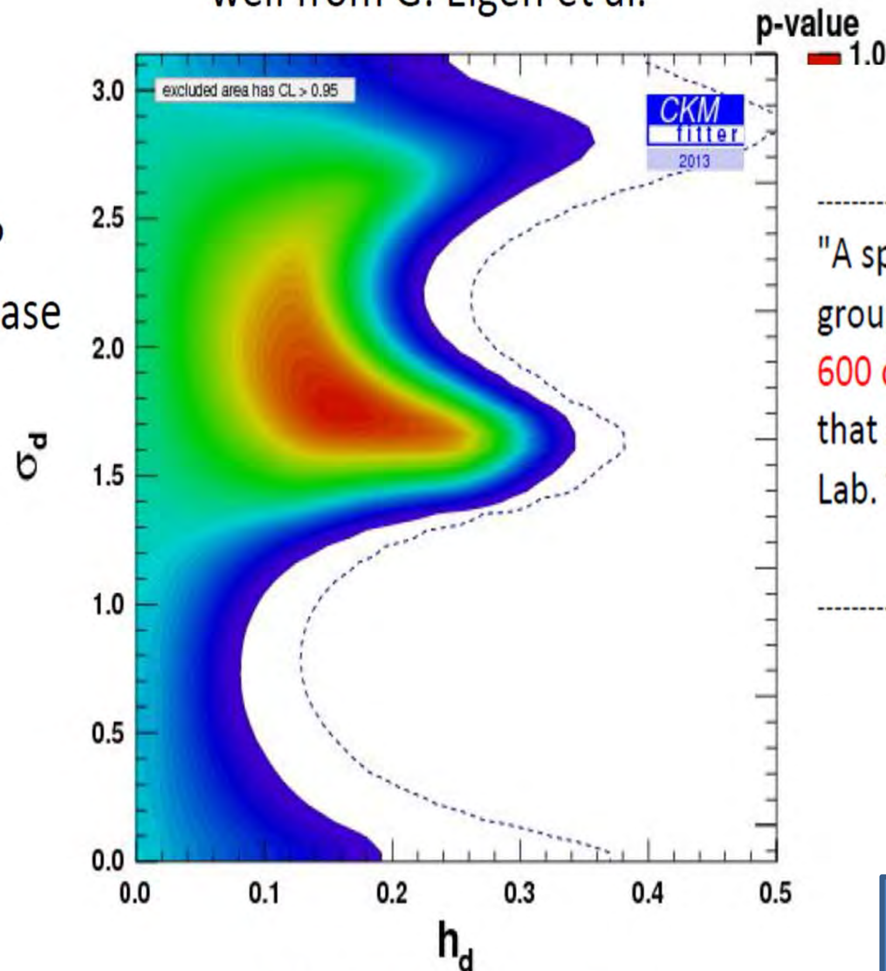
$x_j = m_j^2 / m_W^2$

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

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

Current O(few%) tests are far away from O(0.1%) asymmetry in KL=>pi pi

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= 2×10^{-3}

A failure of imagination ? Lack of patience ?

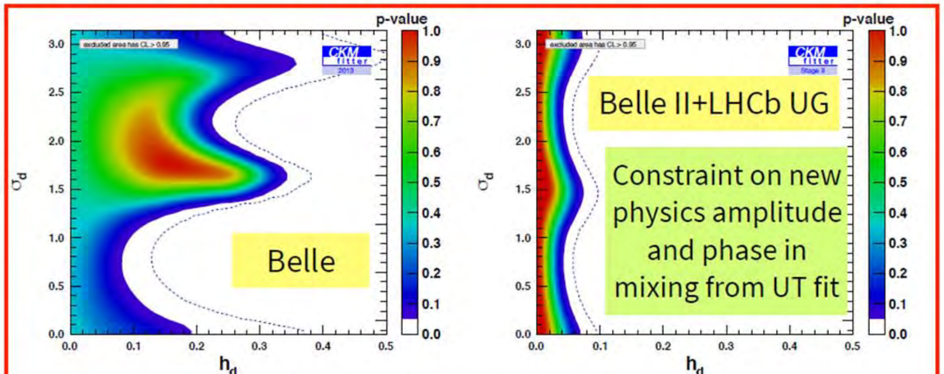
Had KL=>pi pi been abandoned, history of Particle Physics would have been significantly different!

V_{CKM} - Summary

URQUIJO @ICHEP2018

- **$|V_{cb}|$ puzzle addressed by Belle**
  - **$B \to D^{(*)} \tau \nu$ anomaly needs new $B \to D^{**} l \nu$ 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)



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

- **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 in coming years VITAL

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?

PHYSICAL REVIEW D VOLUME 56, NUMBER 1 1 JULY 1997

Two key papers

QCD with domain wall quarks

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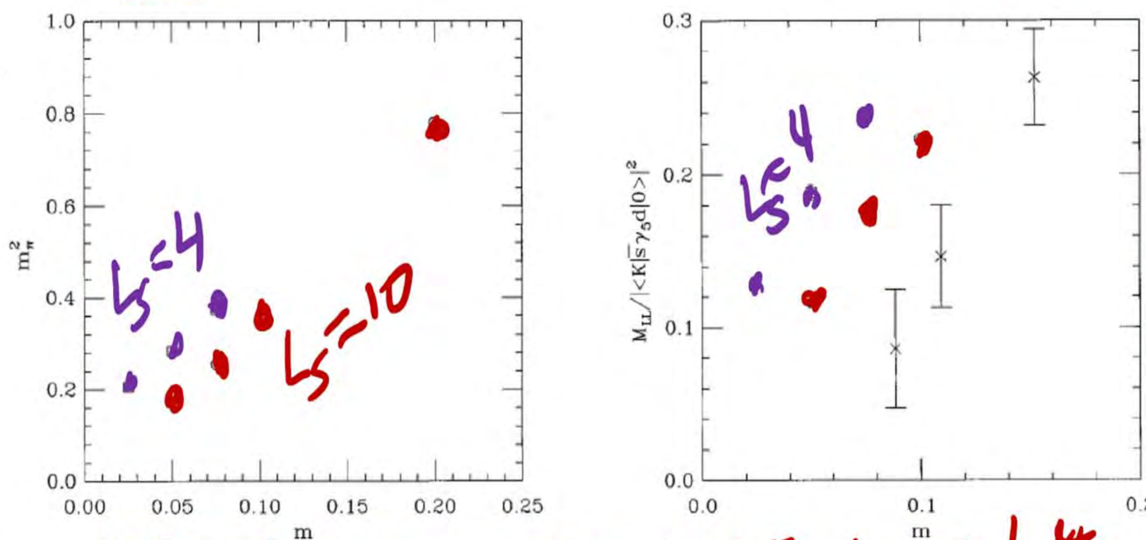
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973

(Received 27 November 1996)

1st Simulation with DWQ Feb '97

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



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

MAJOR BREAKTHROUGH FOR K→ππ Lattice Calculations i.e No ChPT

CMP/01.

a new method

another major development for K→ππ on lattice

Direct K-> ππ (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

35

Relating lattice ME to physical amplitudes

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

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

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

→ Phase shift

A/M is LL factor F

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

↳ $\sim \frac{\delta}{q}$ for small p

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

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 match Lehner+Sturm PRD'11

Results for ε'

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

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

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

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

EWP

QCDP

~80%

LARGE CANCELLATION!!

RBC-UKQCD PRL'15 EDITOR'S CHOICE

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

with expt

Computed ReA0 good agreement with expt

Offered an "explanation" of the Delta I=1/2 enhancement

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

A possible difficulty: strong phases

- The continuum and our lattice determinations of strong phase

diffe

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

Colangelo et al

ChPT etc

RBC-UKQCD

-

- Total error on Re(ε'/ε) is ~3x the experimental error
- Find reasonable (2.1σ) consistency with Standard Model
- "This is now a quantity accessible to lattice QCD"!
- Focus since has been to improve statistics and reduce / improve understanding of systematic errors.

↳ use much larger stats

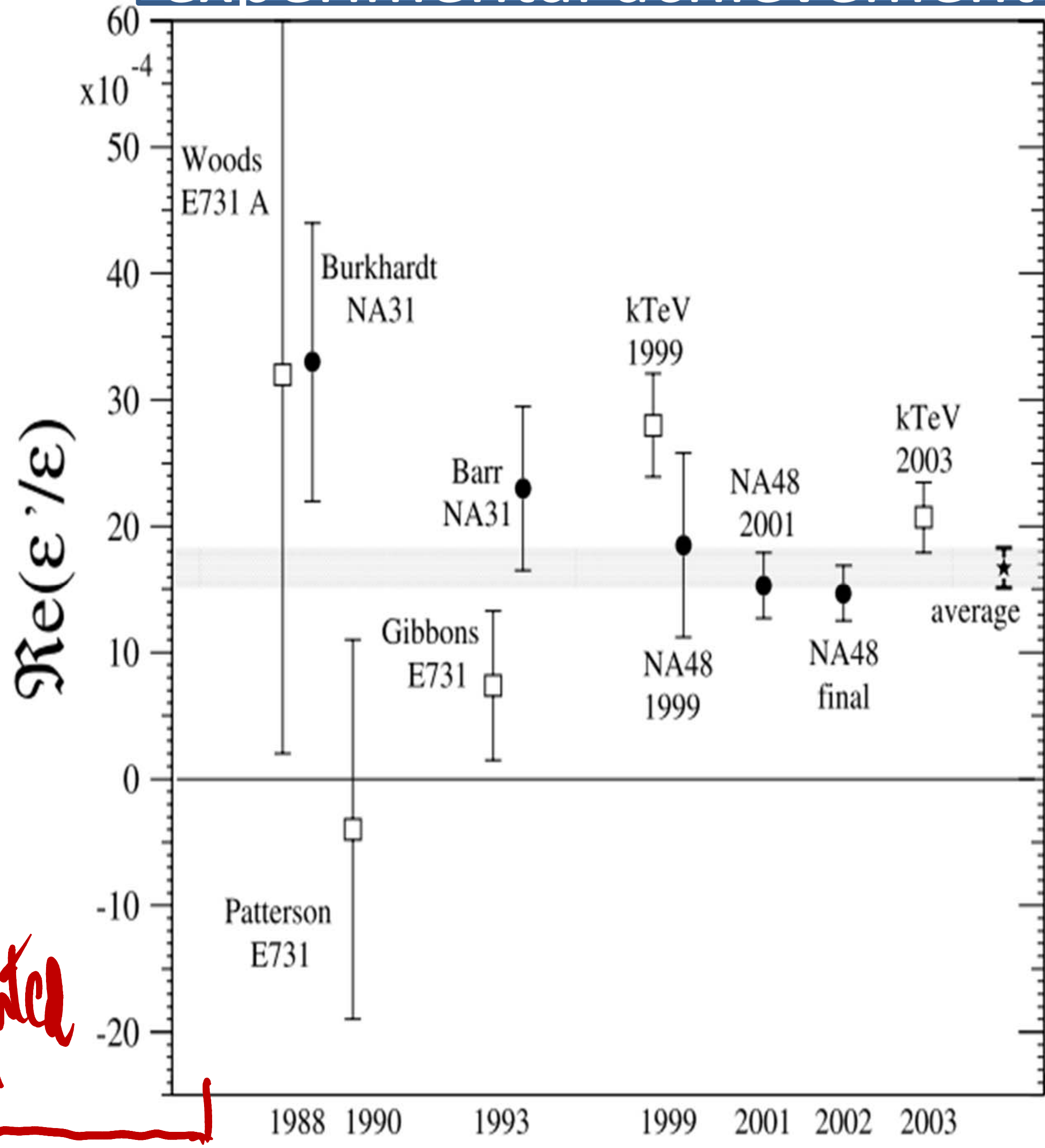
Statistics increase

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

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

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

A monumental experimental achievement!



Konrad Kleinknecht "Uncovering CPV"

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

LATTICE work started

Challenges of physical K=>pi pi kinematics on the lattice

- Primary challenge is to assure physical kinematics: For periodic BCs, amplitude with 2 stationary pions in final state dominates. However

$$2m_\pi \approx 240 \text{ MeV} \ll m_K \approx 500 \text{ MeV}$$

280

- Desired state with moving pions is next-to-leading term: require 2exp fits?

- Avoid 2-exp fits by removing stationary pion state from system through manipulating lattice spatial boundary conditions:

  - Antiperiodic BCs on down-quark for A_2
  - G-parity BCs on both quarks for A_0

$$p_\pi = 0 \rightarrow \pi/L$$

tune L to match E_K and $E_{\pi\pi}$

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

PHYSICAL MASSES of Kinematics!

m_K=490.6(2.4) MeV

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

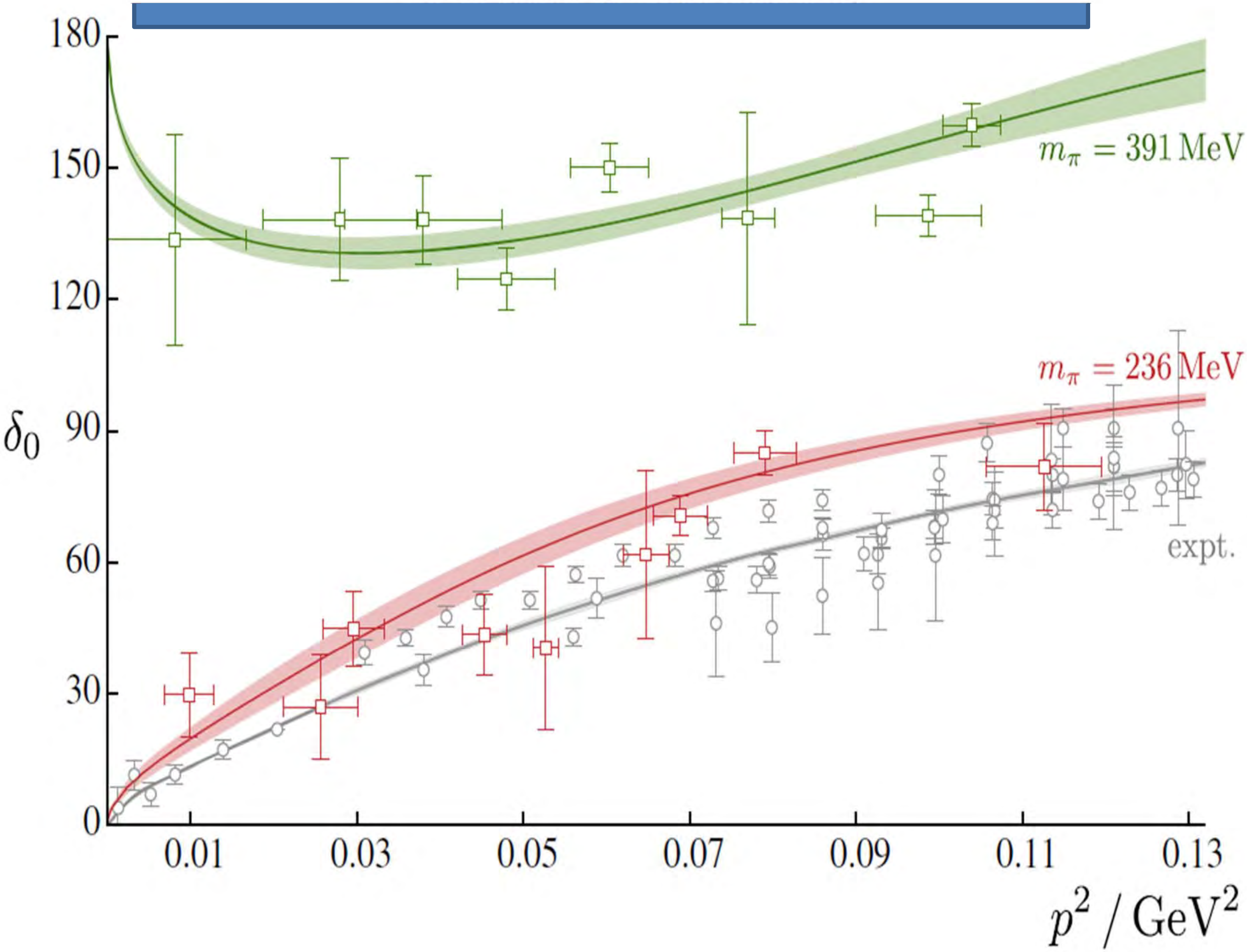
$E_{\pi\pi}$(I=2) = 573.0(2.9) MeV

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

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



Resolving the [I=0] Energy & phase shift in the pi pi channel

- 2015 result has 2σ+ discrepancy between our I=0 ππ phase shift (δ_0=23.8(4.9)(1.2)°) and dispersion theory prediction (~34°).

[RBC&UKQCD PRL 115 (2015) 21, 212001]
[Colangelo *et al*, Nucl.Phys. B603 (2001) 125-179]

- Observed discrepancy more significant (~5σ) with 6.5x stats.
- Most likely explanation is excited-state contamination.
- To address added scalar (σ=[illegible]) ππ operator to the 2-pt function calculation.
- Combined fits (or GEVP) to ππ→ππ, σ→ππ and σ→σ correlators result in considerably lower ground-state energy:

508(5) MeV [1386 cfgs] from ππ→ππ alone
vs
483(1) MeV [501 cfgs] from sim. fit of all 3 correlators.

- New phase shift δ_0=30.9(1.5)(3.0)° [prelim] compatible with dispersive result.

- Strong evidence for nearby excited finite-volume ππ state.
Indeed such a state with E ~ 770 MeV is predicted by dispersion theory.

Implications for K→ππ and resolution

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

New result on ε' likely ~6 months

Over the past ~6 years, RBC-UKQCD developed methods for extended application of L-L method to 2 insertions of weak operators

⇒ LD or non-local contribution to ME

All loop suppressed weak amps receive some LD

⇑

Δm_K extremely sensitive to non-$(V-A)^2$ ⇒ Beall, Bander, AS 1982 PRL

1st application

K_L-K_S mass difference

I. Jianglei Yu PhD '14

II Ziyuan Bai PhD '16

III Bigeng Wang ongoing

N^2LO pert Th Brod + Gorbahn

~ O(40%) LD contamination

PRL 2012

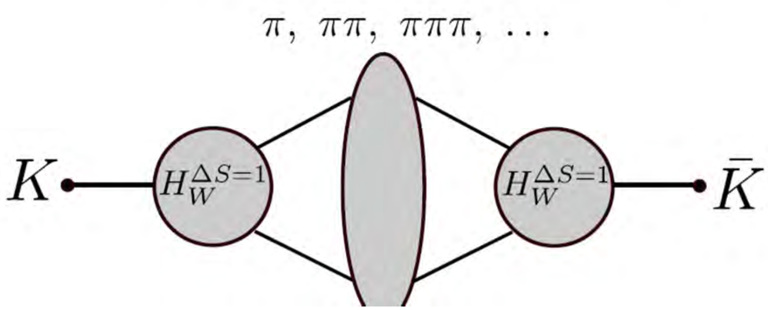
CKMCKM'18

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

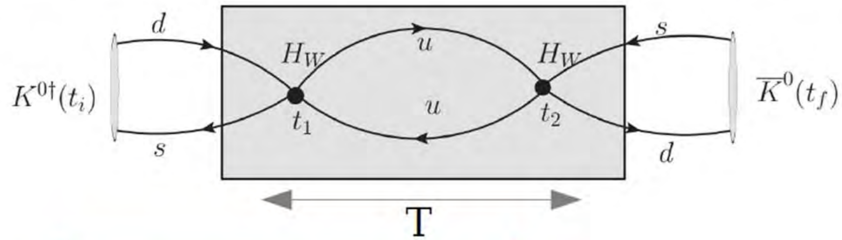
B.Wang @ LAT'18

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

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



Lattice method and challenges



$$\mathscr{A} = N_K^2 e^{-M_K(t_f-t_i)} \sum_n \frac{\langle \overline{K}^0 | H_W | n\rangle\langle n | H_W | K^0\rangle}{M_K - E_n}\left(-T - \frac{1}{M_K - E_n} + \frac{e^{(M_K-E_n)T}}{M_K - E_n}\right)$$

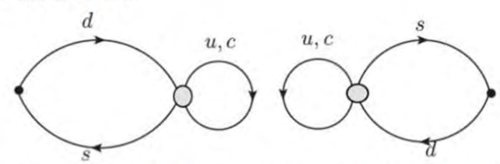
→ requires subtraction for $M_K \to E_n$

- Vary integration window T to extract desired matrix element as term linear in T
- Require subtraction of exponentially-growing terms when $E_n < m_K$: |π>, |ππ>, |0>
- Use ability to shift H_W by total divergence $\bar{s}\gamma^5 d$ to directly remove |0>
  Similarly use $\bar{s}d$ to remove |η>, which although $m_\eta > m_K$ gives noisy contribution

$$\langle \eta | H_W - c_s \bar{s} d | K\rangle = 0 \qquad\qquad \langle 0 | H_W - c_p \bar{s}\gamma^5 d | K\rangle = 0$$

a la BDSPW-85

- Pion and two-pion terms contributions explicitly subtracted
- Disconnected diagrams make the calculation noisy. Requires large statistics and maximal translation of sources.



- Divergence when operators approach removed by GIM – requires (valence) charm on lattice. Need fine lattice to control discretization errors.

Calculation status

- First complete calculation in 2014 with large statistics (800 configs) on single, somewhat coarse (a^{-1}=1.73 GeV) lattice

[Phys.Rev.Lett. 113 (2014) 112003]

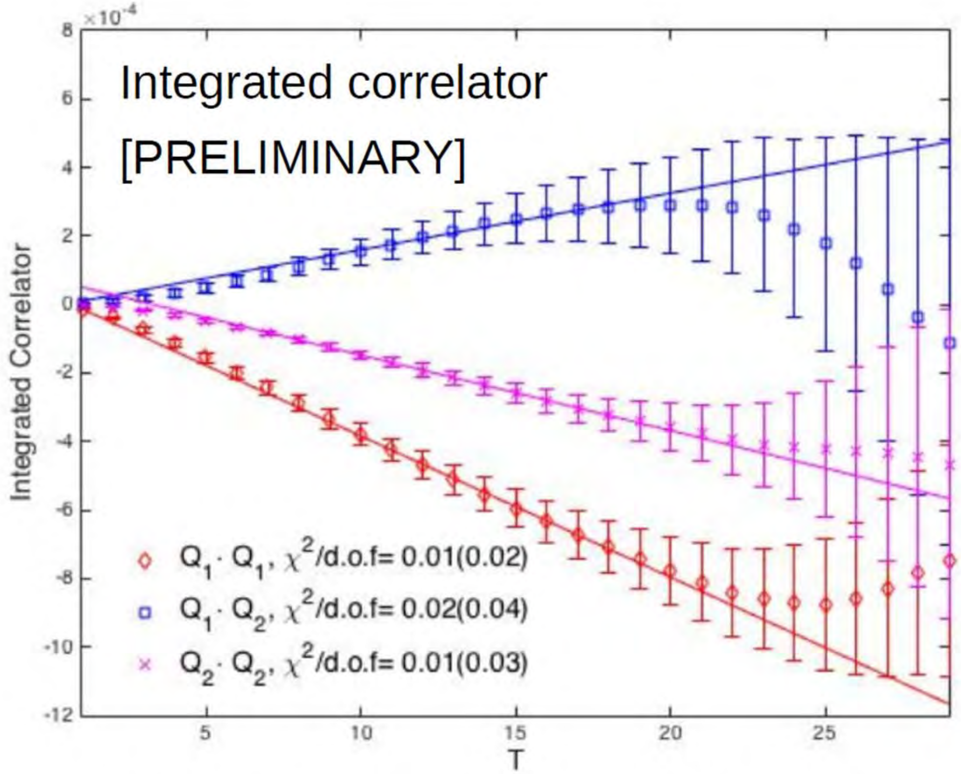
Unphysical masses: 330 MeV pions (no ππ intermediate state) , m_c = 950 MeV

est. of dominant charm disc err. only

lattice: $$\Delta M_K = 3.19(41)(96) \times 10^{-12}\ \text{MeV}$$

experiment: $$3.483(6) \times 10^{-12}\ \text{MeV}$$

- Presently repeating calculation on large $(5.5\ \text{fm})^3$, fine a^{-1}=2.36 GeV lattice
- Physical charm and pion mass
- Prelim. results for 129 configs presented by B.Wang at Lattice 2018



$$\Delta M_K = 7.0(1.7)_{\rm stat} \times 10^{-12}\ \mathrm{MeV}$$ (syst?)

- η-state gives significant stat. err. contrib as divergent op. subtraction coeff noisy
- Charm discretization error estimate from naive $(m_c a)^2 \sim 25\%$
- However only 3-10% observed errors in f_D and dispersion relation of η_c
- Aim to continue measurements on ORNL Summit computer and ultimately a second lattice spacing to understand disc. effects.

Next improvement

Determination of syst error + more stat now underway

Emphasize the obvious

PHYSICS IS AN EXPTAL SCIENCE

Testing SM in the era of Belle-II

- I. **A new thousand pound gorilla is in our midst:**

Toru Iijima @ SCGP May 31, 2018

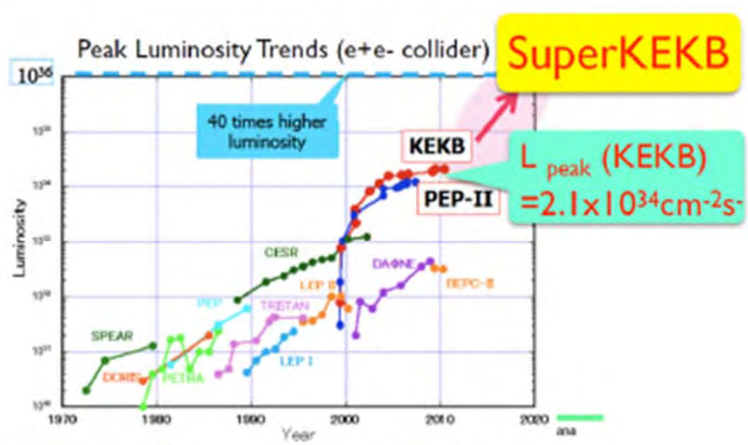
SuperKEKB/Belle II

New intensity frontier facility at KEK

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

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

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



The first particle collider after the LHC !

IN MY VIEW

New physics discovery potential is no less than when we moved From Tevatron to LHC!!!

Looking forward at LHCb

HL-LHC →

7 - 8 TeV	13 TeV	14 TeV		
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 (before Run 3) — Upgrade II (before Run 5)

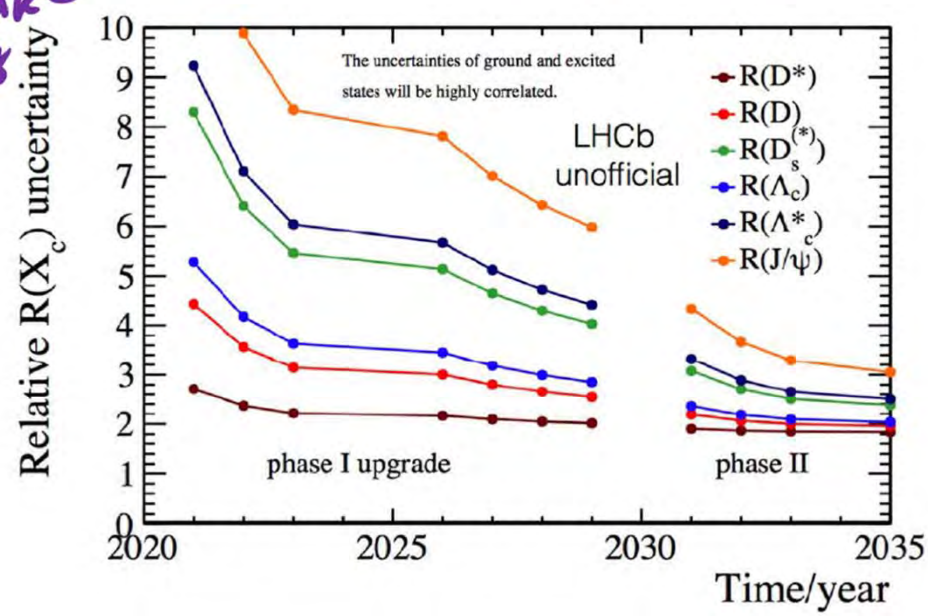
Mark Smith @ FPCP2018

C also T SZUMLAK @ FPCP 2018

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

Continued improvement reliant on:

- Simulation size
- Theory collaboration
- Experimental input



The RBC & UKQCD collaborations

BNL and BNL/RBRC

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

UC Boulder

Oliver Witzel

Columbia University

Ziyuan Bai
Norman Christ
Duo Guo
Christopher Kelly
Bob Mawhinney
Masaaki Tomii
Jiqun Tu
Bigeng Wang
Tianle Wang
Evan Wickenden
Yidi Zhao

University of Connecticut

Tom Blum
Dan Hoying (BNL)
Luchang Jin (RBRC)
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Edinburgh University

Peter Boyle
Guido Cossu
Luigi Del Debbio
Tadeusz Janowski
Richard Kenway
Julia Kettle
Fionn O'haigan
Brian Pendleton
Antonin Portelli
Tobias Tsang
Azusa Yamaguchi

KEK

Julien Frison

University of Liverpool

Nicolas Garron

MIT

David Murphy

Peking University

Xu Feng

University of Southampton

Jonathan Flynn
Vera Guelpers
James Harrison
Andreas Juettner
James Richings
Chris Sachrajda

Stony Brook University

Jun-Sik Yoo
Sergey Syritsyn (RBRC)

York University (Toronto)

Renwick Hudspith

Anomalies galore!

- **RD(*)** ~ 4.6(?)
- **RK(*):** 2.6σ(RK) ; ~ √2 * 2.6 => 3.5σ
- **g -2…BNL’06 =>FNAL expt…** ~ 3.6σ major lattice progress by RBC-UKQCD + others
- **Ɛ’: a personal obsession….for a long^3 time=>’cause of the strong conviction that it is super-sensitive to NP** EVER LOOMING

216[RBC-UKQCD PRL 2015] => ~1400 C. Kelly

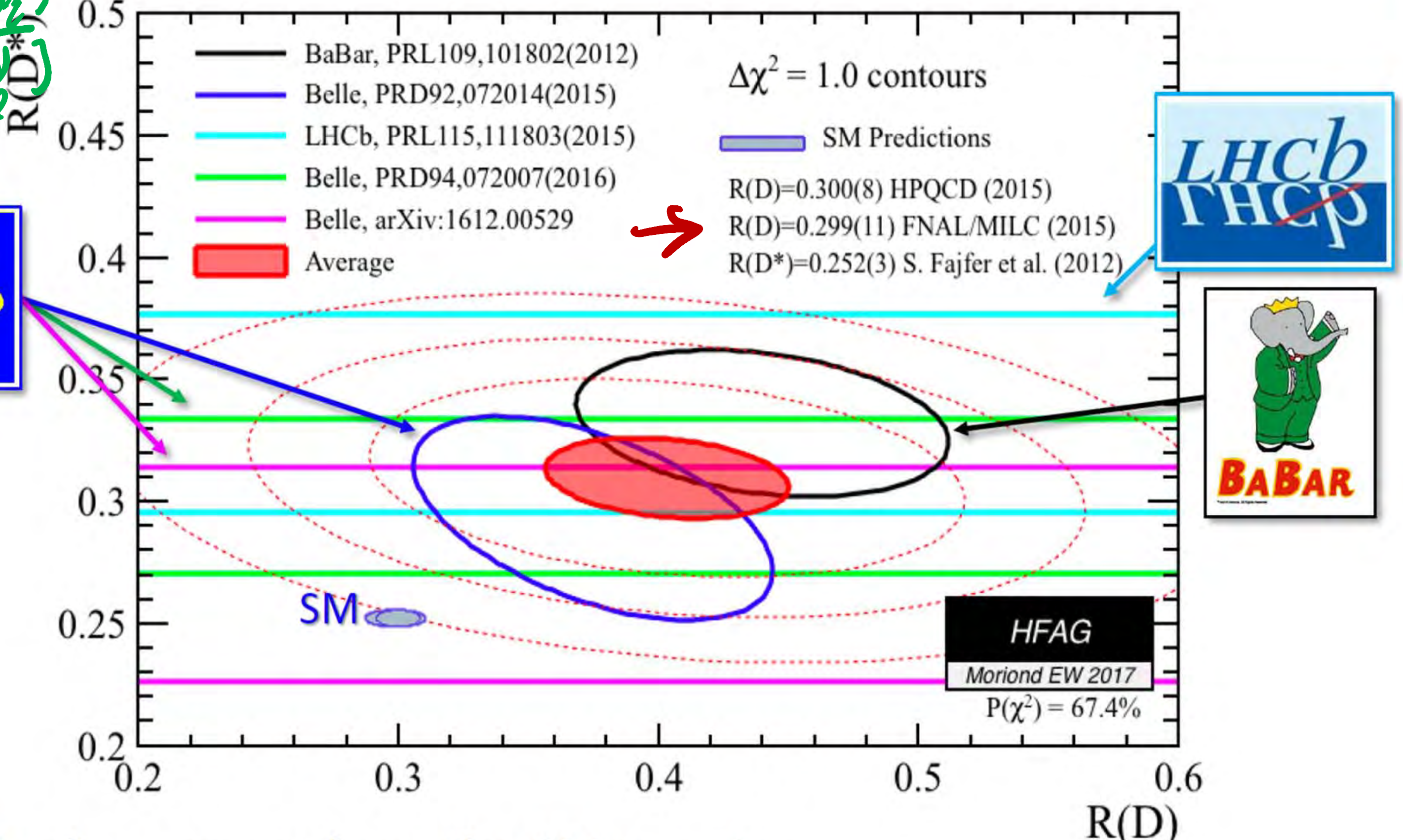
[2.1σ (2.9σ Buras; Nierste) => ??] …..few more months to new results

REAL or fake : Lattice + EXPT DECIDERS

In decoding SM or not, lattice input is vital for each case!

■ $R(D^{(*)})$ by HFAG

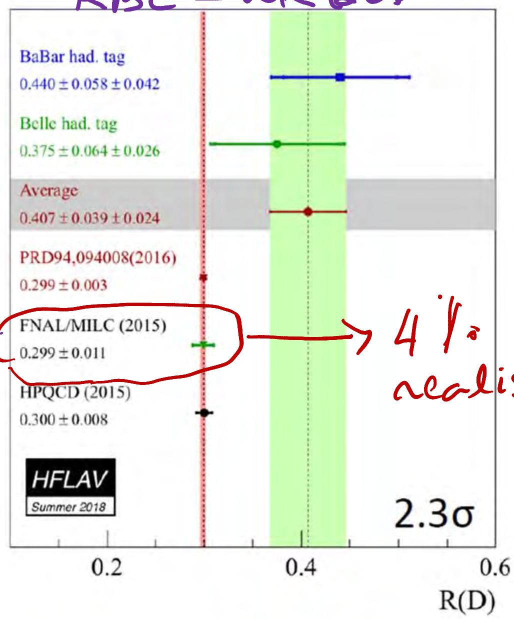
Hirose [BELLE]@EW MORIOND Mar. 2017

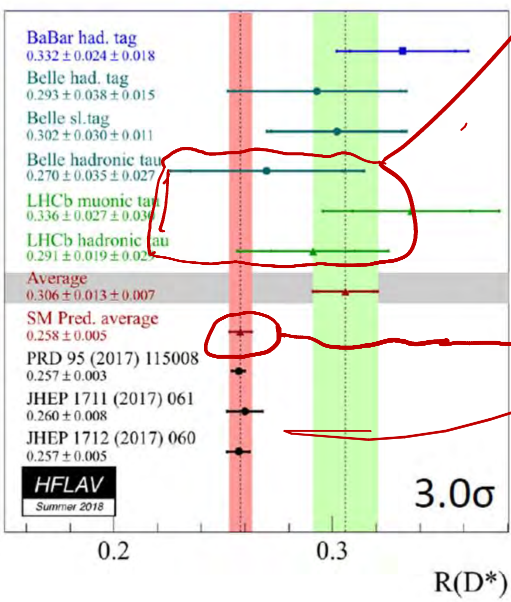


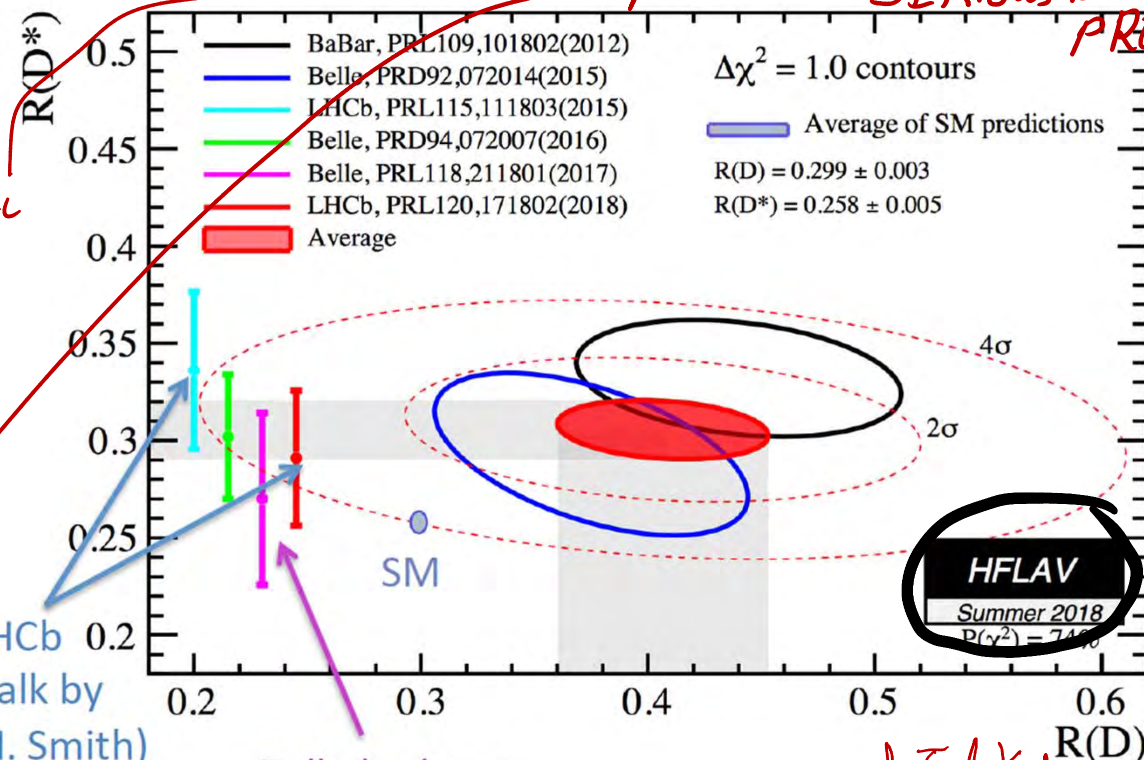
- ~4σ discrepancy from the SM remains
  - All the experiments show the larger $R(D^{(*)})$ than the SM
- More precise measurements at Belle II and LHCb are essential

Belle deviations quite mild

Status of R(D$^{(*)}$) results







LHCb (talk by M. Smith)

Belle had. tag (τ polarization)

Deviation from SM prediction 3.9 σ

also WITZEL et al RBC–UKQCD

4% realistic

R_D Theory much cleaner but QED radiative corr needed. More expt effort on R_D needed

POTENTIALLY VERY SERIOUS EXPTAL PROBLEM

A

Serious

Likely also affects V_{cb}

also on recoil τ likely problem

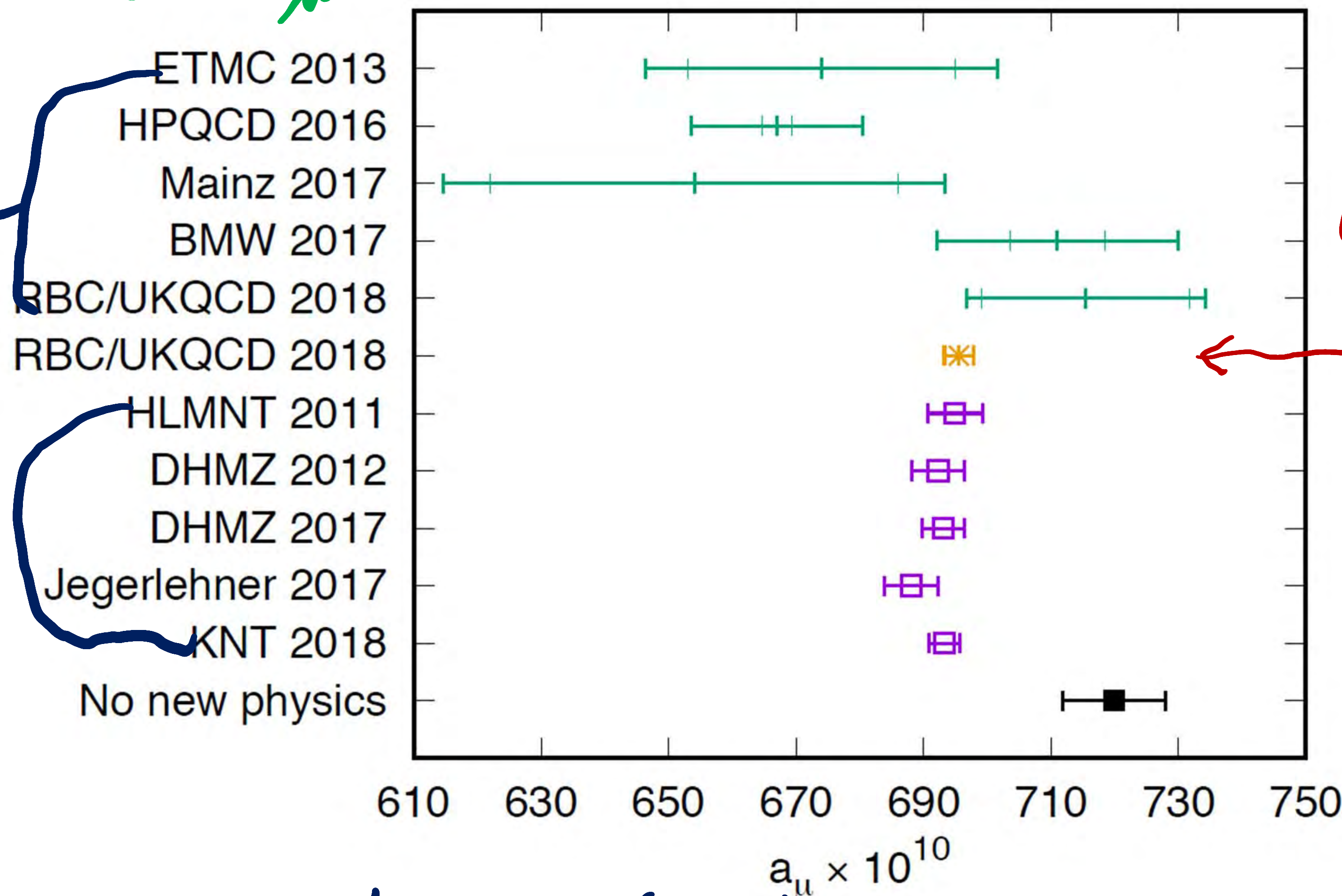
No Theory errors Because D^* has spin B

V LIKELY OVERESTIMATE

$(g-2)_\mu$ on + off the Lattice

PURE Lattice

Pheno



C Lehner et al RBC-UKQCD HYBRID

SUMMARY: C. LEHNER (BNL)

We need to improve the precision of our pure lattice result so that it can distinguish the "no new physics" results from the cluster of precise R-ratio results.

HET Lunch Seminar 03/09/18

Importance of the “IF”: score card

- Beta decay => Gf => W….
- Huge suppression of KL => mu mu; miniscule ΔmK=> charm
- KL =>2 pi but very rarely; mostly to 3pi =>CP violation => 3 families
- Largish Bd –mixing => large top mass
- etc…….
- => extremely unwise to put all eggs in HEF
- info from IF complementary to HEF can be a crucial guide for pointing to new thresholds as well as to provide important clues to the nature of the signals there from

Testing LUV in the era of Belle-II

- II. **On the lattice technical front, RBC-UKQCD collab**

has developed the methodology over the past ~6 years for calculating from 1st principles contributions from non-local operators

- **Here we illustrate this use in the simplest example that can have important phenomenological impact in light of larger data samples that will become available in the era of Belle-II**
- **The simplest illustrative reaction to display developments in the exptal and in the lattice front that we choose is M_hl =>** $\tau/\ell\, \nu\, \gamma$
- **Lets start with a very simple observation that LUV is very difficult to test with respectable accuracy via the simplest reaction**
- **Br** $B \to \tau\nu/\mu\nu$ **because the denominator suffers from severe helicity suppression. Indeed,**
- **Br[B+ =>mu+ nu] ~ 2 X 10^-7**
- **Note, however that naïve models seem to suggest** → Atwood, Eilam, AS hep-ph/9411367
- **Br [B => mu nu gamma]/Br[B=> mu nu] ~16**

$[B \Rightarrow e\nu\gamma]/[B \to e\nu] \sim 5\times 10^{5}$!!

Radiative leptonic decays of heavy-light mesons

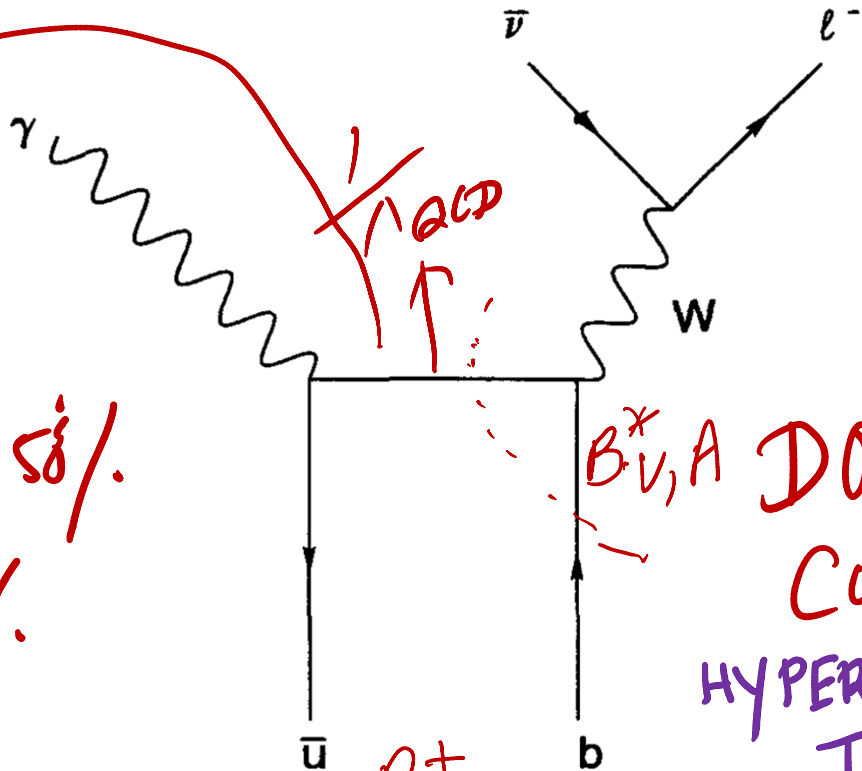


Fig. 1. Feynman graph for the dominant contribution to $B \to \ell\nu\gamma$.

Non-local [RBC-UKQCD]

$\Delta m_K \to$ Bigeng $\sim 5\%$

$\epsilon_K^{LD} \sim 5-10\%$

$K^+ \to \pi^+ \nu\bar{\nu}$ X_u $\sim 5-10\%$

$1/\Lambda_{QCD}$

B^+

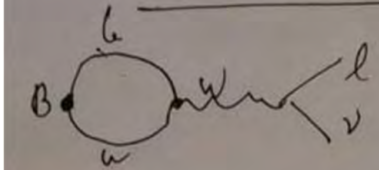
$B^*_{V,A}$ DOMINANT Contribution + ...

HYPERFINE Transition

c. also, AOKI + X. F + S.H . . . $\pi^0 \to 2\gamma$ PRL 2012

Essentially solvable approx model

Dim - Analysis



$$\Gamma_2 \sim \frac{G_F^2}{8\pi} m_B^2 f_B^2 m_\ell V_{ub}^2 \qquad \frac{m_\ell}{m_B} \to 0$$

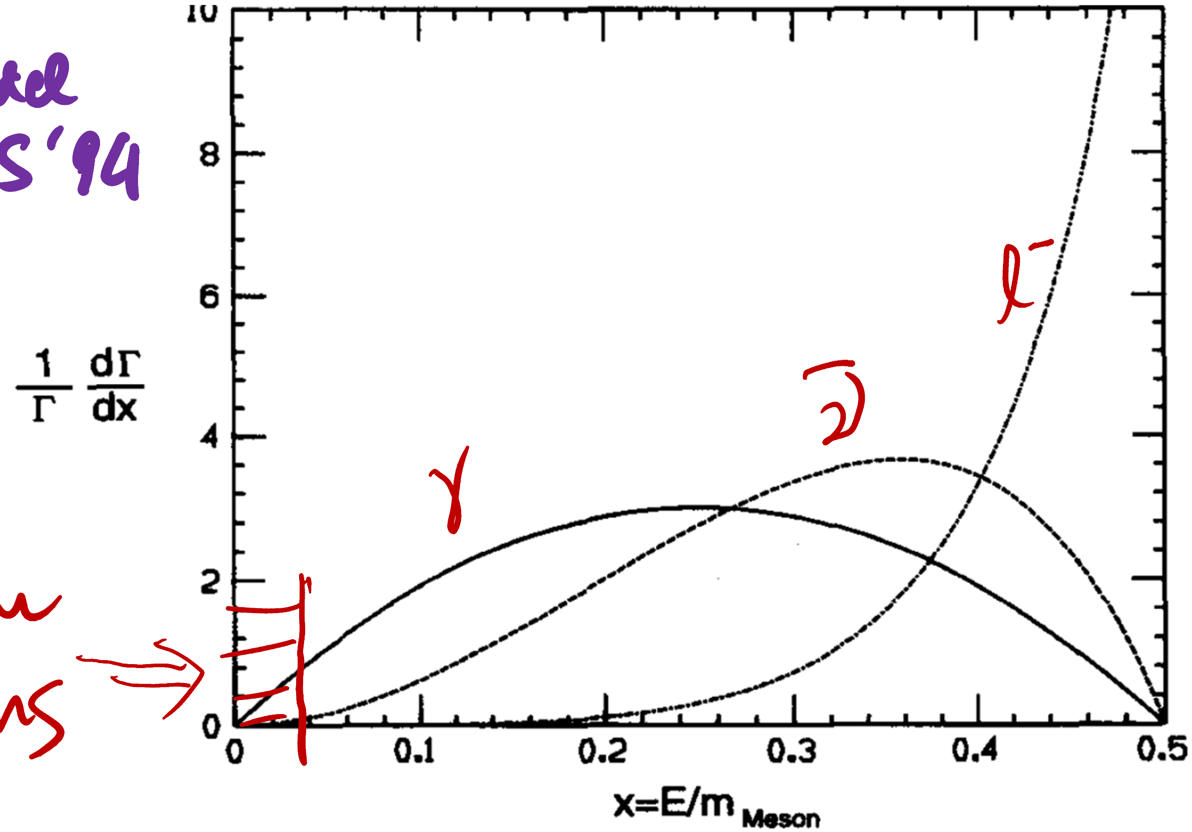
$$\Gamma_3 \sim \frac{G_F^2 m_B^3 f_B^2}{192\pi^3} \left(\frac{m_B}{\Lambda_{eff}}\right)^2 \alpha 4\pi V_{ub}^2$$

For $m_\ell = m_\mu$

$$\frac{\Gamma_3}{\Gamma_2} \sim \frac{\alpha}{\pi} \left(\frac{m_B}{m_\ell}\right)^2 \left(\frac{m_B}{\Lambda_{eff}}\right)^2 \frac{1}{48} \sim 15$$

Toy, s double model
Atwood, Eilam, AS '94

B^-



Stay away from soft photons

Fig. 2. $B \to \ell^- \bar{\nu} \gamma$ normalized energy spectra are shown. Solid line is for the photon energy, the dashed is for the neutrino energy (which is directly related to invariant mass of the electron–photon combination) and the dash-dot for the electron energy. For the case of $D_s \to \ell^+ \nu \gamma$ the dashed curve represents the neutrino energy spectrum while the dash-dot curve represents the lepton energy since in this case the roles of the lepton and neutrino are reversed.

D_s^+

The radiative leptonic B-meson decay amplitude[1]

$$A(B^- \to \gamma \ell \bar{\nu}_\ell) = \frac{G_F V_{ub}}{\sqrt{2}} \langle \ell \bar{\nu}_l \gamma | \bar{\ell} \gamma^\nu (1-\gamma_5) \nu_\ell \bar{u} \gamma_\nu (1-\gamma_5) b | B^- \rangle \tag{2.1}$$

can be written in terms of two form factors, F_V and F_A, defined through the Lorentz decomposition of the hadronic tensor

$$\begin{aligned} T_{\mu\nu}(p,q) &= -i \int d^4x \, e^{ipx} \langle 0 | T\{ j_\mu^{em}(x) \, \bar{u}(0) \gamma_\nu (1-\gamma_5) b(0) \} | B^-(p+q) \rangle \\ &= \epsilon_{\mu\nu\tau\rho} p^\tau v^\rho F_V + i \big[-g_{\mu\nu}(pv) + v_\mu p_\nu \big] F_A - i \frac{v_\mu v_\nu}{(pv)} f_B m_B + p_\mu\text{-terms} \,. \end{aligned} \tag{2.2}$$

Here p and q are the photon and lepton-pair momenta, respectively, so that $p + q = m_B v$ is the B-meson momentum in terms of its four-velocity. In the above $j^\mu_{\rm em} = \sum_q e_q \bar{q} \gamma_\mu q$ is the electromagnetic current. The $v_\mu v_\nu$ term is fixed by the Ward identity [9, 17]

$$p^\mu T_{\mu\nu} = -i f_B m_B v_\nu \tag{2.3}$$

Beneke et al
1804.04962
(also DESCOTES-GENON + CTS '03

μ_0	1 GeV		
$\Lambda^{(4)}_{\rm QCD}$	0.291552 GeV	$\alpha_s(\mu_0)$	0.348929
μ	(1.5 ± 0.5) GeV	μ_h	$m_b/2 \div 2m_b$
m_b	(4.8 ± 0.1) GeV	$\bar{\Lambda}$	$m_B - m_b$
λ_E^2/λ_H^2	0.5 ± 0.1	$2\lambda_E^2 + \lambda_H^2$	(0.25 ± 0.15) GeV^2
s_0	(1.5 ± 0.1) GeV^2	M^2	(1.25 ± 0.25) GeV^2
$\langle \bar{u}u \rangle(\mu_0)$	$-(240 \pm 15$ MeV$)^3$		
m_B	5.27929 GeV	m_ρ	0.77526 GeV
G_F	1.166378×10^{-5} GeV^{-2}	τ_B	$1.638 \times 10^{-12} s$
f_B	(192.0 ± 4.3) MeV [23]	$\lvert V_{ub} \rvert^{\rm excl}$	$(3.70 \pm 0.16) \times 10^{-3}$ [24]

Table 1. Central values and ranges of all parameters used in this study. The four-flavour $\Lambda_{\rm QCD}$ parameter corresponds to $\alpha_s(m_Z) = 0.1180$ with three-loop evolution and decoupling of the bottom quark at the scale m_b.

9 non-pert params!!
HUGE Buffalo!

Beneke et al
'2018

Amarjit Soni

BNL-HET

Lattice 2018 MSU 07/27/18

Based in part on
C. Lehner, S. Meinel + A. S
+ disc with Taku Izubuchi[WIP] ; RBC-UKQCD

Lattice efforts now in progress

On the lattice

2012

- On the lattice this calculation of B^+ [Ds^-]=>l ν γ is rather similar to π^0 => 2 γ [see Xu Feng et al, PRL] and to RBC-UKQCD recent attempts at LBL contribution to muon g-2 via the π^0 exch.*
- Except now 1 photon gets replaced by the V, A

[heavy –light states] which dominate the transition to the final l + nu [w/o helicity suppression]

- The dominant graph is when the light quark emits the photon, though of course [QED] gauge invariance requires emission from all charged legs.
- The emission of photon off the charged lepton will be helicity suppressed so it will also be an important contributor when emitted from tau
- The details of Minkowski-Euclidean connection closely follow pi^0 => 2 gamma with appropriate changes

* c also X d Ji + C w Jung PRL '01

$$M_{\mu\nu}^{\mathrm{mink}}(p_1, p_2) = i \int d^4x e^{ip_1x} \langle 0 | T\{j_\mu(x) j_\nu(0)\} | \pi^0(q) \rangle \tag{1}$$

EMC

CL NOTES

$$= \varepsilon_{\mu\nu\alpha\beta} p_1^\alpha p_2^\beta \mathcal{F}_{\pi\gamma\gamma}(m_\pi^2, p_1^2, p_2^2) \tag{2}$$

$p_1 = (\omega, \vec{p}_1)$

$q = [E_{\pi,\vec{q}}, \vec{q}]$; $E_\pi^2 = m_\pi^2 + \vec{q}^{\,2}$

$p_2 = [E_{\pi,\vec{q}} - \omega, \vec{q} - \vec{p}_1]$

$$M_{\mu\nu}^{\mathrm{mink}}(p_1, p_2) = i \int d^3x e^{-i\tilde{p}_1\tilde{x}} \left[\sum_n \int_{-\infty}^{0} dt e^{i(\omega + \tilde{E}_n - i\varepsilon)t} \langle 0 | j_\nu(0) | n \rangle \langle n | j_\mu(\tilde{x}) | \pi^0(q) \rangle \right.$$
$$\left. + \sum_n \int_0^\infty dt e^{i(\omega - E_n + i\varepsilon)t} \langle 0 | j_\mu(\tilde{x}) | n \rangle \langle n | j_\nu(0) | \pi^0(q) \rangle \right] \tag{7}$$
$$= \sum_n \frac{1}{\tilde{E}_n + \omega} \langle 0 | j_\nu(0) | n \rangle \langle n | j_\mu(-\tilde{p}_1) | \pi^0(q) \rangle$$
$$+ \sum_n \frac{1}{E_n - \omega} \langle 0 | j_\mu(-\tilde{p}_1) | n \rangle \langle n | j_\nu(0) | \pi^0(q) \rangle . \tag{8}$$

with $j_\mu(t, \tilde{x}) = e^{iHt} j_\mu(\tilde{x}) e^{-iHt}$, $\tilde{E}_n = E_n - E_{\pi,\tilde{q}}$, $H|n\rangle = E_n|n\rangle$, and

$$j_\mu(\tilde{p}) \equiv \int d^3x e^{i\tilde{p}\tilde{x}} j_\mu(\tilde{x}) . \tag{9}$$

$$M^{eucl}_{\mu\nu}(p_1, p_2) = \int d^3x e^{-i\tilde{p}_1\tilde{x}} \int dt e^{\omega t}\langle 0|T\{j_\mu(\tilde{x}, t)j_\nu(0)\}|\pi^0(q)\rangle \tag{10}$$

$$= \sum_n \int_{-\infty}^{0} dt e^{(\omega+\tilde{E}_n)t}\langle 0|j_\nu(0)|n\rangle\langle n|j_\mu(-\tilde{p}_1)|\pi^0(q)\rangle$$

$$+ \sum_n \int_{0}^{\infty} dt e^{(\omega-E_n)t}\langle 0|j_\mu(-\tilde{p}_1)|n\rangle\langle n|j_\nu(0)|\pi^0(q)\rangle \tag{11}$$

$$= \sum_n \frac{1}{\tilde{E}_n + \omega}\langle 0|j_\nu(0)|n\rangle\langle n|j_\mu(-\tilde{p}_1)|\pi^0(q)\rangle$$

$$+ \sum_n \frac{1}{E_n - \omega}\langle 0|j_\mu(-\tilde{p}_1)|n\rangle\langle n|j_\nu(0)|\pi^0(q)\rangle\,, \tag{12}$$

with Euclidean $j_\mu(t, \tilde{x}) = e^{Ht}j_\mu(\tilde{x})e^{-Ht}$ and where both integrals converge as long as $-\tilde{E}_n < \omega < E_n$. With this restriction of domain of ω, we can therefore relate Minkowski and Euclidean space

$$M^{mink} = M^{eucl}\,. \tag{13}$$

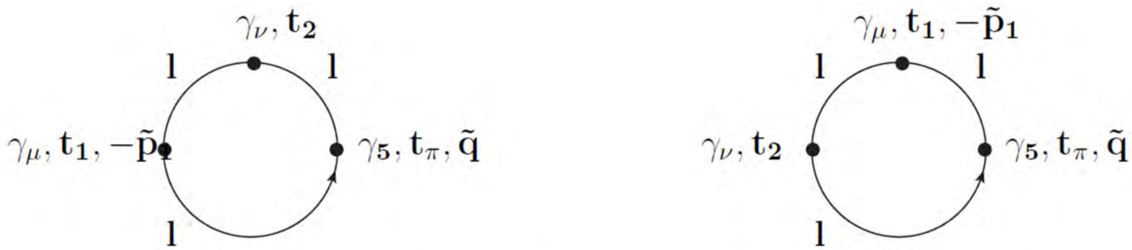


Figure 1: $\pi^0 \to \gamma\gamma$ diagram A (left) and B (right). There are additional disconnected diagrams not yet drawn here.

$$T_{\mu\nu} = -i \int d^4x e^{iPx} \langle 0 | T\{j_\mu(x) j_\nu^W(0)\} | B^-(P+Q) \rangle \qquad (19)$$

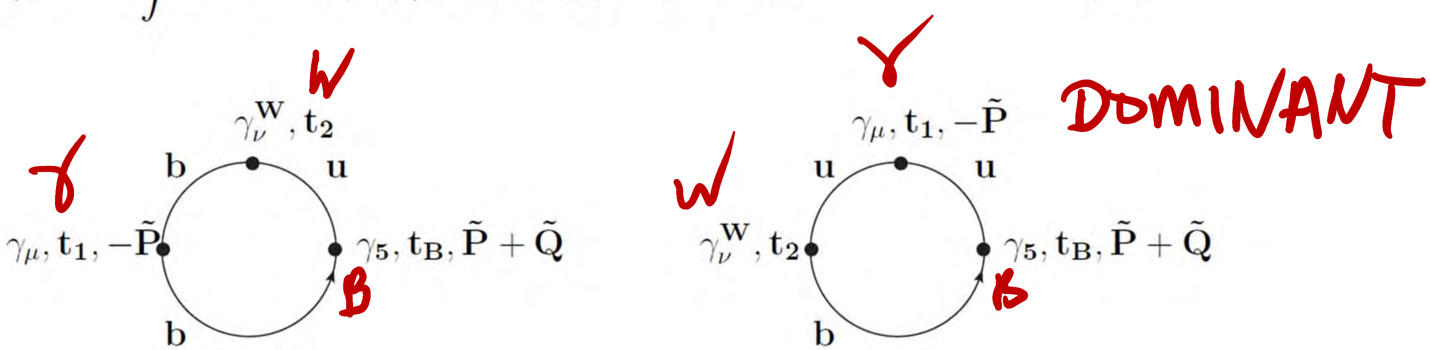
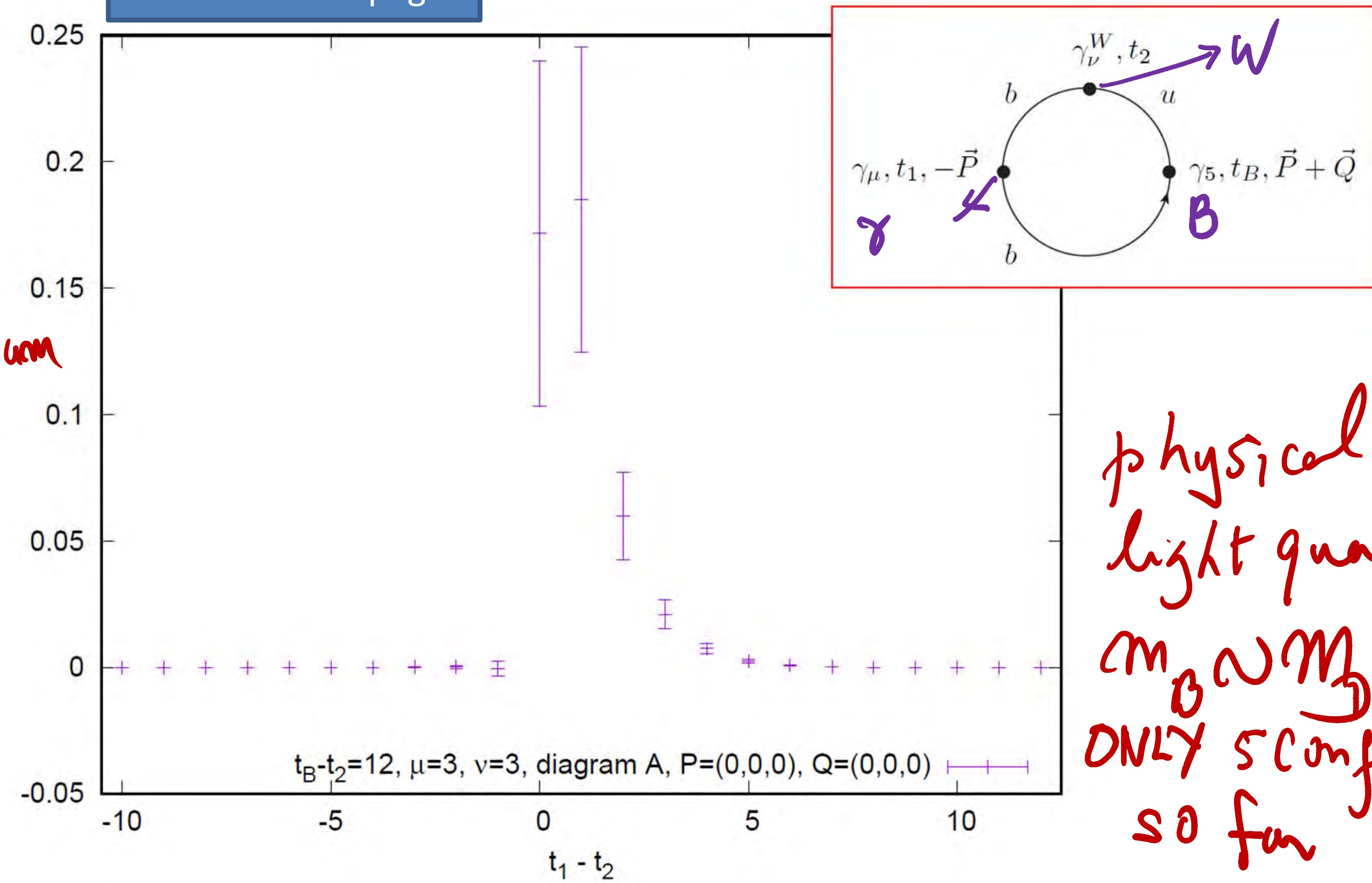


Figure 3: Radiative leptonic B decay diagram A (left) and B (right). There are additional disconnected diagrams not yet drawn here.

C some lattice
Details in back pages



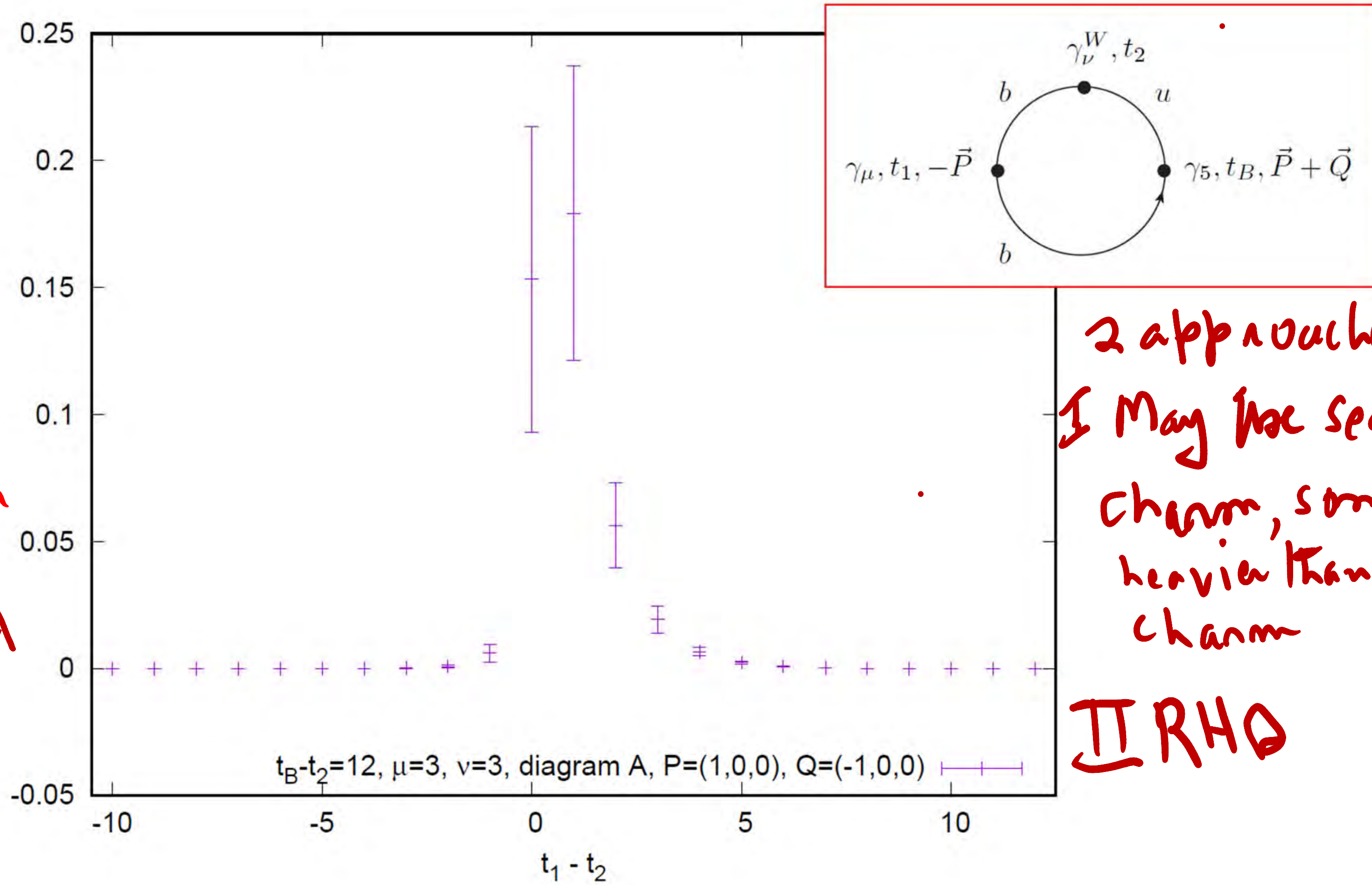
0 Momentum

diagram A b quark emits γ

physical light quarks $m_B \sim m_D$; ONLY 5 configs so far

Show $\sum_{\vec{x}} e^{-i\vec{p}_1\vec{x}} \langle 0| T\{j_\mu(\vec{x}, t_1) j_\nu^W(\vec{0}, t_2)\} |B^-(P+Q)\rangle$ for $m_\pi = 139$ MeV, $m_B \approx m_D$, $a^{-1} = 1.73$ GeV; MDWF, $M_5 = 1.4$, $b = 1.75$, $c = 0.25$

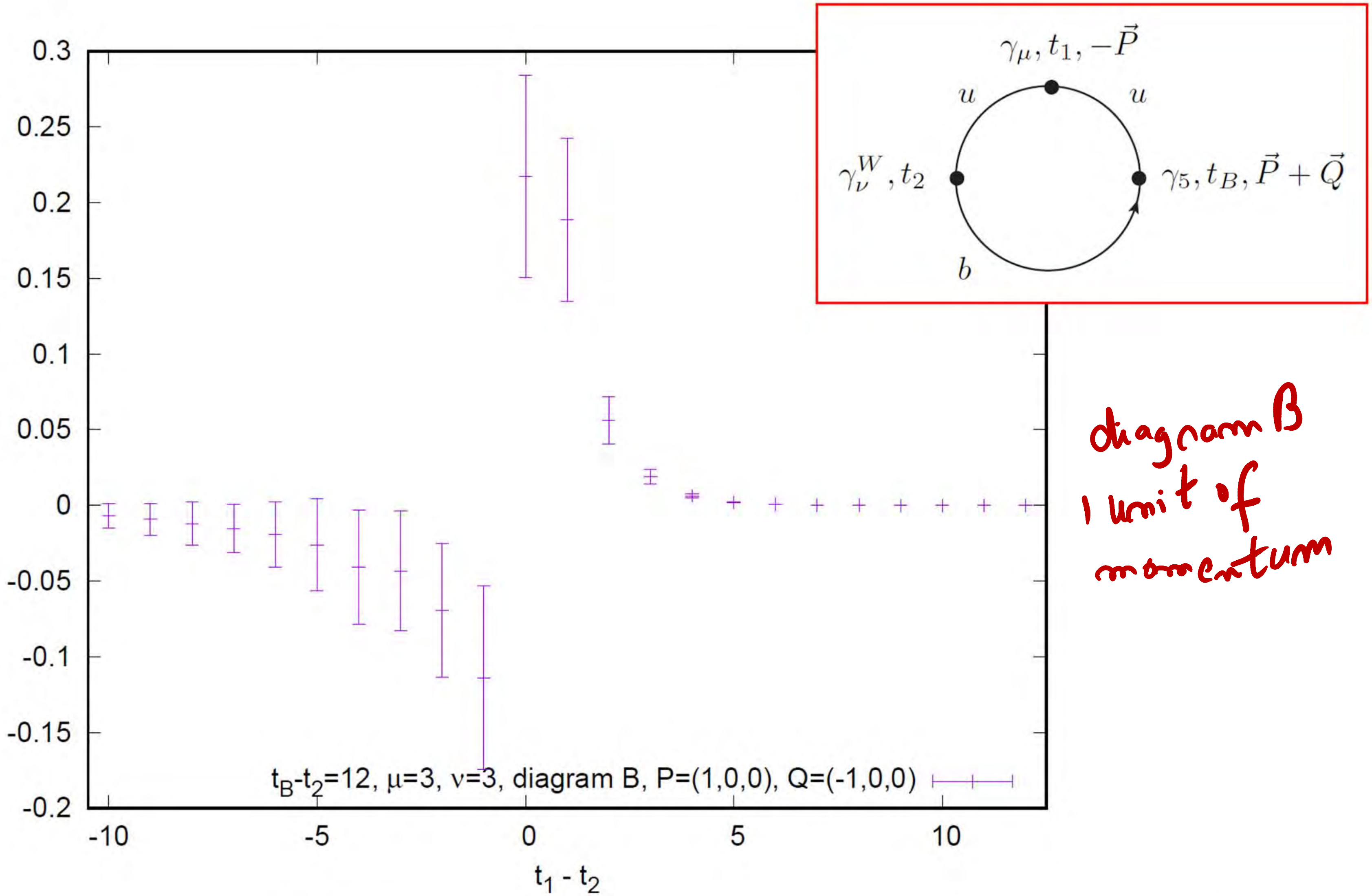
$48^3 \times 96$



1 unit of momentum ~210 MeV
diagram A

2 approaches
I May use seq of charm, some heavier than phys charm
II RHQ

Show $\sum_{\vec{x}} e^{-i\vec{p}_1\vec{x}}\langle 0|\, T\{j_\mu(\vec{x}, t_1) j_\nu^W(\vec{0}, t_2)\}|B^-(P+Q)\rangle$ for $m_\pi = 139$ MeV, $m_B \approx m_D$, $a^{-1} = 1.73$ GeV



Show $\sum_{\vec{x}} e^{-i\vec{p}_1\vec{x}} \langle 0| T\{j_\mu(\vec{x}, t_1) j_\nu^W(\vec{0}, t_2)\} |B^-(P+Q)\rangle$ for $m_\pi = 139$ MeV, $m_B \approx m_D$, $a^{-1} = 1.73$ GeV

CL
10/28/18

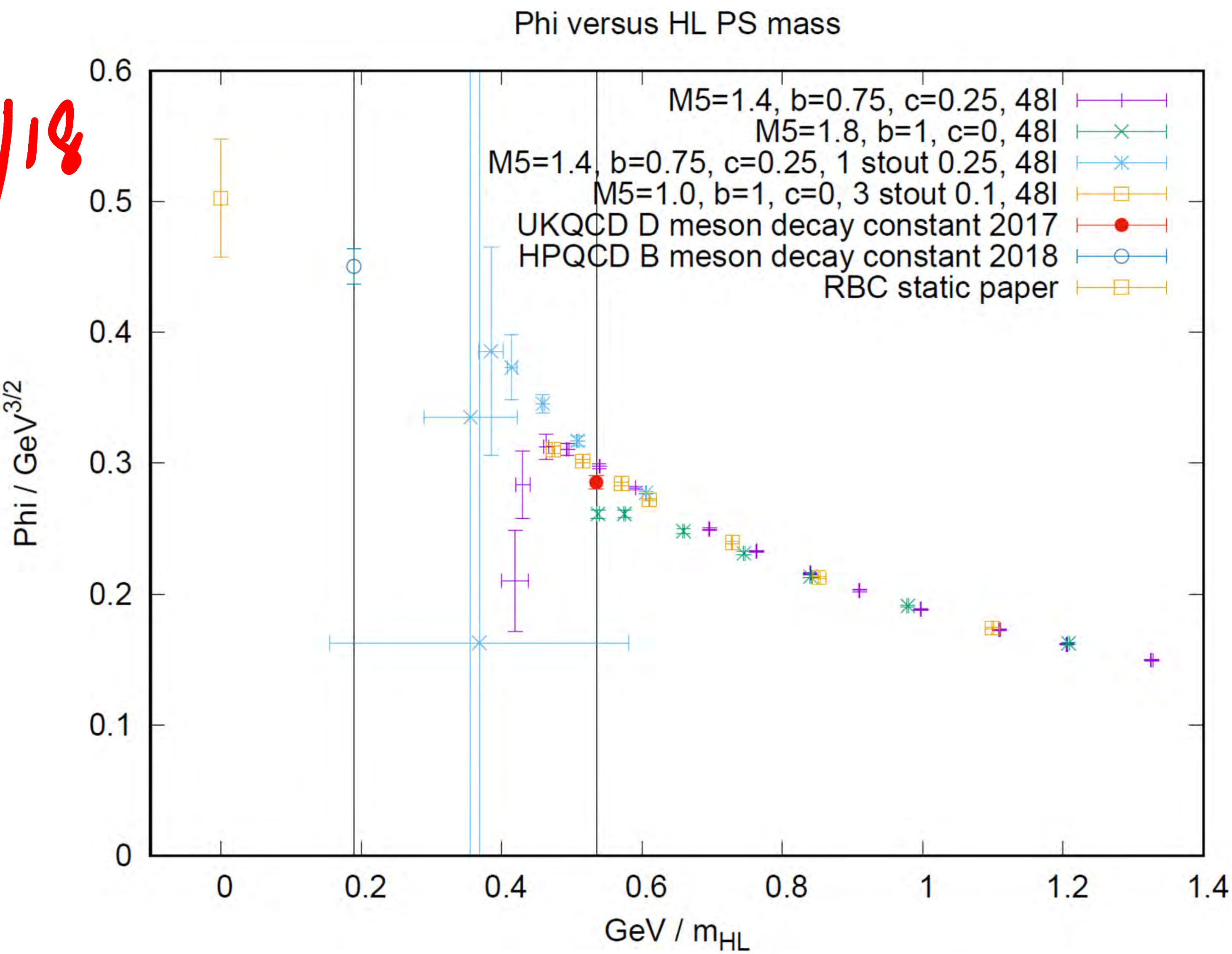


Figure 4: Decay constants versus heavy-light pseudoscalar mass with several heavy-quark formulations.

WE HOPE TO HAVE RESULTS OF 1^{ST} CALCULATION OF L NU GAMMA AS A FUNCTION OF PHOTON ENERGY IN THE NEAR FUTURE

Possible new physics opportunities in tau's

Ack: preliminary lattice discussions with local [RBC-UKQCD] Bruno, Izubuchi, Lehner and Meyer;

+ pheno. Passemar

[NO LATTICE RESULTS YET]

motivation

- **Huge increase in fluxes of tau's=>monitor tau closely**
- **Rather serious several anomalies => NP esp 3rd family => also BSM-CP**
- **Charge current: tau is the central character**
- **A very interesting special case: tau => nu Ks pi+**
- **Lattice can calculate rather precisely**
- **Moreover, Babar claimed [BSM]CP**
- **Most models for anomalies imply LFV in tau and in B-decays**

LQ Revival Circa 2018

"Ingenious w/ G/F"

Are There Anomalous Lepton-Hadron Interactions?

Jogesh C. Pati*
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

and

Abdus Salam
International Centre for Theoretical Physics, Trieste, Italy, and Imperial College, London, England
(Received 5 February 1974)

Severely constrained by $\pi^0 \to e^+e^-$, $K_L \to \mu e$!

Anomaly ~1973/74

It is remarked that the recently observed near constancy of $\sigma(e^+e^- \to \text{hadrons})$ over a large range of center-of-mass energy may reflect the presence of a new class of short-range lepton-hadron interactions. This can be tested by a comparison of e^-p versus e^+p scatterings and a study of the spin, parity, and charge conjugation of the final product in annihilation as well as apparent deviations from scaling in $e^{\pm}p$ and $\mu^{\pm}p$ scatterings.

Recent experimental studies[1] of the electron-positron-annihilation cross section into hadrons $[\sigma_h(s)]$ as a function of s, the square of the total center-of-mass energy, seem to reveal a remarkable feature—that it is nearly constant at about 25–30 nb (within 30%) from $s \simeq 9$ to $s \simeq 25$ [in units of $(\text{BeV})^2$]. On the other hand, $\sigma(e^+e^- \to \mu^+\mu^-) \equiv \sigma_\mu(s)$ appears to fall according to the quantum-electrodynamic (QED) s^{-1} law. The near "constancy" of $\sigma_h(s)$ over such a wide region of s does not seem to obtain a simple explanation in terms of the familiar one-photon mechanism.[2] We consider in this note an alternative explanation for the behavior of $\sigma_h(s)$ based on a new class of short-range lepton-hadron interactions (leading to process such as $e^-e^+ \to q\bar{q}$, etc.) which may arise within the class of gauge schemes[3] proposed by us earlier, and point out that this leads to a variety of testable predictions; these should enable one to distinguish our explanation from all others based on the one-photon mechanism.[4]

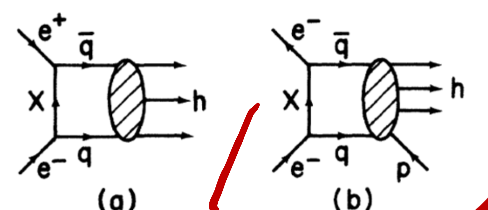
heavy exotic[6] spin-1 mesons X (with nonzero baryon and lepton numbers) coupled to electron-quark (and possibly also to muon-quark[7]) currents as follows:

$$\mathfrak{L}^X = f(\bar{e}\gamma_\mu q)X_\mu + \text{H.c.} \quad (1)$$

There could, of course, be a triplet of X's corresponding to three baryonic colors. It is possible that there are vector and axial-vector mesons X_V and X_A coupled to currents $\bar{e}\gamma_\mu q$ and $\bar{e}\gamma_\mu\gamma_5 q$ with strengths f_V and f_A, respectively. For the present, we need not specify the $(\mathcal{P}, \mathfrak{N}, \lambda)$ indices of q.

Let us assume that the effective low-energy

c, τ Revol '74

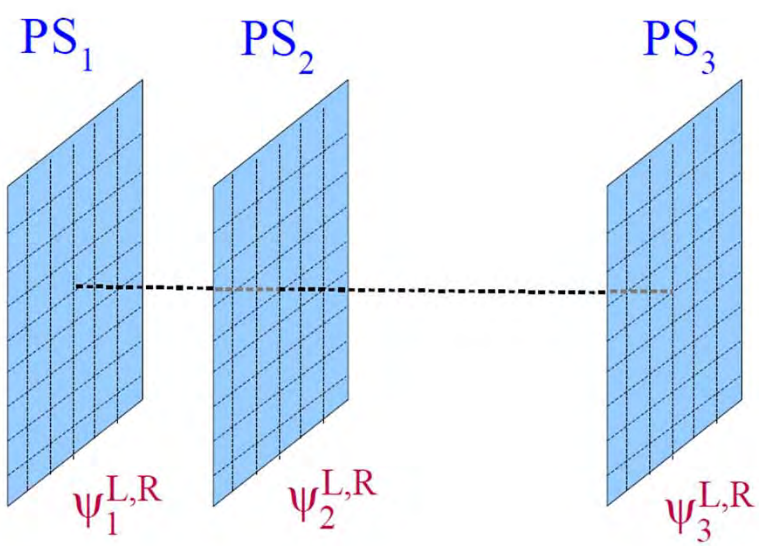


SALAMIONS

LQs: New Game in town

See also Fajfer et al, Gherghetta et al + many more

My (*currently*) favorite UV completion

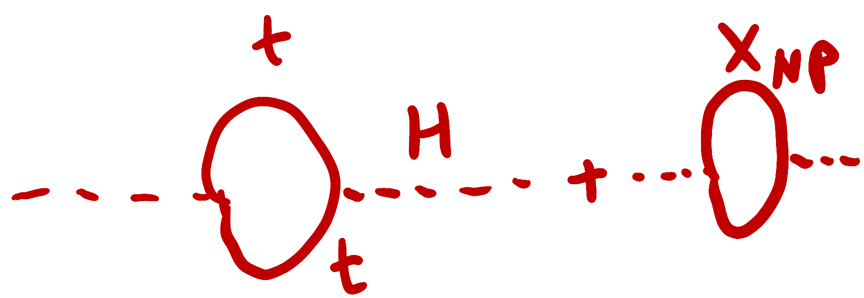


RPV_3

Altmannshoff, Dev, AS

- **ASSUMING the anomaly is REAL & HERE TO STAY [BIG ASSUMPTION due to caveats mentioned]**
- **Anomaly involves simple tree-level semi-leptonic decays**
- **Also b => tau (3rd family)**
- **Speculate: May be related to Higgs naturalness**
- **Seek minimal solution: perhaps 3rd family super-partners(a lot) lighter than other 2 gens > proton decay concerns may not be relevant=> RPV ["natural" SUSY]**
- **RPV natural setting for LUV …can accommodate g-2 and eps' if needs be**
- **Collider signals tend to get a lot harder than (usual-RPC) SUSY**
- **RPV makes leptoquarks natural**
- **Moreover, RPV should be viewed as an umbrella i.e. under appropriate limits other models are incorporated**

$m_H \lesssim 126$ GeV



RPV$_3$ preserves gauge coupling unification irrespective of # of effective gens. 1, 2 or 3.

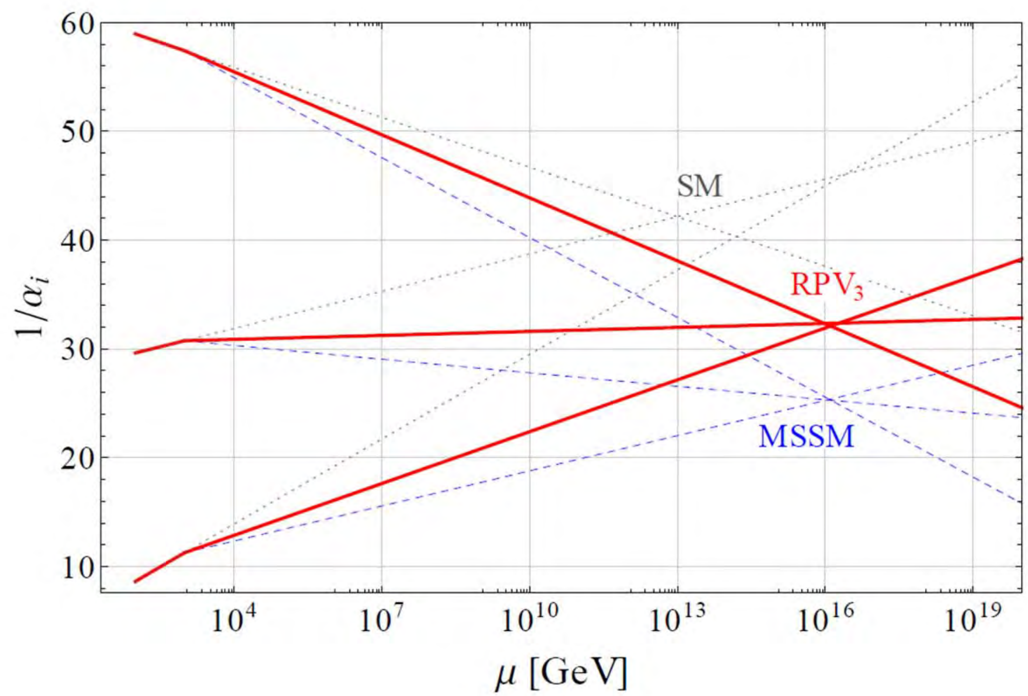
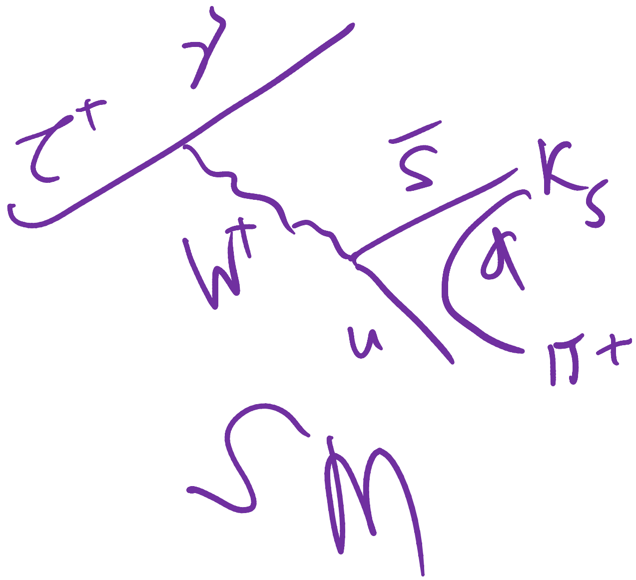
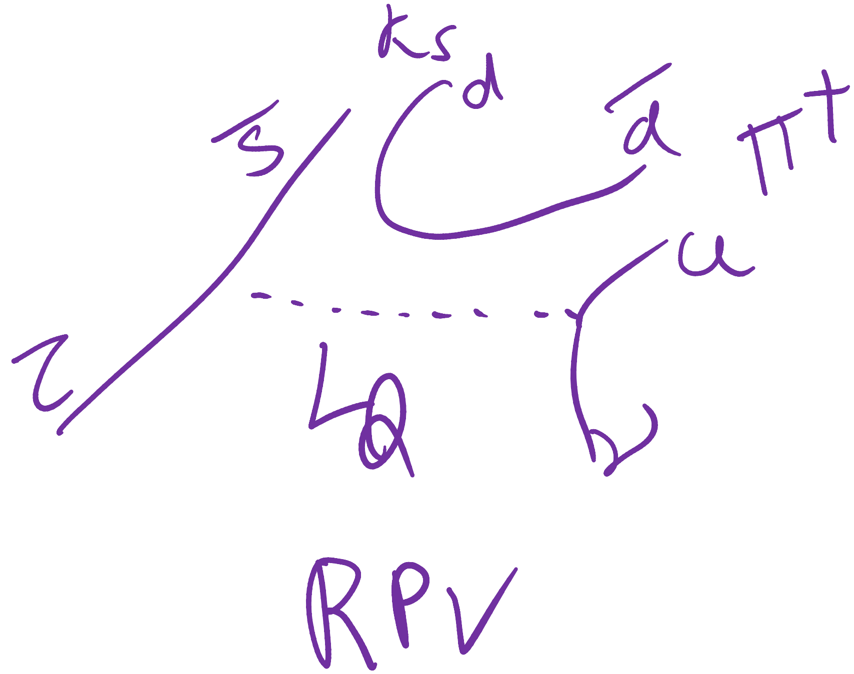


FIG. 2. RG evolution of the gauge couplings in the SM, MSSM and with partial supersymmetrization.

Unification scale ~ stays same, only value of couplings shifts

Possible NP in tau=> Ks pi nu





See Altmannshofer, Dev + AS [ADS']
1704.06659

(BABAR Collaboration)

Great for BELLE-II & STCF

PHYSICAL REVIEW D **85,** 031102(R) (2012)

Search for *CP* violation in the decay $\tau^- \to \pi^- K_s^0(\geq 0\pi^0)\nu_\tau$

Asy $\sim -4\times10^{-3}$

(Received 9 September 2011; published 13 February 2012)

We report a search for *CP* violation in the decay $\tau^- \to \pi^- K_S^0(\geq 0\pi^0)\nu_\tau$ using a data set of 437×10^6 τ-lepton pairs, corresponding to an integrated luminosity of 476 fb^{-1}, collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage rings. The *CP*-violating decay-rate asymmetry is determined to be $(-0.36 \pm 0.23 \pm 0.11)\%$ approximately 2.8 standard deviations from the standard model prediction of $(0.36 \pm 0.01)\%$.

NOTE $Br[\tau \to \nu \pi^- \bar{K}^0] = (8.40 \pm .14) \times 10^{-3}$ $\sim 2\%$

$N_\tau \sim 10^9$ needed

3 g & New Physics

- How can we use the non-perturbative set-up of the lattice to look for clues?
- t, b, tau, nu_tau
- Suitable targets b and tau
- Because of its mass b is often a challenge though progress is constantly being made
- tau is the BEST: lattice has no excuses
- Lattice can check that every aspect of tau agrees (or not wth SM)

gave 1 simple example;
MORE to COME

tau => Ks pi^- nu on and off the lattice

- tau plays a central role in indications of LUV from semi-leptonic charge current RD(*) anomaly
- If these indications of new physics become a reality, then naturalness arguments strongly suggest the new physics will entail also a new

CP-odd phase.

tau => Ks pi^+ nu is an excellent final state for experimental study and a good candidate for BSM phase or not

$\tau \to \nu K^- \rho^0$ Also very good

Can test for BSM via CP-conserving observables

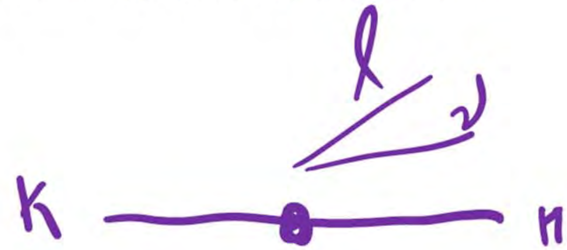
- **Select a FS where [CP conserving observables] like rate or differential distributions can be calculated precisely…**

- **A good example is tau => Ks pi^+ nu total or partial rate, or Ks pi invariant mass distribution; in the SM this can be calculated PRECISELY using lattice [and to some extent off the lattice methodology]**

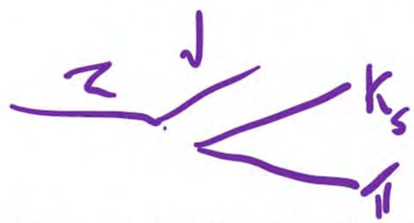
There is an interesting Crossing-Symmetry connection between the K=> pi semi-leptonic [Kl3] form factors and tau => nu Ks pi^+ ....~~by exploiting flavor SU3~~. For Kl3

Analogous to K_{l3}

$\langle K | J_\mu^{W,S} | \pi \rangle$



q^2 [with q= p_K – p_pi], q^2 >~ 0 is positive, while in the decay amplitude relevant to tau => nu Ks pi, Q^2 [with Q = p_K + p_pi], Q^2 > ~0, is positive.



But Complex amplitude

Need Kπ scattering phase

In the tau decay calculation, final-state interaction phase enters and it'd be very interesting if this complex amplitude can be calculated on the lattice.

It'd also be very useful to study the case when pi^+ can be replaced with rho^+, if possible.

Strong [i.e. CP-conserving] FS interaction phases

- **We can calculate these phases on the lattice**

for K, pi scattering see RBC-UKQCD [exploratory for K-pi; see T.Janowski et al, Lattice 2014]

and also now for pi pi

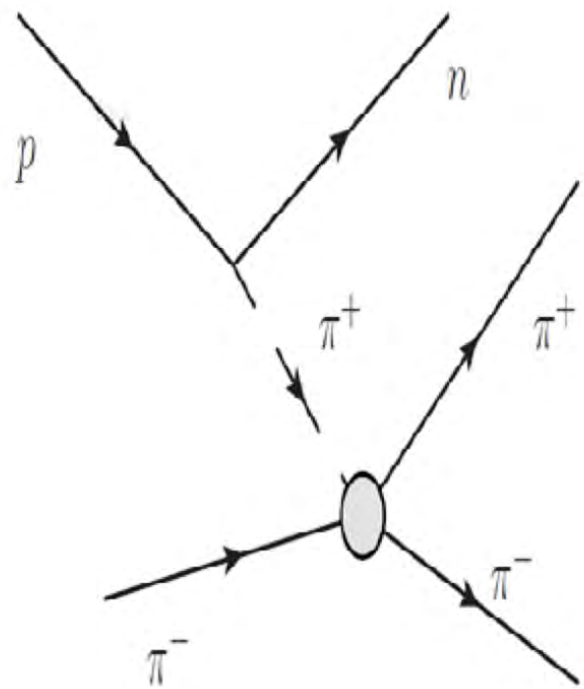
Tianle Wang [RBC-UKQCD]

Talk @ Lattice 2018

→ M. Bruno

However, for an approximate result flavor SU(3) can also be used to relate them to pi pi scattering phases from Kl4 and from pi N => N pi pi following Colangelo et al…..get K pi phases upto SU(3) corrections

- **T.W. talk at Lattice 2018 shows pi pi I=0 phases in good agreement with Colangelo**



Data ~1GeV

See G. Colangelo et al ; M. Bruno

WIP ON AND OFF THE LATTICE ON THIS CLASS OF STUDY

Summary + Outlook [2 pages]

- **Lattice methods are now quite advanced and are now becoming a powerful tool for searching new physics**
- **A very sensitive observable for this search is ε′:**

The direct CP violation parameter for K=>ππ. First (2015) complete calculation by our RBC-UKQCD collab with limited stats found consistency with experiment at about 2 σ…Analysis with ~6.5 more stats is now underway and is expected to complete in a few months and is eagerly awaited.

- **Can now also calculate non-local [long-distance] matrix elements…1st target ΔmK well underway and soon will become another observable for testing SM and NP**

Summary + Outlook (p.2)

- Thanks to Belle-II + LHCb Runs/upgrade(s) anticipated vast increase in data samples of

b, c, tau + new lattice [esp NLME] techniques etc motivate using lattice for addressing additional observables

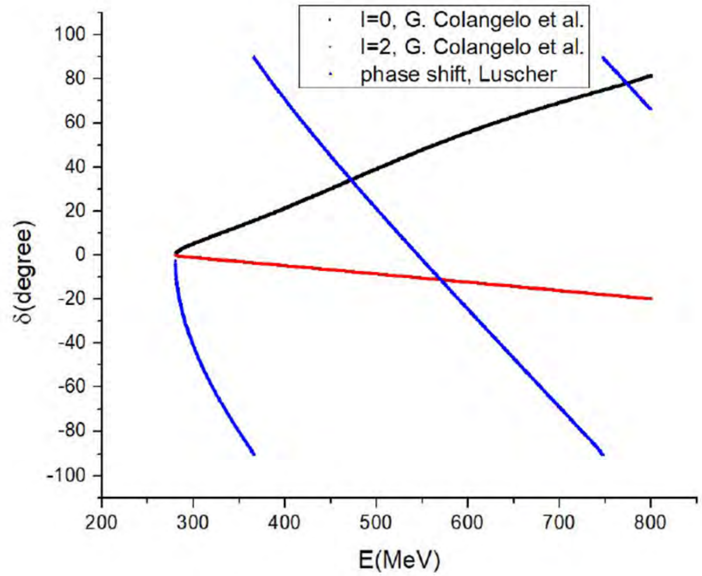
- To start out two simple examples: b => l nu gamma, possible applications to LFU/CP; hopefully 1st lattice results within some months; tau =>Ks pi nu, test SM…..WIP
- Hope all these lattice efforts, in conjunction with experiments will soon result in 1st compelling sightings of new physics.

XTRAS

Dispersion

- Schenk's ansatz
  $$tan\delta_I = \sqrt{1-\frac{4M_\pi^2}{s}}(A_I + B_I q^2 + C_I q^4 + D_I q^6)(\frac{4M_\pi^2 - s_I}{s - s_I})$$
- Luscher's formula (GPBC)
  $$tan\delta = \frac{\pi^{3/2}\sqrt{\bar{m}}}{Z_{00}^{0,G}(1,\bar{m})}$$

Tianle Wang
@LAT18



S wave phase shift and Luscher's formula.[1]

[1] G. Colangelo, Nuclear Physics B 603 (2001) 125 - 179

Extracting Spectra from Correlation Functions

Dan Hoying LAT'18

We can define a generalized eigenvalue problem (GEVP) from an NxN matrix of correlators we compute on the lattice

$$C_{ij} \equiv \left\langle 0 | \hat{O}_i(t) \hat{O}(0)_j^\dagger | 0 \right\rangle = \sum_{n=1}^{\infty} \left(e^{-E_n t} + e^{-E_n(L_t-(t-t_0))} \right) \psi_{ni} \psi_{nj}^*$$

$$\psi_{ni}^* = \left\langle 0 | \hat{O}_i | n \right\rangle$$

$$\Rightarrow C(t) v_n(t, t_0) = \lambda_n(t, t_0) C(t_0) v_n(t, t_0)$$

$$\lambda_n(t, t_0) = e^{-E_n(t-t_0)} + e^{-E_n(L_t-(t-t_0))}$$

Important points:

- Systematic error in nth energy state: $\epsilon_n \sim e^{-(E_{N+1}-E_n)t}$ if $t_0 \geq t/2$[2]

Extracting Spectra (cont'd)

Dan Hoying @ LAT'18

- Operator basis is composed of single particle operators $\overline{q}q$, $\overline{q}\gamma_\mu q$ and two particle operator $\overline{q}\gamma_5 q$, with various momentum combinations and non-zero $\vec{p}_{CM}$ up to $\pm(1,1,1)$.
- Operators are projected onto A_1 irrep and definite isospin $(0,1,2)$.
- t_0 is arbitrary, we fix it to be either $\left\lceil \frac{t}{2} \right\rceil$ or $t-1$ (if later times aren't very noisy)
- GEVP also exists for matrix elements [3]. We plan to use this for $K \to \pi\pi$.

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……**

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	BG/Q ~ 100TF@BNL;	

HUGE # of OBSTACLES HAD to be overcome

~2006

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

$$m_{\Xi}^{\text{latt}} = m_{\Xi}^{\text{phys}} \longrightarrow a$$

$$M_{\pi}^{\text{latt}}/m_{\Xi}^{\text{latt}} = M_{\pi}^{\text{phys}}/m_{\Xi}^{\text{phys}} \longrightarrow m_u(a) \approx m_d(a)$$

$$\cdots$$

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 ($M_\pi \lesssim 200$ 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.

Contrarian/Complementary view

- **flavor physics is actually hanging by perhaps the weakest link i.e. a single CP-phase endowed by the 3g –SM.**
- **[This is infact my rationale for going after eps' for over 35 continuous years and the effort is sill continuing]**
- **In many ways this is a contrarian (or complementary) point of view, in sharp contrast to the overwhelming majority following the naturalness lamp post via Higgs radiative stability.**
- **In this context it is useful to stress**
- **We hold these truths to be self-evident…**

BSM-CP searches…2 illustrative examples

- **The presence of the tau [its decays are self-analyzers of its spin] provides a powerful tool in tau/l nu gamma FS….**
- **Both Tn even [say photon energy and rates, differential or integrated, …] and Tn-odd [tau polarization say transverse]**
- **Accurate calculation of photon energy specrum may be also useful for this CP test**

K→2π ChPT   With DWQ in Quench Approx

PHYSICAL REVIEW D 68, 114506 (2003)

1st application of BDSPW'84 with DWQ

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

K→2π & ε'/ε "Flagship Project" Now ~20 yrs!

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

1st Large Scale Simulation with DWQ

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 $(-4.0\pm2.3)\times10^{-4}$ (statistical error only) compared to the current experimental average of $(17.2\pm1.8)\times10^{-4}$. 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 $B_{K,\overline{MS}}(2\text{ GeV})=0.532(11)$. 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.

RBC Collaboration   QCDSP ~98→~'05 1TF

Led to an important development: For the 1st time NPR Of Delta S=1 Heff for I=0 due DWF

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)
$\mathrm{Re}\, A_0$(GeV)	3.33×10^{-7}	$(2.96 \pm 0.17) \times 10^{-7}$
$\mathrm{Re}\, A_2$(GeV)	1.50×10^{-8}	$(1.172 \pm 0.053) \times 10^{-8}$
ω^{-1}	22.2	(25.3 ± 1.8)
$\mathrm{Re}(\epsilon'/\epsilon)$	$(15.3 \pm 2.6) \times 10^{-4}$(NA 48)	$(-4.0 \pm 2.3) \times 10^{-4}$
	$(20.7 \pm 2.8) \times 10^{-4}$(KTEV)	

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

Quench approx

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

Q_6 gets unphysical contribution fr Q_8

(8,1) (8,8)

Full QCD But ChPT a la BDSPW

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

Conclusion

Quantity	This analysis	Quenched	Experiment
$\mathrm{Re}A_0$ (GeV)	$4.5(11)(53)\times10^{-7}$	$2.96(17)\times10^{-7}$	3.33×10^{-7}
$\mathrm{Re}A_2$ (GeV)	$8.57(99)(300)\times10^{-9}$	$1.172(53)\times10^{-8}$	1.50×10^{-8}
$\mathrm{Im}A_0$ (GeV)	$-6.5(18)(77)\times10^{-11}$	$-2.35(40)\times10^{-11}$	
$\mathrm{Im}A_2$ (GeV)	$-7.9(16)(39)\times10^{-13}$	$-1.264(72)\times10^{-12}$	
$1/\omega$	50(13)(62)	25.3(1.8)	**22.2**
$\mathrm{Re}(\epsilon'/\epsilon)$	$7.6(68)(256)\times10^{-4}$	$-4.0(2.3)\times10^{-4}$	1.65×10^{-3}

- 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.)

[m_M too large for ChPT... HINDSIGHT]

LARGE SYSTEMATIC errors DUE ChPT

Lattice N. Christ @LAT08

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!

Improvements in lattice ε' determination underway for past ~3 years

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

Radiative leptonic decays of heavy-light mesons

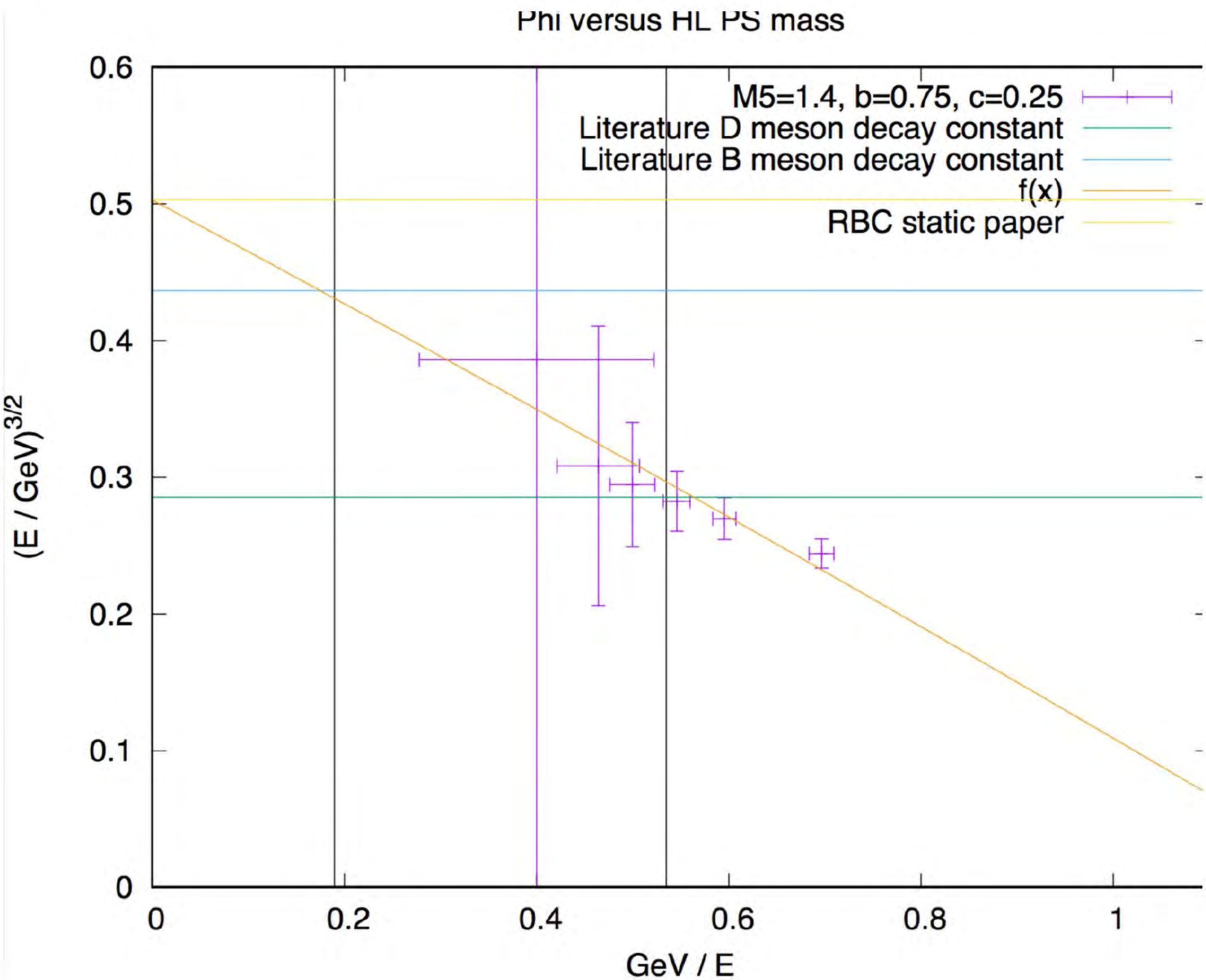
- **These are distinctly 3-body final state not to be confused with soft photons that necessarily accompany physical processes and their treatment is strictly linked to detector resolution….also typically these are brehmms with steeply falling spectrum**

GM+ CTS et al

- **In contrast, final state such as Ds, B+ => l nu gamma that are emphasized here are strictly 3-body FS distinct from pure leptonic decays l + nu. The importance of these 3-body FS has been stressed due to their ability to overcome helicity suppression via hyperfine transitions**
- **To get a clear intutive understanding it may help to think in terms of a soluble but approx model based on naïve quark model ideas. [though from the outset one recognizes its limitation in accuracy esp for a heavy-light system]**
- **In that naïve picture, one can resort to the Weisskopf-Van Royen text book approx and clearly identify the underlying physical processes:**

Useful refs

- A: 1803.05881
- B) 1806.06997; 1806.09853


Phi versus HL PS mass
M5=1.4, b=0.75, c=0.25
Literature D meson decay constant
Literature B meson decay constant
f(x)
RBC static paper
(E / GeV)^3/2
0.6
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1
GeV / E

Bit on operator renorm.

Operator renormalization for heavy-light case: either use unmixed action with heavy quarks using M5=1.8 Mobius, or normalize everything w.r.t. fB such that ZV/ZA cancels.

Or better: for light-ish quarks (0.9 GeV or so) do both calculations and calculate ratio of mixed versus unmixed action decay constants to get ZV/ZA up to discretization errors.

Few more details on the lattice calculation

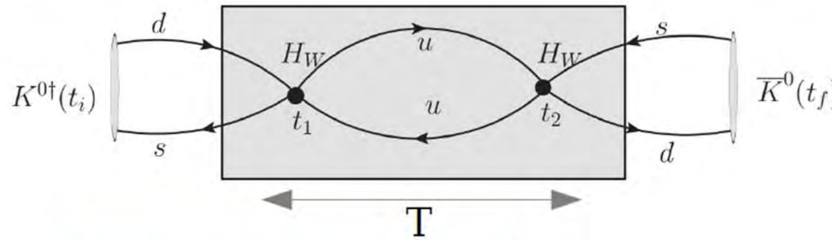
- It means P_x=2pi/48 * 1.73 GeV = 226 MeV, P_y=P_z=0. Average is not needed due to lattice symmetries and is here not advisable because of cost/error analysis (would be more correlated than just solving with new z2 source at W insertion)
-
- It is indeed nice that the error does not grow much.
-
- 3) We will use AMA but the data that we have so far are only

"exact" solves. We start at the W insertion and then do a sequential solve over the B meson either through the light or heavy quark (diagram A/B). The source is z2-wall and it looks like this works quite well noise-wise (it has a full volume average at the B meson and the photon and a stochastic volume average at the W). In this way we also get all 16 spinors at both gamma and W position for free.

- And finally, so far the B meson is a point operator and we are optimizing

a smeared operator right now so that we could have multiple operators for Excited state studies.

Lattice method and challenges



$$\mathscr{A} = N_K^2 e^{-M_K(t_f-t_i)} \sum_n \boxed{\frac{\langle \overline{K}^0 | H_W | n \rangle \langle n | H_W | K^0 \rangle}{M_K - E_n}} \left(-T - \frac{1}{M_K - E_n} + \frac{e^{(M_K-E_n)T}}{M_K - E_n} \right)$$

Need active charm now

ckeckmis

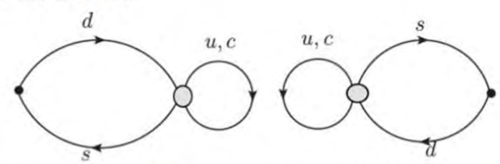
→ requires subtraction for $M_K \to E_n$

- Vary integration window T to extract desired matrix element as term linear in T
- Require subtraction of exponentially-growing terms when $E_n < m_K$: |π>, |ππ>, |0>
- Use ability to shift H_W by total divergence $\bar{s}\gamma^5 d$ to directly remove |0>
  Similarly use $\bar{s}d$ to remove |η>, which although $m_\eta > m_K$ gives noisy contribution

$$\langle \eta | H_W - c_s \bar{s} d | K \rangle = 0 \qquad \langle 0 | H_W - c_p \bar{s}\gamma^5 d | K \rangle = 0$$

a la BDSPW-85

- Pion and two-pion terms contributions explicitly subtracted
- Disconnected diagrams make the calculation noisy. Requires large statistics and maximal translation of sources.



II

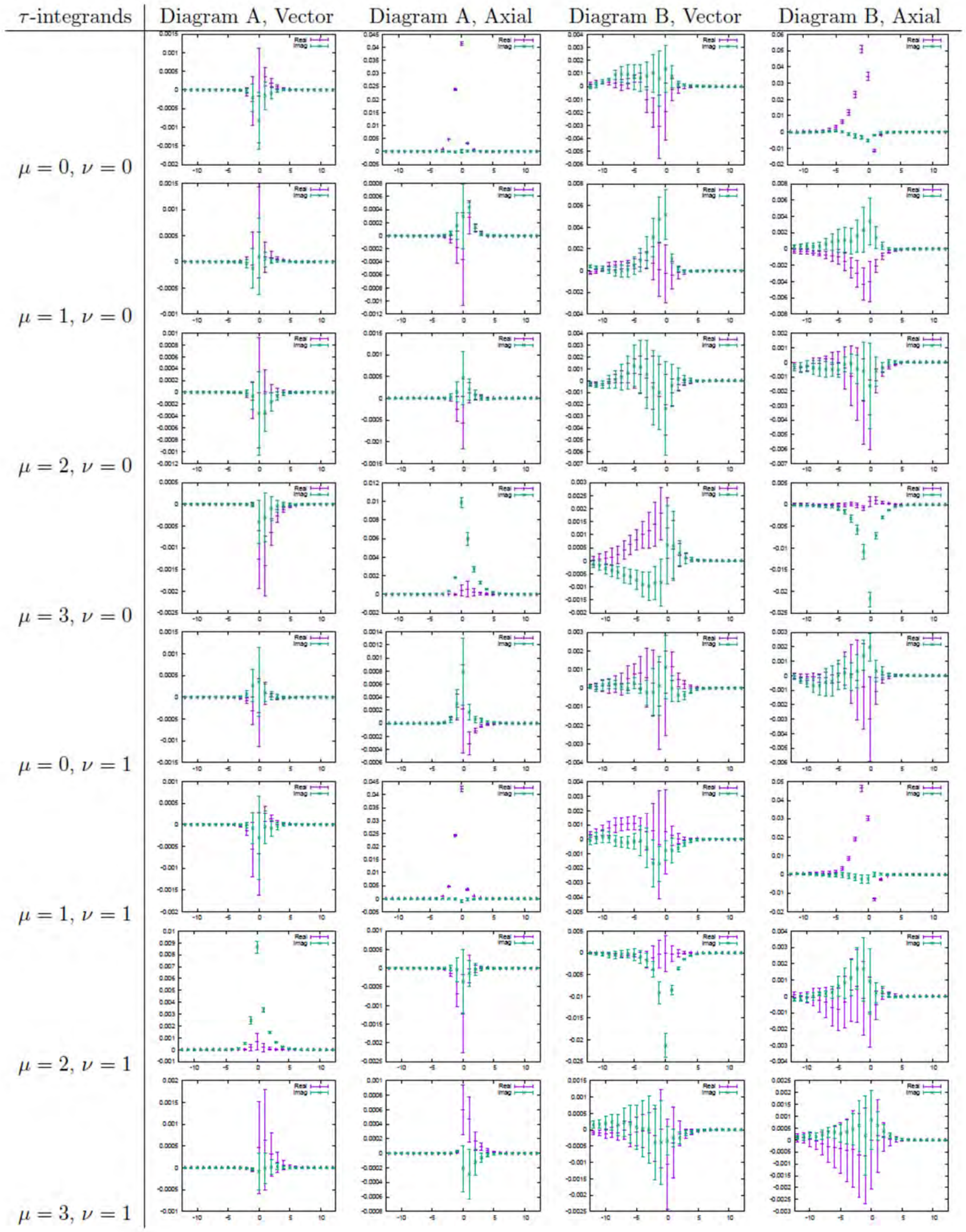
- Divergence when operators approach removed by GIM – requires (valence) charm on lattice. Need fine lattice to control discretization errors.

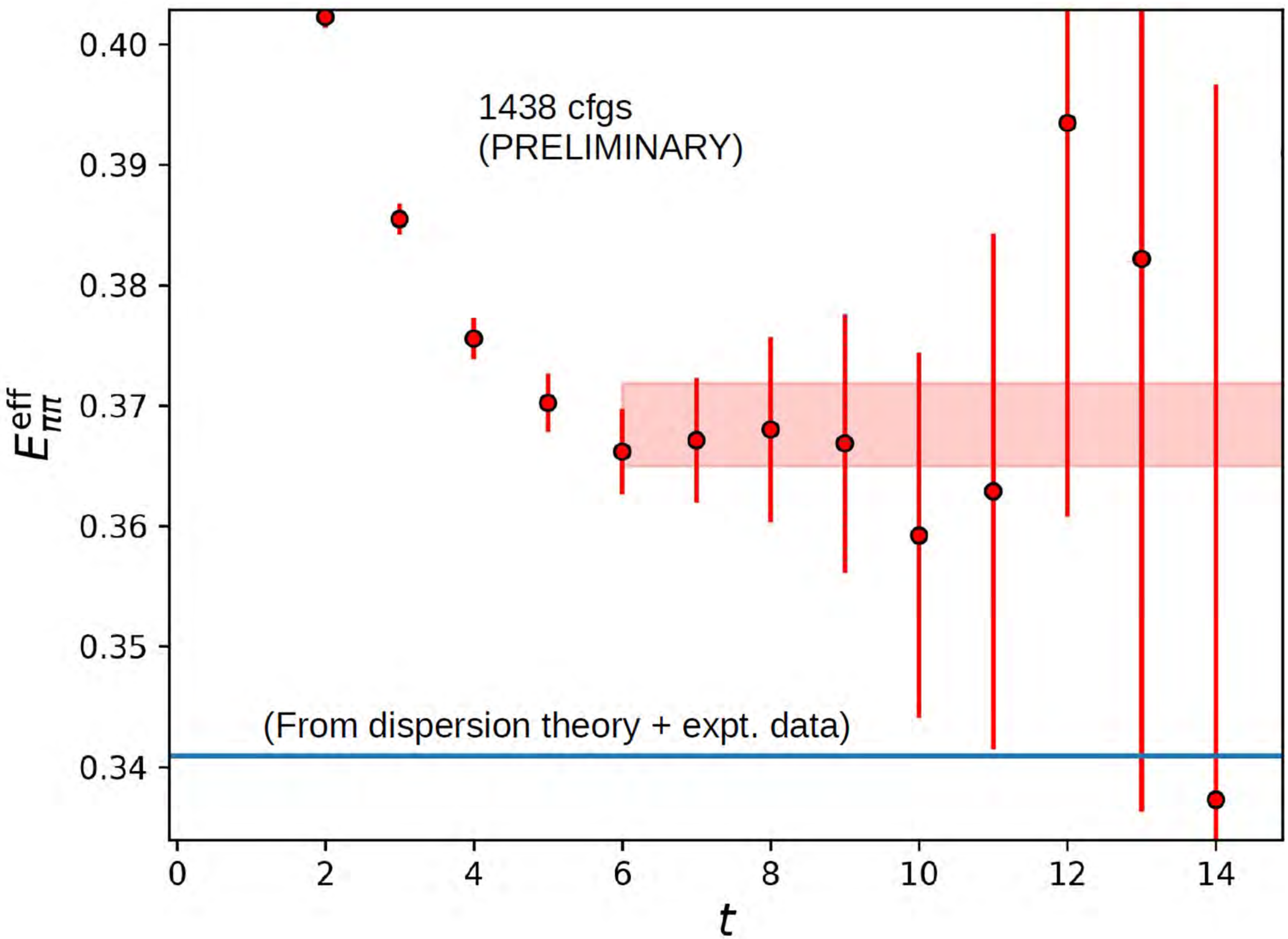
Raw

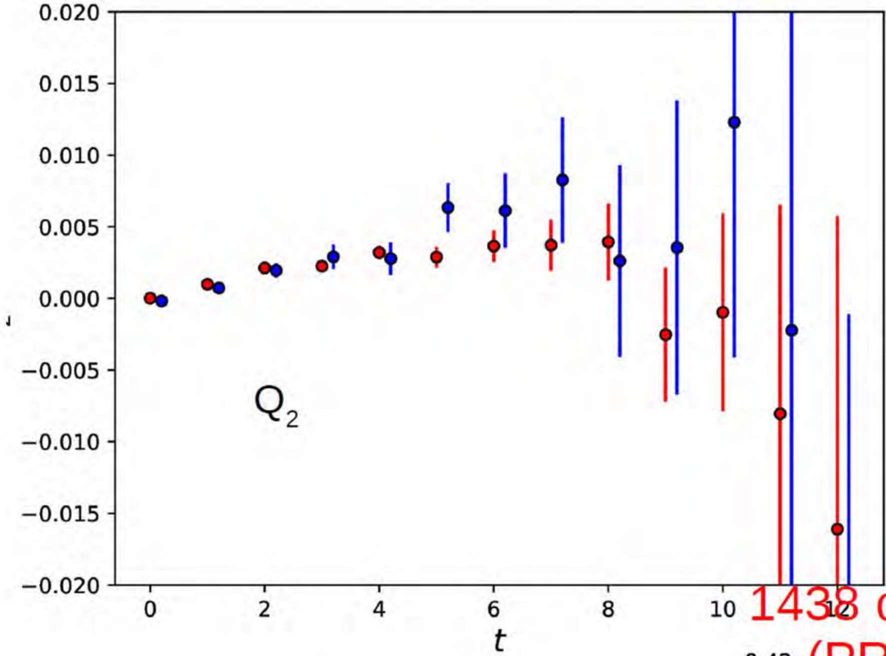
CL 10/28/18

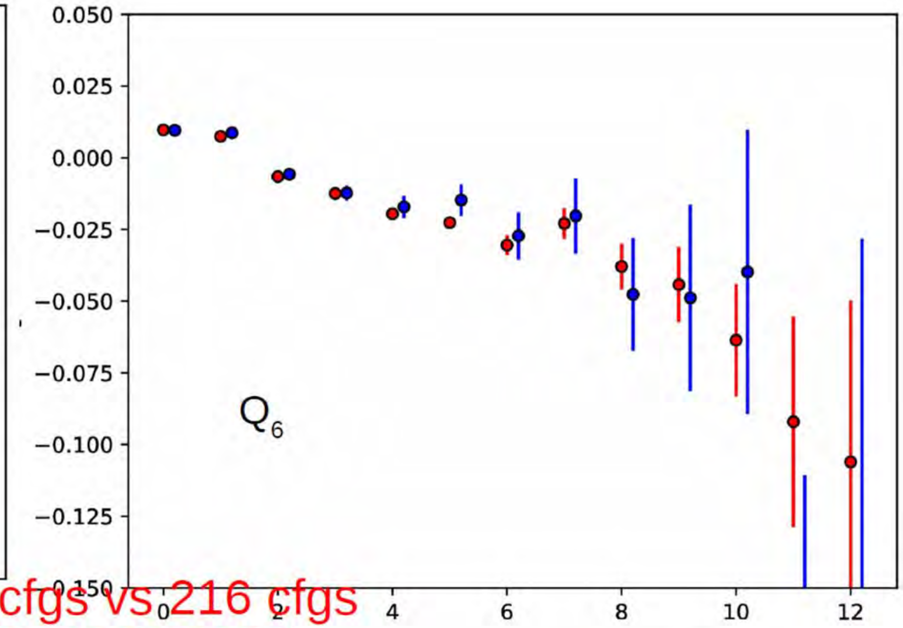
3.5 First results for $T_{\mu\nu}$

The results are for a photon energy of 226 MeV and heavy-light mass 1.6399(16) GeV.

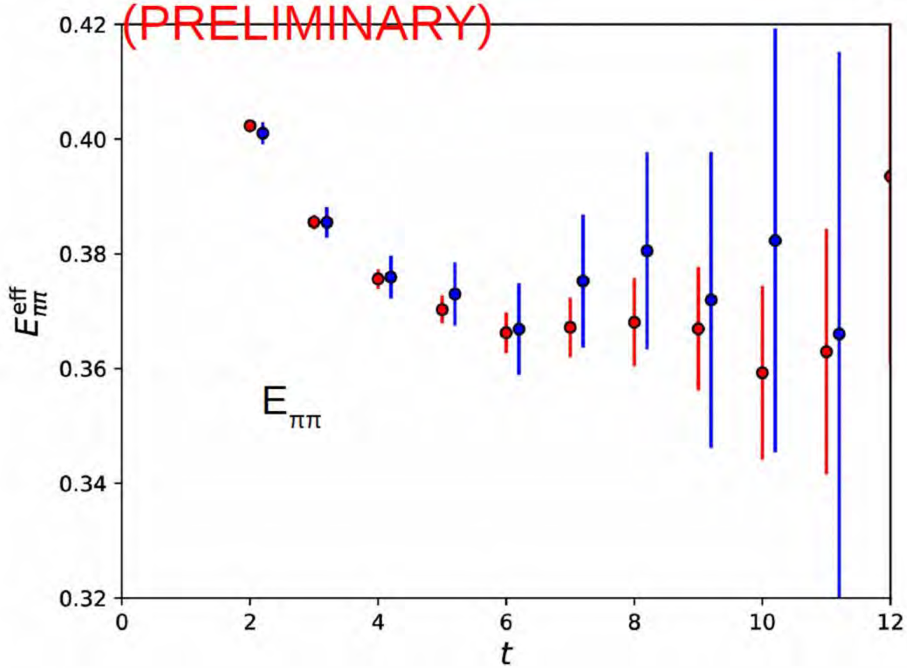

τ-integrands
Diagram A, Vector
Diagram A, Axial
Diagram B, Vector
Diagram B, Axial
$\mu = 0, \nu = 0$
$\mu = 1, \nu = 0$
$\mu = 2, \nu = 0$
$\mu = 3, \nu = 0$
$\mu = 0, \nu = 1$
$\mu = 1, \nu = 1$
$\mu = 2, \nu = 1$
$\mu = 3, \nu = 1$


1438 cfgs
(PRELIMINARY)
(From dispersion theory + expt. data)
$E_{\pi\pi}^{\text{eff}}$
0.40
0.39
0.38
0.37
0.36
0.35
0.34
0
2
4
6
8
10
12
14
t





1438 cfgs vs 216 cfgs
(PRELIMINARY)



- Since 2015 have increased statistics from 216 to over 1400!

6.7x increase

u quark emits γ

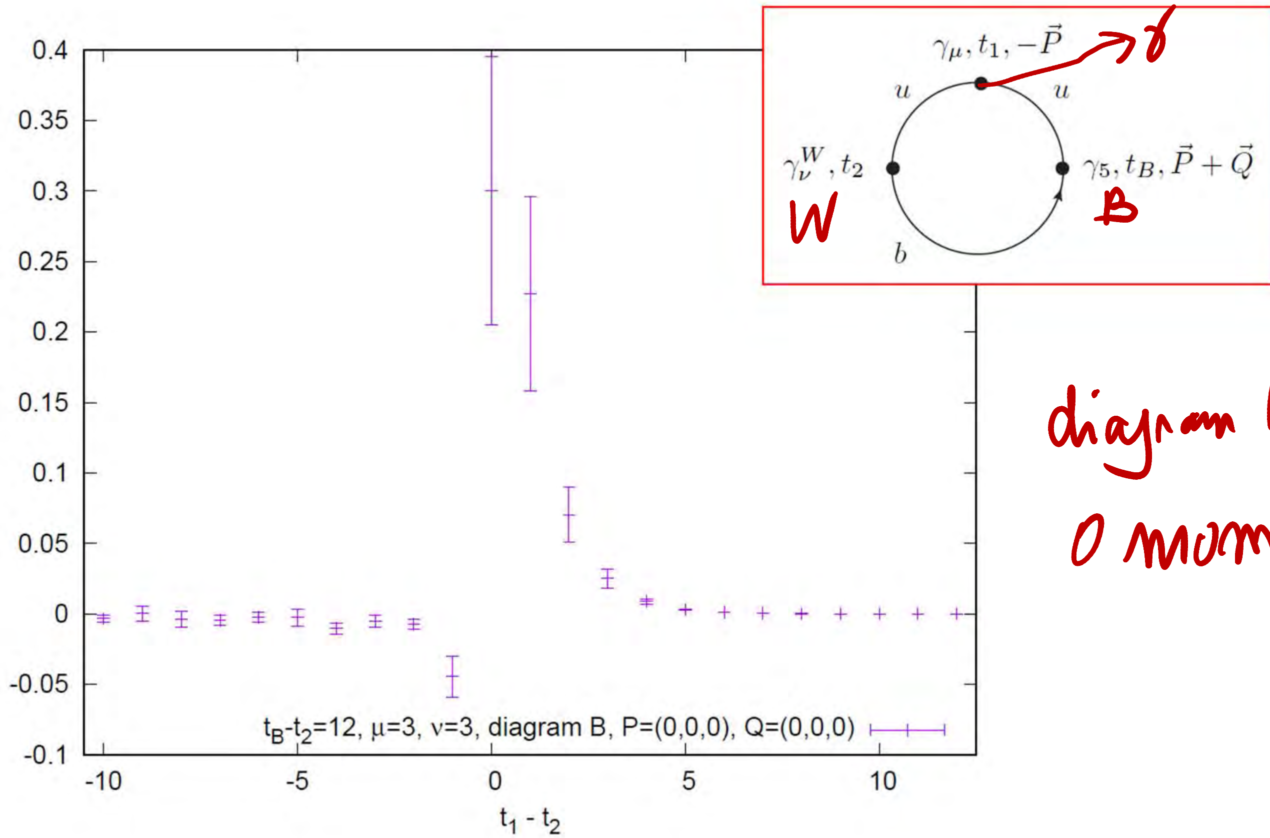


diagram B

0 momentum

Show $\sum_{\vec{x}} e^{-i\vec{p}_1\vec{x}} \langle 0 | T\{j_\mu(\vec{x}, t_1) j_\nu^W(\vec{0}, t_2)\} | B^-(P+Q)\rangle$ for $m_\pi = 139$ MeV, $m_B \approx m_D$, $a^{-1} = 1.73$ GeV