CP violation and lattice matrix elements: a thirty year saga

Color meets flavor: Alex Khodjamirian Fest, Siegen, Oct 13-14,2100

Ode to Alex Khodjamirian!

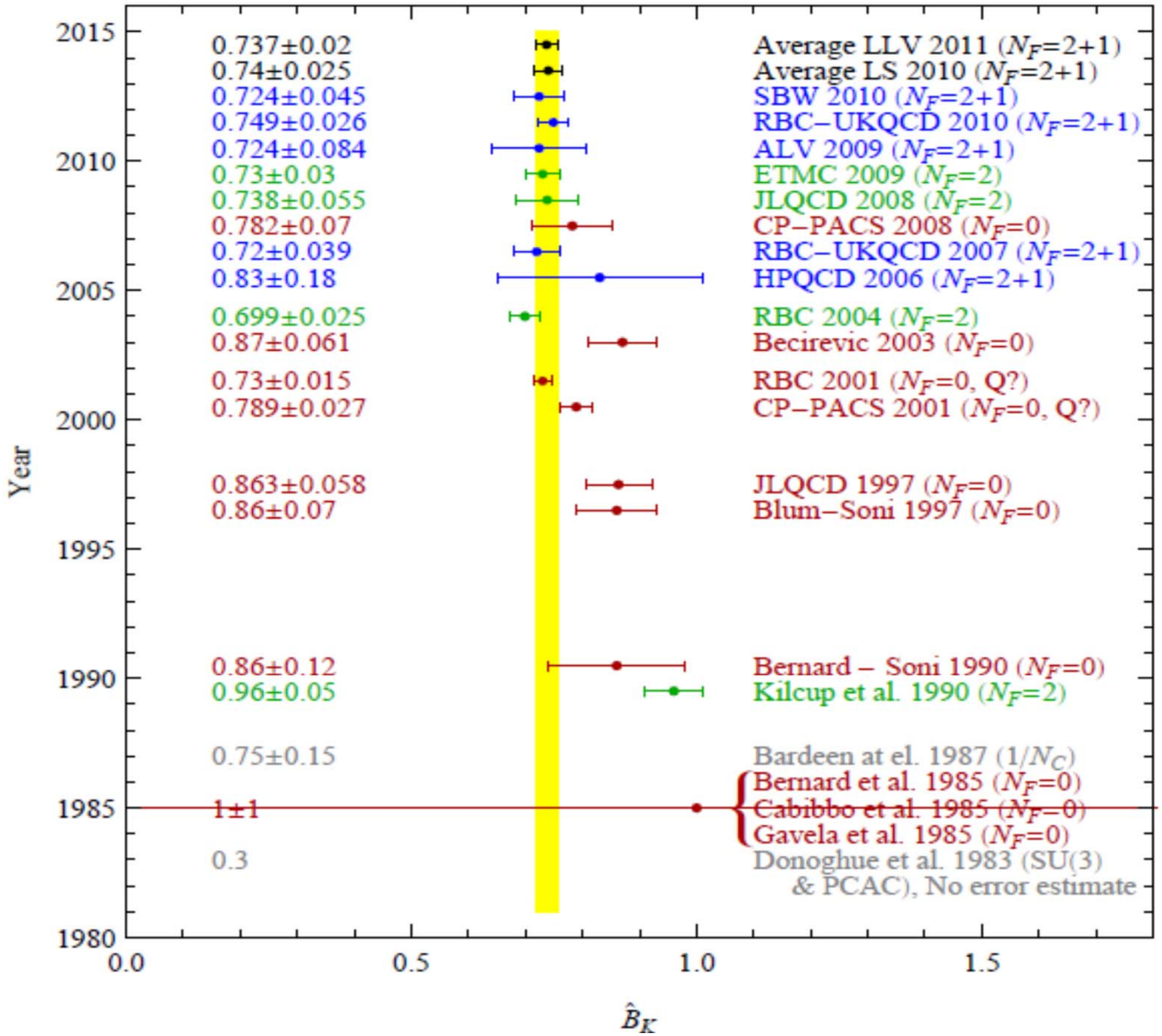
CP violation: the Focus

- **Practically any extension of SM by addition of fermions, gauge bosons or scalars is likely to endow BSM CP-odd phase(s)**
- **Precise calculation of hadronic ME relevant to CP violating observables could provide important tests of the SM and clues for what lies beyond**

A. S : Proceedings of LATTICE ’85 (FSU)…1st lattice meeting ever attended

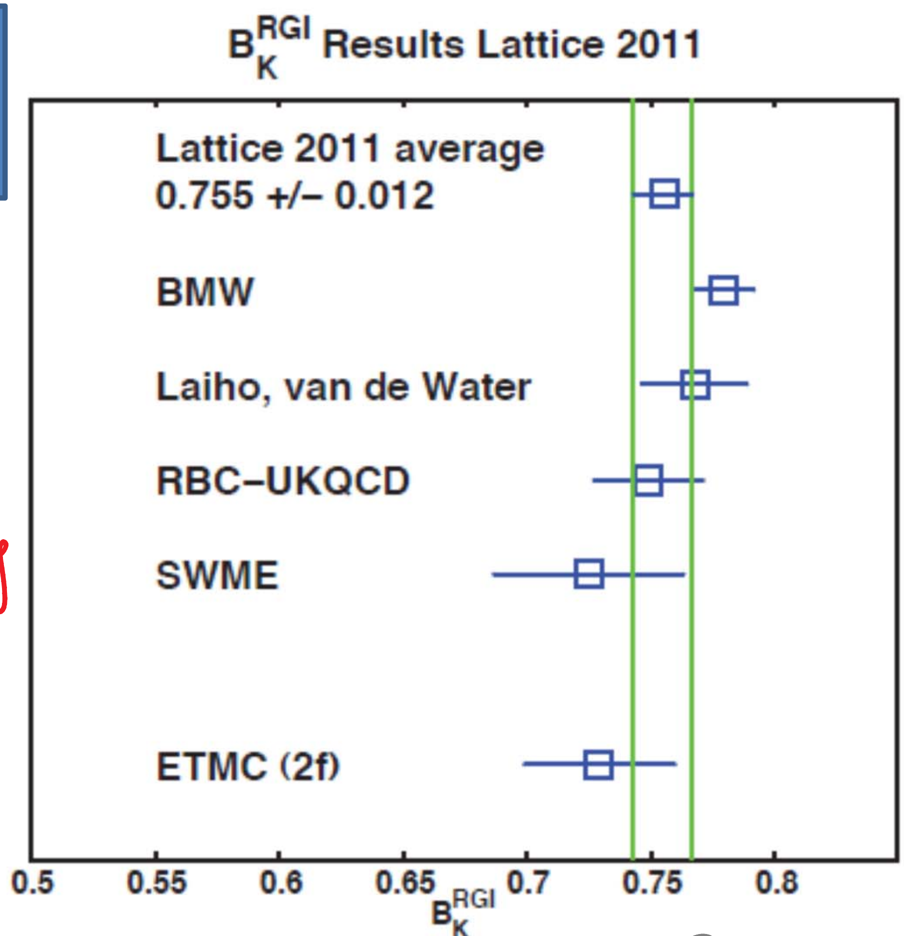
The matrix elements of some penguin operators control in the standard model another CP violation parameter, namely ϵ'/ϵ.[6,8] Indeed efforts are now underway for an improved measurement of this important parameter.[10] In the absence of a reliable calculation for these parameters, the experimental measurements, 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 problem of non-leptonic weak decays.

A BRIEF ~25 years history of B_K



Mawhinney, plenary
LAT'11

Several Lattice groups using completely diff methods reporting B_K with total error $\lesssim 3\%$!



HUGE STRIDES IN LATTICE CALCULATION OF BK!

BURAS (BBG) '98 .70 ±.07

- Average the four 2+1 flavor calculations presented
- Except for BMW, all are preliminary, although all groups have recently published B_K results from earlier datasets, so preliminary work should be fairly reliable.

See also recent summary by FLAG working group of FLAVIANET (arXiv:1011.4408)
They quote $\hat{B}_K = 0.738(20)$ for $N_f = 2+1$

K->pi pi dragon & the lattice:
a sequence of many failed attempts
each teaching us valuable lessons

PHYSICAL REVIEW D VOLUME 32, NUMBER 9 1 NOVEMBER 1985

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

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

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

(Received 3 December 1984)

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

LO ChPT

J.LAIHO & AS ~2004 NLO

VOLUME 55, NUMBER 25 PHYSICAL REVIEW LETTERS 16 DECEMBER 1985

Lattice Calculation of Weak Matrix Elements

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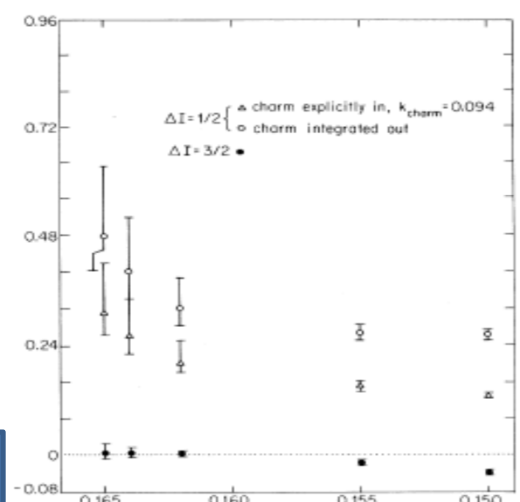
University of California, Los Angeles, California 90024, and University of California, Irvine, California 92717, and Argonne National Laboratory, Argonne, Illinois 60439

(Received 17 October 1985)

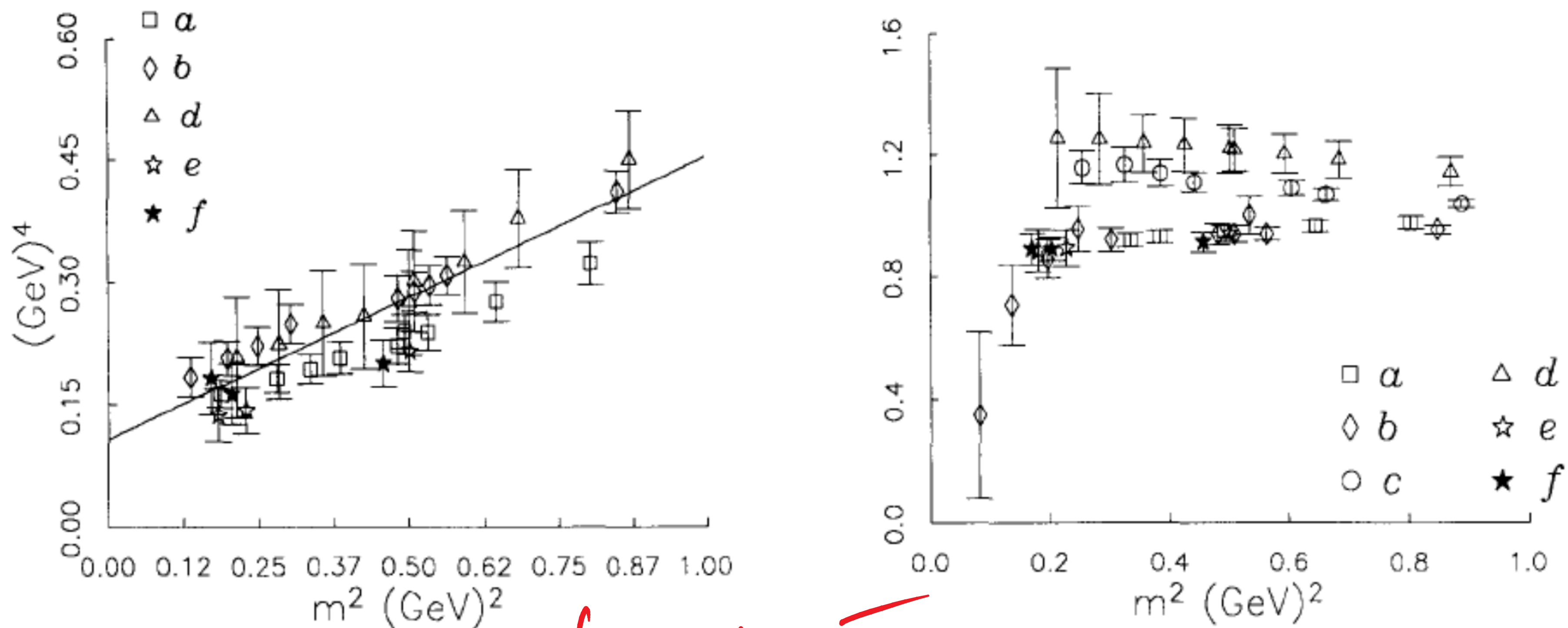
We present the first results from a small-lattice $(6^3\times 10)$ calculation of nonleptonic weak matrix elements. The $\Delta I=\frac{1}{2}$ rule is studied as a test case. For a lattice meson of approximately the kaon mass we find a significantly enhanced $\Delta I=\frac{1}{2}$ amplitude and a $\Delta I=\frac{3}{2}$ amplitude compatible with zero within our statistics. The dominance of the $\Delta I=\frac{1}{2}$ amplitude appears to be due to a class of graphs called the eye graphs. Qualitatively similar results are found whether or not the charm quark is integrated out *ab initio*. We also report preliminary results on other weak matrix elements.

WILSON Fermions



LARGE VIOLATION of χS esp by ΔI=1/2 Amp

32^3X64X16/6^3X10 ~12,500



XS Violation by K-$\bar{K}$

Digression: Initiate Heavy-light WME program-> important application to UT constraints

RATIONALE: Chiral symmetry less of a concern, utilize in a profitable way stored away light quark propagators towards exploratory application to important physical observables

Lattice calculation of weak amplitudes of *D* and *B* mesons

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(Received 27 June 1988)

A lattice calculation of the pseudoscalar decay constants and the [Δ(flavor)=2] mixing matrix elements for *D* and *B* mesons is reported. Calculations are done (in the quenched approximation) with $\beta=6.1$ on a $12^3\times33$ lattice; results from $\beta=5.7$ on a $16^3\times25$ lattice contribute to our estimate of the systematic errors. An extrapolation to large meson mass is required in order to treat the *B* meson. We find $f_{bd}=105\pm17\pm30$ MeV, $f_{bs}=155\pm31\pm48$ MeV, $f_{cd}=174\pm26\pm46$ MeV, $f_{cs}=234\pm46\pm55$ MeV (with normalization such that $f_\pi=132$ MeV). The ratios of these quantities have considerably smaller errors: $f_{bd}/f_{cd}=0.60\pm0.01\pm0.03$, $f_{bs}/f_{cs}=0.66\pm0.004\pm0.09$, $f_{bs}/f_{bd}=1.47\ \pm0.07\pm0.30$, and $f_{cs}/f_{cd}=1.35\pm0.07\pm0.21$. For the lattice "*B* parameters" we find $B_{LL}^{\rm latt}=1.01\pm0.06\pm0.18$ and $B_{LR}^{\rm latt}=1.16\pm0.01\pm0.11$ for the *bd* system, with quite similar values for the *cu* and *bs* systems. These *B* parameters are defined slightly differently than in the continuum and are effectively renormalization-group invariant. The first error in each of our results is statistical; the second is an estimate of the systematic errors due to scale-breaking, finite-size, extrapolation and operator-renormalization effects.

1st application to B-physics
COARSE Lattice; Large syst. error

Lattice computation of the decay constants of *B* and *D* mesons

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Amarjit Soni
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(Received 1 July 1993)

A lattice calculation of the pseudoscalar decay constant of heavy-light mesons is reported. Results are obtained (in the quenched approximation) from lattices at $\beta=6.3$ through a procedure that interpolates between the static approximation of Eichten and the conventional ("heavy" Wilson fermion) method. The previously observed discrepancy between these two approaches has been resolved: we find the scaling quantity $f\sqrt{M}$ to be significantly smaller than previous calculations had indicated (e.g., at $\beta=6.0$); in addition, we discuss a modification which is required in normalizing the conventional amplitude to correct for large-*am* lattice errors. This change guarantees that $f\sqrt{M}$ will smoothly approach its value in the static limit. From the numerical interpolation of the static and intermediate-mass results, we find, in units of MeV, $f_B=187(10)\pm34\pm15$, $f_{B_s}=207(9)\pm34\pm22$, $f_D=208(9)\pm35\pm12$, and $f_{D_s}=230(7)\pm30\pm18$, where the first error is statistical and the second two are estimates of systematics due to (1) fitting and large-*am* effects and (2) scaling. The ratios are better determined: f_D/f_{D_s}, f_B/f_{B_s}, f_B/f_D, and f_{B_s}/f_{D_s} are all 0.90 within a total error of less than 0.05. The purely static values are $f_B^{\rm stat}=235(20)\pm21$ MeV, $f_{B_s}^{\rm stat}=259(19)\pm19$ MeV, and $f_B^{\rm stat}/f_{B_s}^{\rm stat}=0.90(2)\pm0.02$. Finally, using lattices at $\beta=6.3$, $\beta=6.0$, and $\beta=5.7$ and extrapolating to the limit of zero lattice spacing, we have computed $f_K/f_\pi=1.08\pm0.03\pm0.08$ in the quenched approximation, where the first error includes statistical and fitting errors, and the second is an estimate of the error in extrapolation to the continuum limit.

2nd Gen. VAST Improovement

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

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(Received 21 December 1990)

We present our results for the meson form factors of several semileptonic decays. They are computed from the corresponding matrix elements evaluated on the lattice as ratios of Green's functions. The renormalization of the local operators is calculated nonperturbatively. The dependence of the form factors on the four-momentum transfer q^2 is studied by injecting external three-momenta to the initial- and final-state mesons. We study the pseudoscalar decays $K \rightarrow \pi l \nu$, $D \rightarrow K l \nu$, $D \rightarrow \pi l \nu$, $D_s \rightarrow \eta l \nu$, and $D_s \rightarrow K l \nu$ on different lattices. We also analyze scaling, finite-size, and SU(3)-symmetry-breaking effects. The uncertainties in some lattice parameters, e.g., a^{-1}, as a source of systematic errors in this calculation are discussed.

VOLUME 72, NUMBER 10 PHYSICAL REVIEW LETTERS 7 MARCH 1994

Lattice Calculation of the Decays $B \to K^* + \gamma$ and $B_s \to \phi + \gamma$

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[3]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973*
(Received 9 November 1993)

A lattice calculation of the form factors that determine the "hadronization ratios," such as R_{K^*} and R_ϕ, where $R_{K^*} \equiv [\Gamma(B \to K^* \gamma)/\Gamma(b \to s\gamma)]$, is presented in the quenched approximation. Lattice data shows strong evidence for the scaling law suggested by heavy quark symmetry for one of the form factors (i.e., T_2). The data also gives strong support for the simple pole ansatz for the q^2 dependence of T_2 in the range of available q^2. We thus find $T_2(0) = 0.10 \pm 0.01 \pm 0.03$, yielding $R_{K^*} = (6.0 \pm 1.2 \pm 3.4)\%$; we also find $R_\phi = (6.6 \pm 1.3 \pm 3.7)\%$.

PHYSICAL REVIEW D, VOLUME 58, 014501

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

Later ΔM_s
CDF, DΦ

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(Received 28 January 1998; published 5 May 1998)

Results in the quenched approximation for SU(3) breaking ratios of the heavy-light decay constants and the $\Delta F=2$ mixing matrix elements are reported. Using lattice simulations at $6/g^2=5.7$, 5.85, 6.0, and 6.3, we directly compute the mixing matrix element $M_{hl}=\langle \bar{P}_{hl}|\bar{h}\gamma_\mu(1-\gamma_5)l\bar{h}\gamma_\mu(1-\gamma_5)l|P_{hl}\rangle$. Extrapolating to the physical B meson states, B^0 and B_s^0, we obtain $M_{bs}/M_{bd}=1.76(10)^{+57}_{-42}$ in the continuum limit. The systematic error includes the errors within the quenched approximation but not the errors of quenching. We also obtain the ratio of decay constants, $f_{bs}/f_{bd}=1.17(2)^{+12}_{-6}$. For the B parameters we find $B_{bs}(2\text{ GeV})=B_{bd}(2\text{ GeV})=1.02(13)$; we cannot resolve the SU(3) breaking effects in this case. [S0556-2821(98)01313-7]

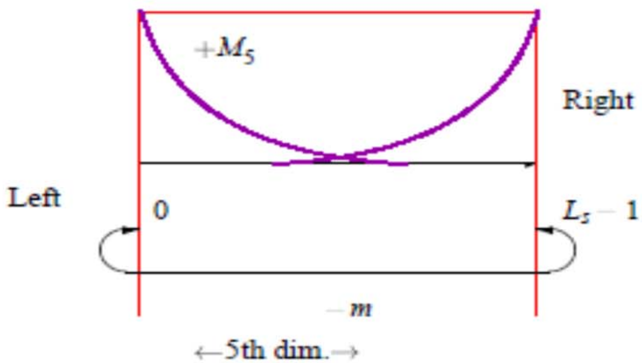
$\Rightarrow \xi$ to UT

Severe limitation of Wilson Fermions for application to light-light physics, e.g. Kaon mixing, K->pipi: A serious fine tuning problem

EXACT CHIRAL SYMMETRY ON THE LATTICE

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)



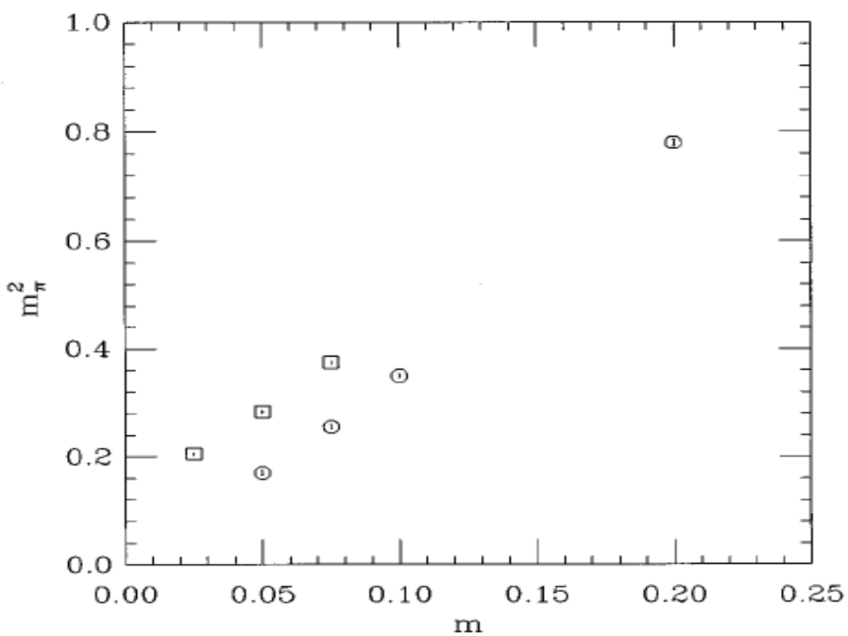
Practical viability of DWF for QCD demonstrated (96-97) Tom Blum & A. S.
Chiral symmetry on the lattice, $a \neq 0$! Huge improvement
$\Rightarrow$ Now widespread use at BNL and elsewhere

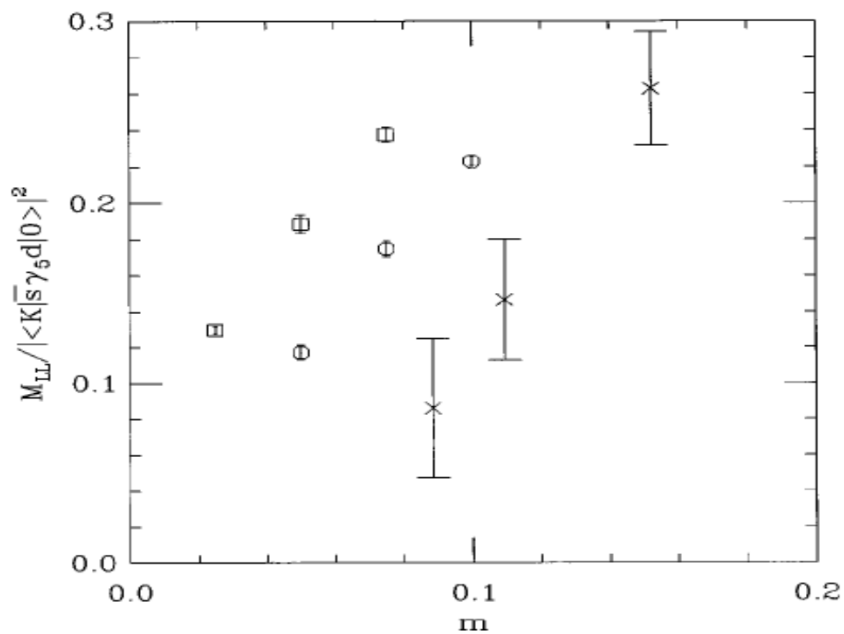
PHYSICAL REVIEW D VOLUME 56, NUMBER 1 1 JULY 1997

QCD with domain wall quarks

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

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





K → 2π via 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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[2]*Physics Department, Columbia University, New York, New York 10027, USA*
[3]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
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[5]*IBM Research, Yorktown Heights, New York 10598, USA*

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

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.

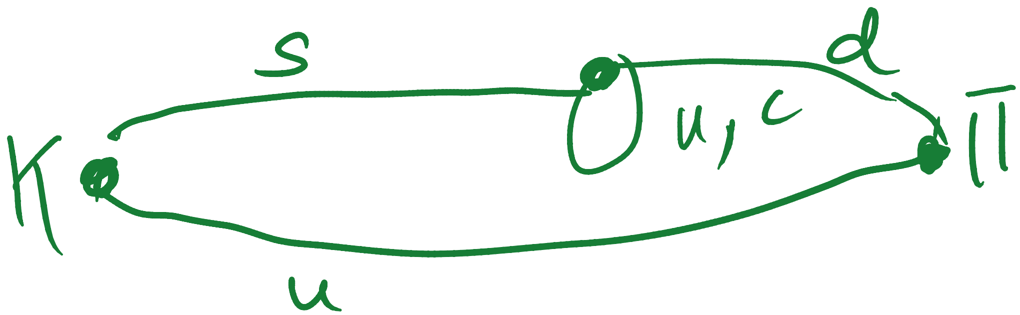
Quantity	Experiment	This calculation (statistical errors only)
Re A_0(GeV)	3.33×10^{-7}	$(2.96 \pm 0.17) \times 10^{-7}$
Re A_2(GeV)	1.50×10^{-8}	$(1.172 \pm 0.053) \times 10^{-8}$
ω^{-1}	22.2	(25.3 ± 1.8)
Re(ϵ'/ϵ)	$(15.3 \pm 2.6) \times 10^{-4}$(NA 48)	$(-4.0 \pm 2.3) \times 10^{-4}$
	$(20.7 \pm 2.8) \times 10^{-4}$(KTEV)	

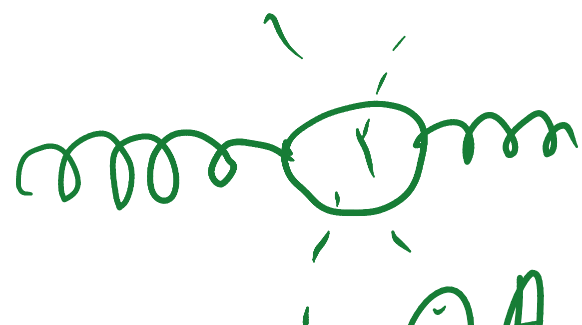
$$Q_c = (\bar{s}_\alpha d_\beta)_{V-A} \sum (\bar{q}_\beta q_\alpha)_{V+A} \qquad (8,1)$$

$$Q_8 = (\bar{s}_\alpha d_\beta)_{V-A} \sum e_q (\bar{q}_\beta q_\alpha) \qquad (8,8)$$

Golterman & Pallante; JHEP'01

Laiho et al [RBC] PRD'06

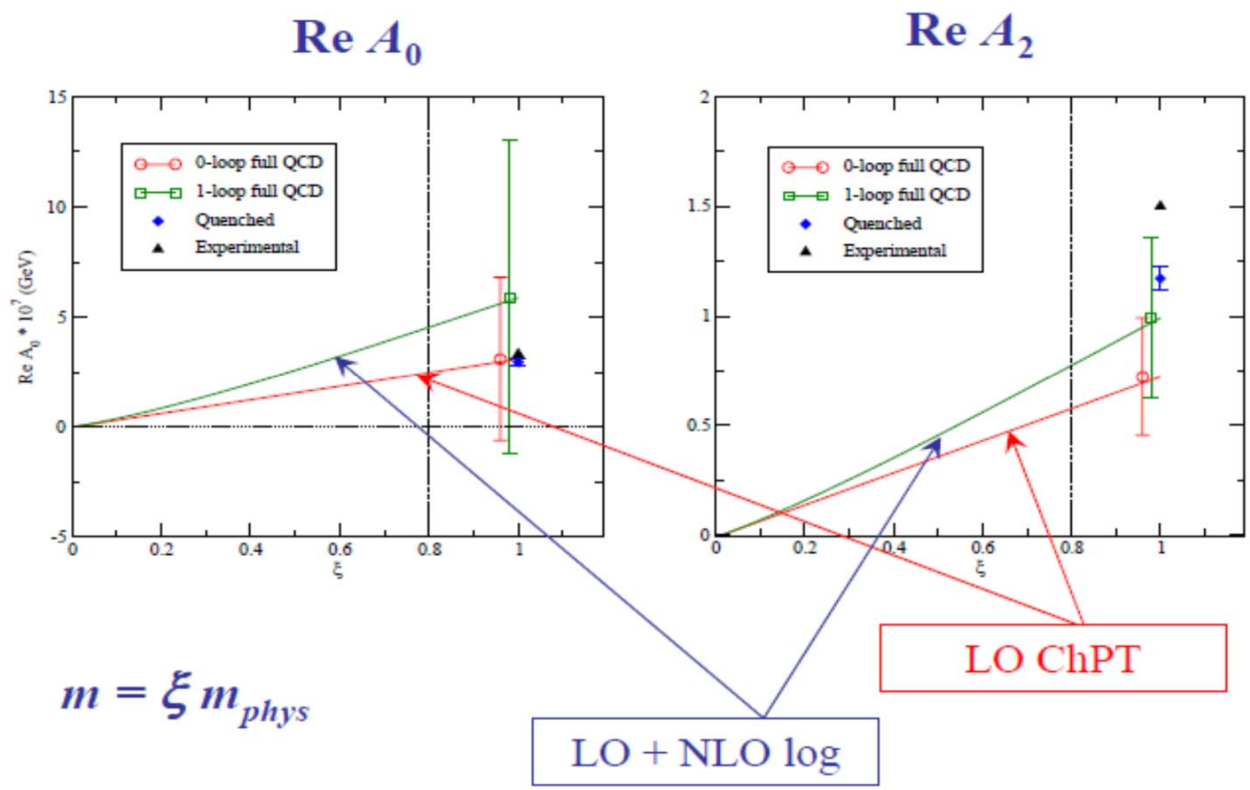




VERY SERIOUS QUENCH PATHOLOGY

Estimate $K \rightarrow \pi\pi$ amplitudes (con't)

ChPT
BUT
WITH
FULLQD



$m = \xi\, m_{phys}$

Lattice 2008, July 14, 2008 (21)

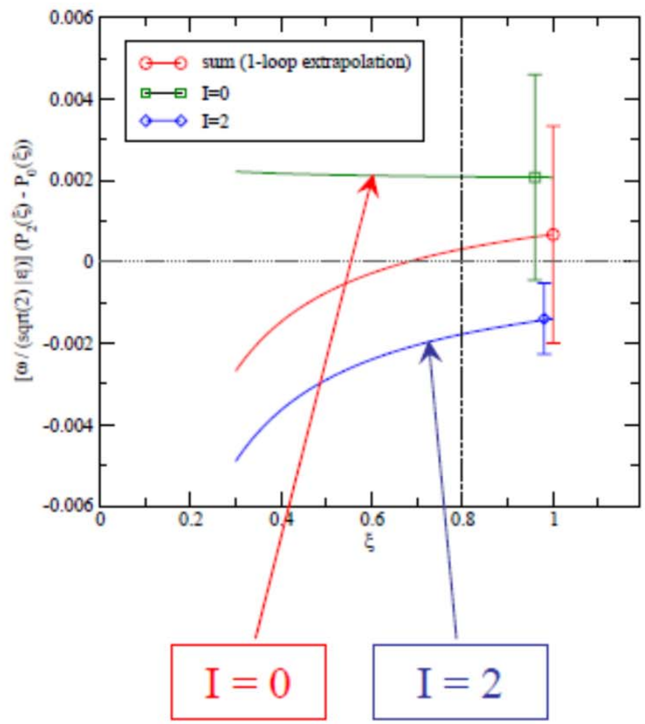
QCDOC 10 Tf NO5 — 11

Sam Li (CU thesis)
N Christ, LAT'08

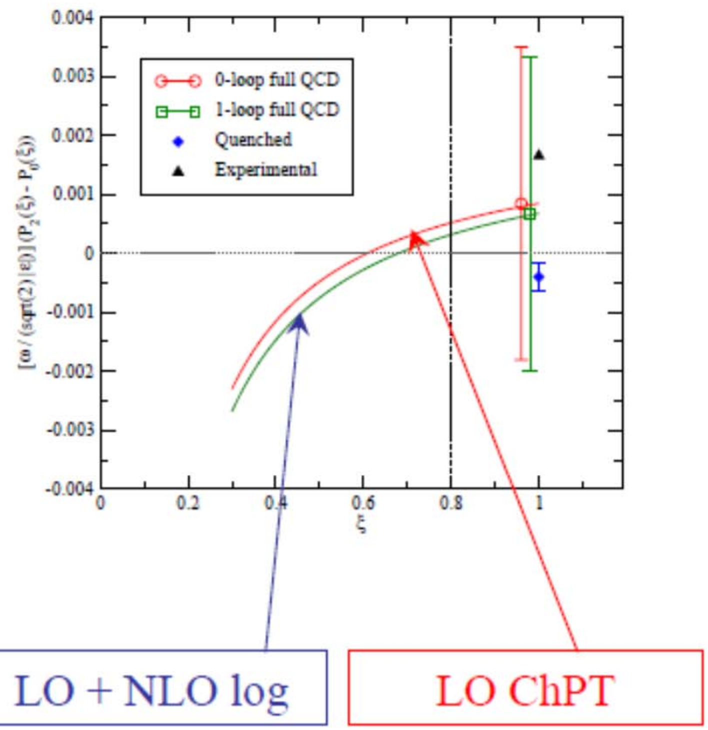
Lattice 2008, July 14, 2

Estimate $K \to \pi\pi$ amplitudes (con't)

Re ε′/ε



Re ε′/ε



$$m = \xi\, m_{phys}$$

Lattice 2008, July 14, 2008 (22)

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

LARGE SYSTEMATIC errors DUE ChPT

Lattice

N. Christ @LAT08

Organization

RBC-UKQCD

- BNL HEP Theory
  M. Creutz, TI, C. Jung*,
  A. Soni, R. Van de Water,
  O. Witzel*,
  R. Arthur, T. Kawanai¥, T. Misumi¥
  (* SciDAC, ¥ JSPS)
- RIKEN BNL Columbia (RBC) Collaboration (1998-)
  - RIKEN-BNL Research Center
    1.5 fellows, 2 PostDocs,
    3 long-term visiting scientists
  - Columbia University
    University of Connecticut
    2 faculties, 2 PostDoc,
    8 Students
  - University of Connecticut
    1 faculties, 2 PostDoc, 2 Students

  Harvard, Yale,
  Virginia (Google), Regensburg
- + UKQCD Collaboration (2005-)
  - Univ. of Edinburgh
    5 faculties, 1 fellows, 1 staff,
    2 PostDocs, 3 students
  - Univ. of Southampton
    2 faculties, 1 Postdoc, 2 students

  CERN, Julich
- + JLQCD (planned since 2010)
  - KEK, Tsukuba & Osaka Univ

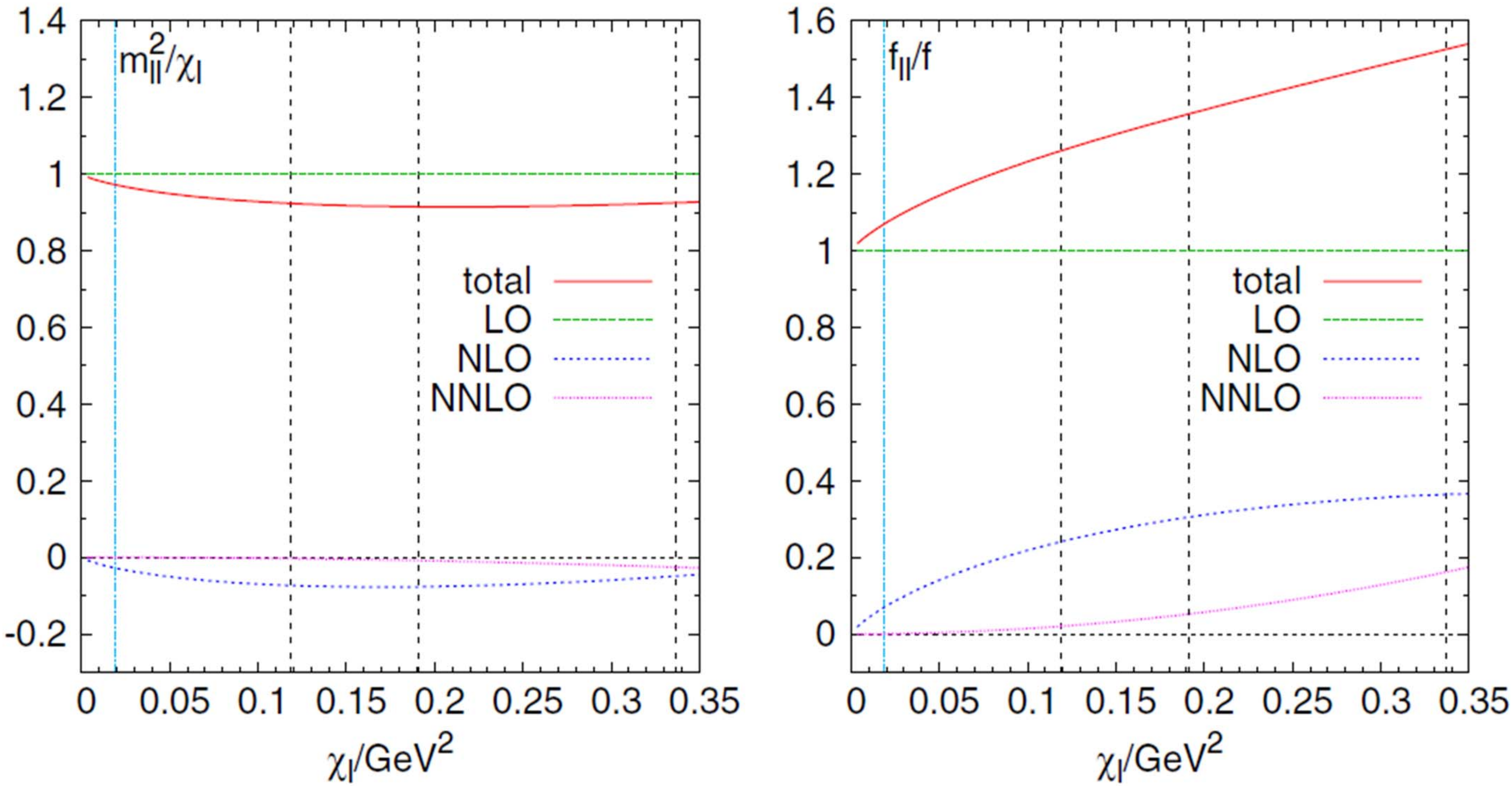
(# of personnel: accumulation of last 3 years
# of PhD thesis: accumulation of last 5 years)

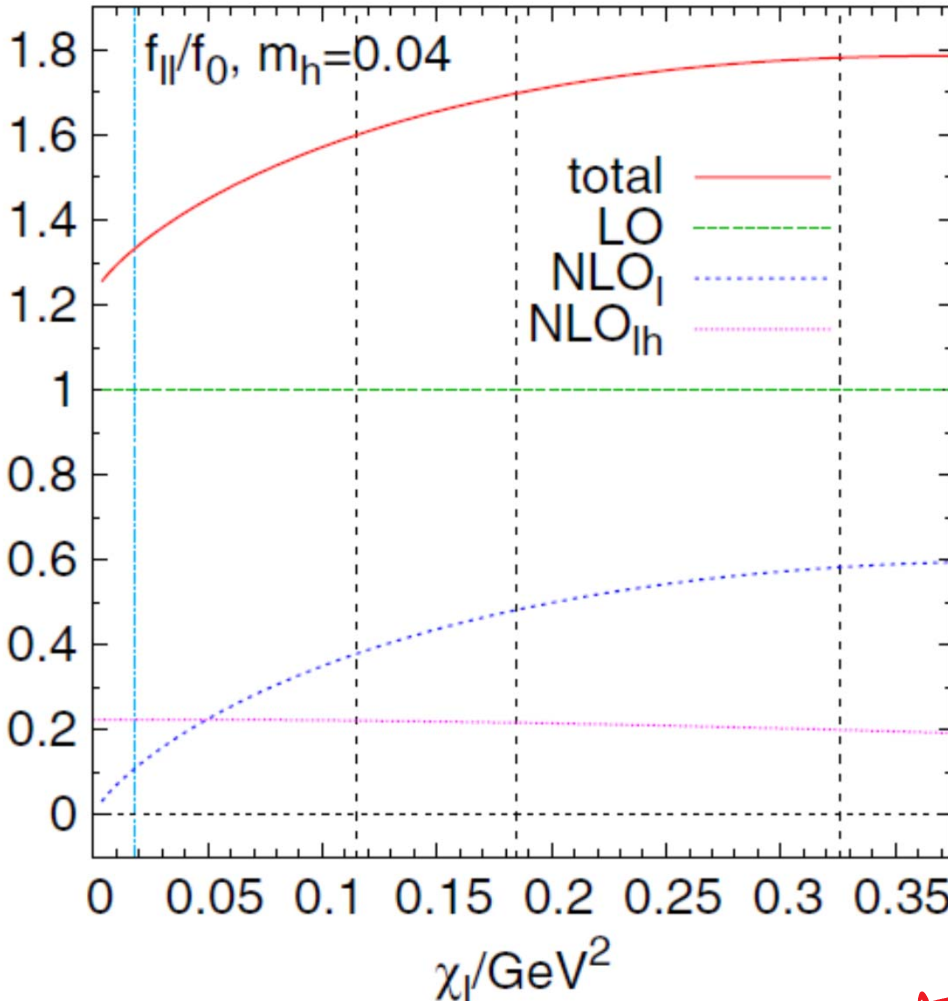
16 current students,
~20 PhD theses since 2005

T Izubuchi

QCDOC → QCDCQ

RBC-UKQCD PRD'08





SU3 ChPT VERY Large corrections: m_K too heavy!

RBC-UKQCD (-07) Initiate use of SU(2)XSU(2) ChPT for chiral extrapolations-> significant improvement in BK and many other light-light entities {07->}

Application of "Hard pion ChPT"

- SU(2) chiral perturbation theory for K(l3) decay amplitudes.
  RBC and UKQCD Collaborations (J.M. Flynn *et al.*). SHEP-08-26. Sep 2008. 20 pp.
  Published in **Nucl.Phys. B812 (2009) 64-80**
  e-Print: **arXiv:0809.1229 [hep-ph]**

Vector Formfactors in Hard Pion Chiral Perturbation Theory.
Johan Bijnens, Ilaria Jemos (Lund U.). LU-TP-10-27. Nov 2010. 24 pp.
Published in **Nucl.Phys. B846 (2011) 145-166**
e-Print: **arXiv:1011.6531 [hep-ph]**

Hard Pion Chiral Perturbation Theory for B→π and D→π Formfactors.
Johan Bijnens, Ilaria Jemos (Lund U.). LU-TP-10-16. Jun 2010. 16 pp.
Published in **Nucl.Phys. B840 (2010) 54-66**
e-Print: **arXiv:1006.1197 [hep-ph]**

K ---> pi pi Decays in SU(2) Chiral Perturbation Theory.
Johan Bijnens, Alejandro Celis (Lund U.). LU-TP-09-14. Jun 2009. 11 pp.
Published in **Phys.Lett. B680 (2009) 466-470**
e-Print: **arXiv:0906.0302 [hep-ph]**

Direct K-> pi pi a la Lellouch-Luscher [w/o ChPT] RBC initiates around 2006

CP-Violating $K \to \pi\pi$ Decay Amplitudes from Lattice QCD

[I=2]

T. Blum,[1] P.A. Boyle,[2] N.H. Christ,[3] N. Garron,[2] E. Goode,[4] T. Izubuchi,[5,6] C. Jung,[5] C. Kelly,[3] C. Lehner,[6] M. Lightman,[3,7] Q. Liu,[3] A.T. Lytle,[4] R.D. Mawhinney,[3] C.T. Sachrajda,[4*] A. Soni,[5] C. Sturm[8]

The RBC and UKQCD Collaborations

In Prep

DWQ + Full QCD + physical Kinematics

ESSENTIALLY Physical K, π and Physical kinematics

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

⇑

	m_{K+}	$m_{\pi+}$	$E_{\pi\pi}$	$m_K - E_{\pi\pi}$
Simulated	511.3(3.9)	142.9(1.1)	492.6(5.5)	18.7(4.8)
Physical	493.677(0.016)	139.57018(0.00035)	m_K	0

Table 1: Kaon and pion masses and the two-pion energy $E_{\pi\pi}$ in the simulation together with the corresponding physical values. The results are given in MeV.

	$\mathrm{Re}A_2$	$\mathrm{Im}A_2$
lattice artefacts	15%	15%
finite-volume corrections	6.2%	6.8%
partial quenching	3.5%	1.7%
renormalization	1.7%	4.7%
unphysical kinematics	3.0%	0.22%
derivative of the phase shift	0.32%	0.32%
Wilson coefficients	7.1%	8.1%
Total	18%	19%

Table 2: Systematic error budget for Re A_2 and Im A_2.

$$\mathrm{Re}\,A_2 = (1.436 \pm 0.063_{\rm stat} \pm 0.258_{\rm syst}) \times 10^{-8}\,\mathrm{GeV},$$

$$\mathrm{Im}\,A_2 = -(6.29 \pm 0.46_{\rm stat} \pm 1.20_{\rm syst}) \times 10^{-13}\,\mathrm{GeV}.$$

$\mathrm{Re}\,A_2^{expt}$ (K+) $= 1.479(4) \times 10^{-8}$ GeV

$$\frac{\mathrm{Im}\,A_0}{\mathrm{Re}\,A_0} = -1.60(19)_{\rm stat}(20)_{\rm syst} \times 10^{-4}\,.$$

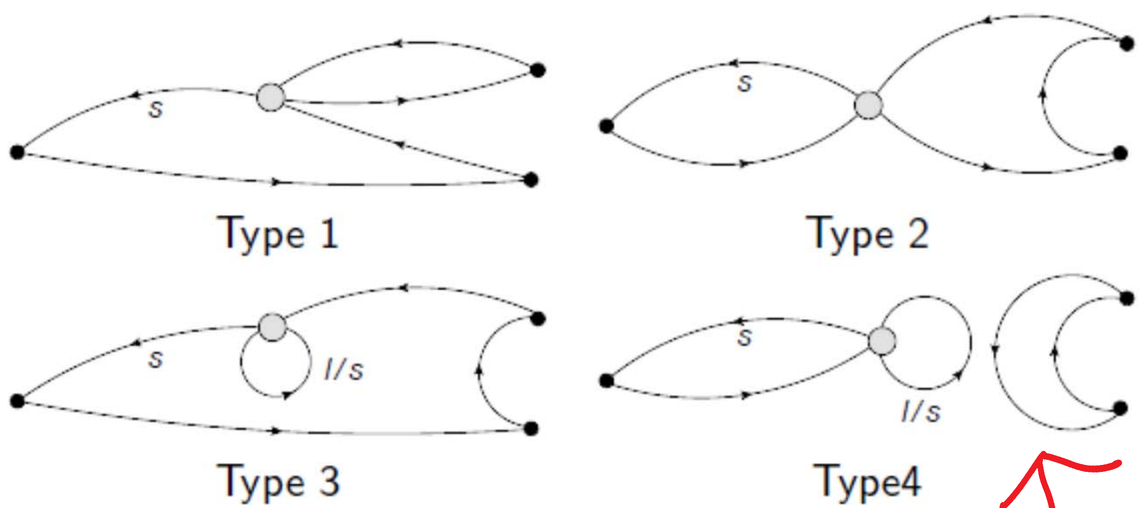
$\overline{K}_\epsilon = 0.95 \pm .01$ [$(\mathrm{Im}\,M_{12})_{LD}$ not included]

BURAS, GUADAGNOLI, ISIDORI $K_\epsilon = .94 \pm .02$

I=0 Channel

Difficulties of a direct Lattice calculation

Disconnected (Vacuum) Graphs!



$$Type4 = \langle K(0)O(t)\pi\pi(t_\pi)\rangle - \langle K(0)O(t)\rangle \langle \pi\pi(t_\pi)\rangle$$

extremely difficult

Qi Liu, LAT'11

K^0 to $\pi\pi$ decay Results

Qi Liu @ LAT'11

Preliminary Results [2]:

We take the kinematics point $m_k \approx 2m_\pi$, therefore, the decay is a little bit off shell because of $\pi - \pi$ interaction. Real part ($\times 10^{-8}$ GeV), Imaginary part ($\times 10^{-12}$GeV) .

m_π	$\mathrm{Re}(A_0)$	$\mathrm{Re}(A_0')$	$\mathrm{Im}(A_0)$	$\mathrm{Im}(A_0')$	$\mathrm{Re}(A_2)$	$\mathrm{Im}(A_2)$
329.3	36.8(6.6)	27.7(1.1)	-31(23)	-34.9(21)	2.663(19)	-0.6527(43)
421.4	45(10)	48.8(24)	-41(26)	-74.6(47)	4.911(31)	-0.5502(40)

16^3 800 gc

24^3 78 gc

$\mathrm{Re}\, A_0^{expt} = 33 \times 10^{-8}$

78 gc -> 140 around 9/15/11 END of QCDOCawaiting QCDCQ to accumulate more data

T. Blum et al {RBC-UKQCD] arXiv:1106.2714 -> PRD'11

TABLE V: Fitted results for the weak, $\Delta I = 1/2$ kaon decay matrix elements using the kaon mass $m_K^{(0)}$. The column $M_i^{\rm lat}$ shows the complete result from each operator. The column $M_i'^{\rm lat}$ shows the result when the disconnected graphs are omitted while the 4th and 5th columns show the contributions of each operator the real and imaginary parts of the physical decay amplitude A_0. These results are obtained using a source-sink separation $\Delta = 16$, and a fit range $5 \le t \le 11$.

i	$M_i^{1/2,\rm lat}(\times 10^{-2})$	$M_i'^{1/2,\rm lat}(\times 10^{-2})$	$\mathrm{Re}(A_0)$(GeV)	$\mathrm{Im}(A_0)$(GeV)
1	-1.6(16)	-1.10(37)	7.6(64)e-08	0
2	1.52(61)	1.92(15)	2.86(97)e-07	0
3	-0.3(41)	0.3(10)	2.1(136)e-10	1.1(76)e-12
4	2.7(33)	3.32(78)	4.2(44)e-09	1.4(14)e-11
5	-3.3(38)	-6.81(86)	3.1(53)e-10	1.6(28)e-12
6	-7.8(48)	-19.6(9)	-5.6(33)e-09	-3.3(20)e-11
7	10.9(14)	15.20(42)	5.2(12)e-11	8.8(20)e-14
8	35.7(28)	47.2(10)	-3.66(28)e-10	-1.79(14)e-12
9	-2.2(12)	-1.79(29)	3.1(15)e-14	-2.01(96)e-12
10	0.9(12)	1.24(29)	1.2(11)e-11	-2.7(27)e-13
Total	-	-	3.46(78)e-07	-2.4(23)e-11

Application to the UT
Lunghi + A. S.

HINTS of CKM breaking

Based on Enrico Lunghi+AS

0707.0212; 0803.4340; 0903.5059;0912.0002

1010.6069

JHEP

JHEP

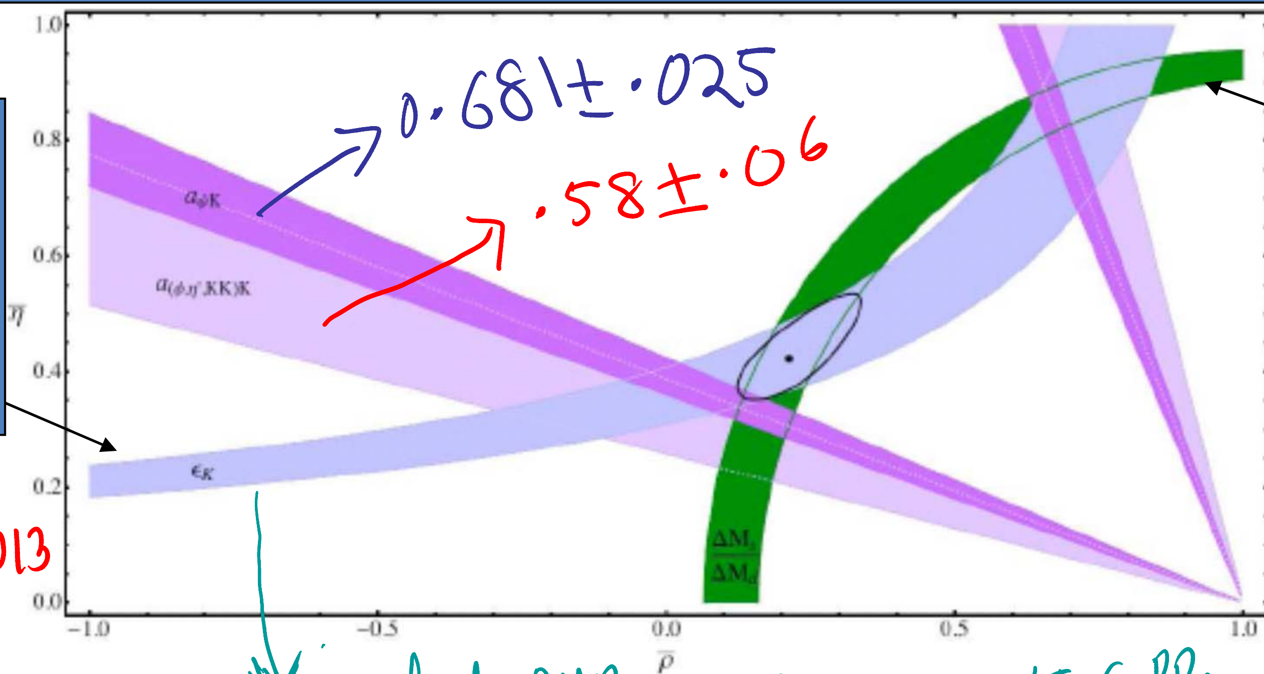
PLB

PRL

PLB

Important to Examine only DeltaF=2 observables:Leave out Vub
sin 2 β = 0.87+-.09{Lunghi+AS,hep-ph/08034340}
(became possible only due significantly reduced error in B_K)

Antonio et al (RBC-UKQCD) 0702042



Gamiz et al; Becirevic; Tantalo
.

$\hat{B}_K = .720 \pm .013 \pm .037$

$|V_{cb}| = 40.8 \pm .6 \times 10^{-2}$

include BURAS + GUADAGNOLI CORR. (0805.3887)

$\xi = 1.20 \pm .06$

FIG. 1: Unitarity triangle fit in the SM. All constraints are imposed at the 68% C.L.. The solid contour is obtained using the constraints from ε_K and $\Delta M_{B_s}/\Delta M_{B_d}$. The regions allowed by $a_{\psi K}$ and $a_{(\phi+\eta'+2K_s)K_s}$ are superimposed.

2.1-2.7 σ- deviation from the directly measured values of sin 2 β requires careful follow-up

Continuing saga of Vub

- For past many years exclusive & inclusive show discrepancy (Latest; gotten worse)
- Exc ~ (29.7 +-3.1)X10^{-4}
- Inc ~ (40.1+-2.7+-4.0)X10^{-4}

[ALEX K, THOMAS M - - -] e.g. $B \to \pi \ell \nu$

lattice continuum $B \to X_u \ell \nu$

-> ***Let's try NOT use Vub: initiated in '08 (EL&AS'08)…Not just for the above reason***

ONLY BECAME VIABLE DUE TO SIGNIFICANT BETTER B_K

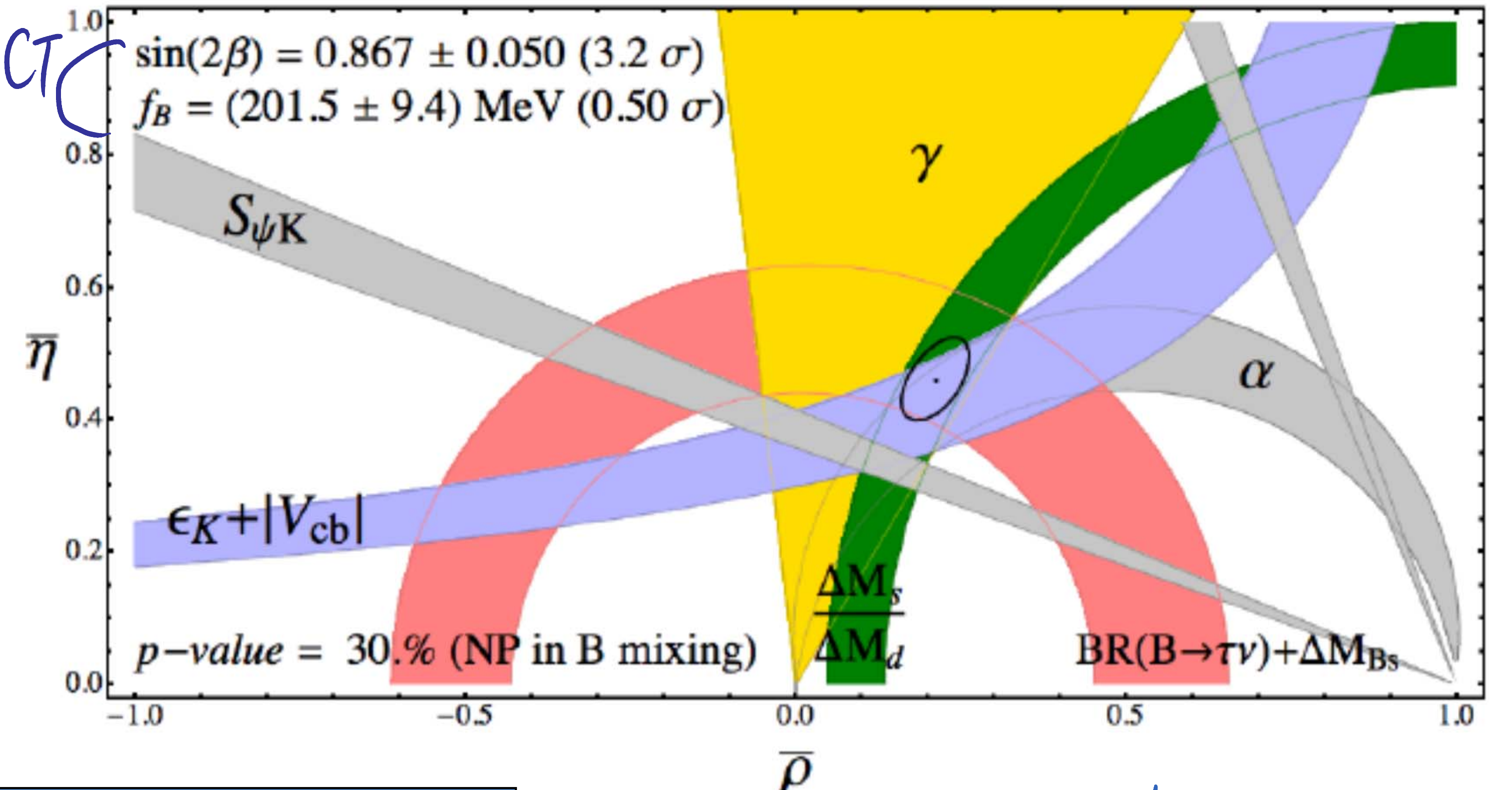
UPDATE 2010

$\|V_{cb}\|_{excl} = (39.5 \pm 1.0) \times 10^{-3}$	$\eta_1 = 1.51 \pm 0.24$ [49]
$\|V_{cb}\|_{incl} = (41.68 \pm 0.44 \pm 0.09 \pm 0.58) \times 10^{-3}$ [50]	$\eta_2 = 0.5765 \pm 0.0065$ [51]
$\|V_{cb}\|_{avg} = (40.9 \pm 1.0) \times 10^{-3}$	$\eta_3 = 0.494 \pm 0.046$ [52, 53]
$\|V_{ub}\|_{excl} = (31.2 \pm 2.6) \times 10^{-4}$	$\eta_B = 0.551 \pm 0.007$ [54]
$\|V_{ub}\|_{incl} = (43.4 \pm 1.6^{+1.5}_{-2.2}) \times 10^{-4}$ [50]	$\xi = 1.23 \pm 0.04$
$\|V_{ub}\|_{tot} = (33.7 \pm 4.9) 10^{-4}$	$\lambda = 0.2253 \pm 0.0009$ [55]
$\Delta m_{B_d} = (0.507 \pm 0.005)\ \mathrm{ps}^{-1}$	$\alpha = (89.5 \pm 4.3)^{o}$
$\Delta m_{B_s} = (17.77 \pm 0.12)\ \mathrm{ps}^{-1}$	$\kappa_\varepsilon = 0.94 \pm 0.02$ [39, 56, 57]
$\varepsilon_K = (2.229 \pm 0.012) 10^{-3}$	$\hat{B}_d = 1.26 \pm 0.11$
$m_{t,pole} = (172.4 \pm 1.2)$ GeV	$f_{B_d} = (208 \pm 8)$ MeV [48]
$m_c(m_c) = (1.268 \pm 0.009)$ GeV	$f_K = (155.8 \pm 1.7)$ MeV
$S_{\psi K_S} = 0.668 \pm 0.023$ [58]	$\hat{B}_K = 0.742 \pm 0.023$
$f_{B_s}\sqrt{\hat{B}_{B_s}} = (291 \pm 16)$ MeV	$\gamma = (78 \pm 12)^{o}$ [59, 60]
$\mathrm{BR}_{B\to\tau\nu} = (1.68 \pm 0.31) \times 10^{-4}$ [61–63]	

Table 1: Lattice QCD and other inputs to the unitarity triangle analysis. The determination of α is obtained from a combined isospin analysis of $B \to (\pi\pi,\ \rho\rho,\ \rho\pi)$ branching ratios and CP asymmetries [50]. Statistical and systematic errors are combined in quadrature; for the error on V_{ub} see [64]. We adopt the averages of Ref. [39, 40] (updates at **www.latticeaverages.org**) for all quantities with the exception of ξ, $f_{B_s}\hat{B}_s^{1/2}$, $\hat{B}_K$ and f_{B_d} (see text).

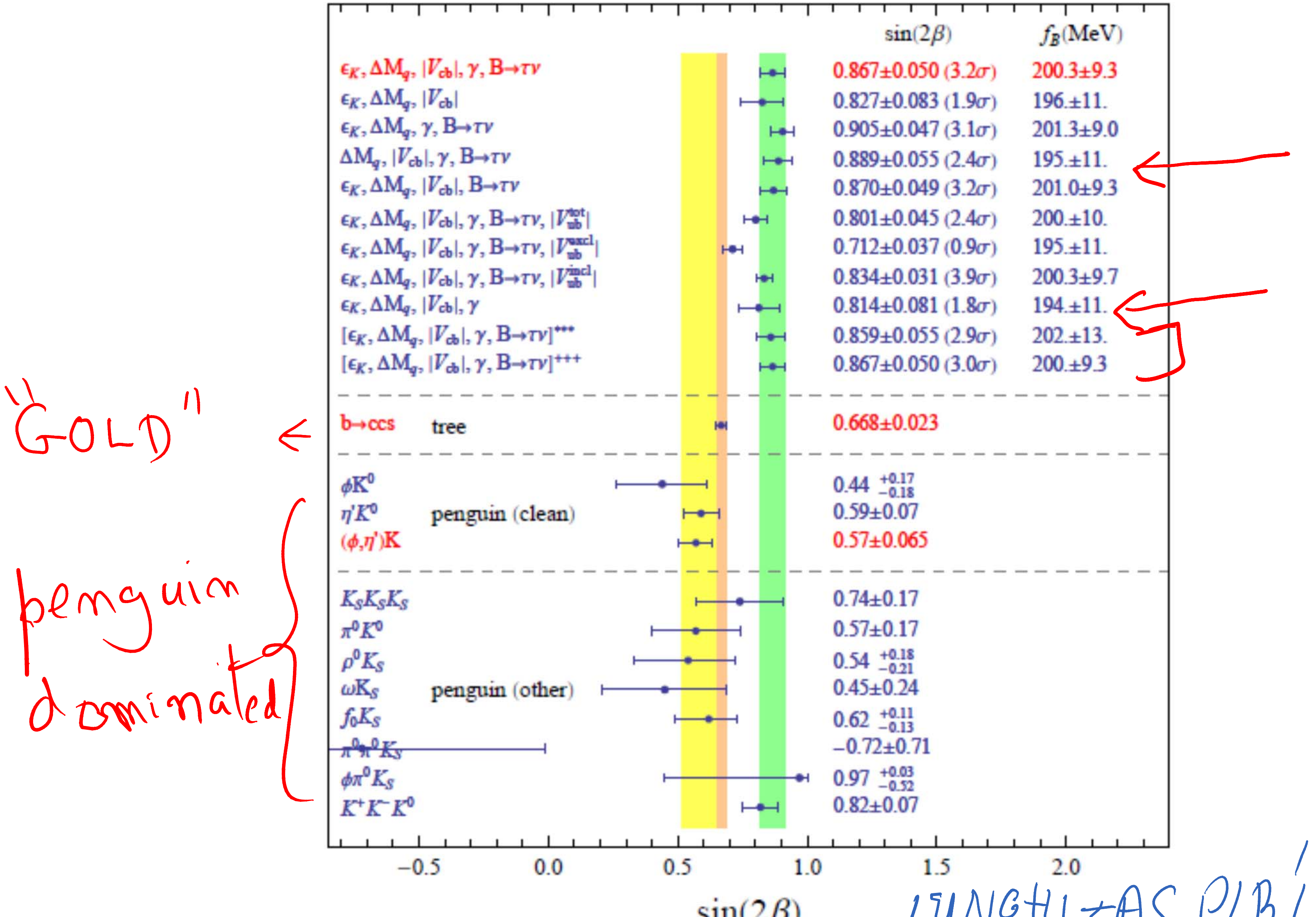
INPUTS: ϵ_K, $\Delta M_{B_s}/\Delta M_{B_d}$, ΔM_{B_s}, γ, $B\to\tau\nu$

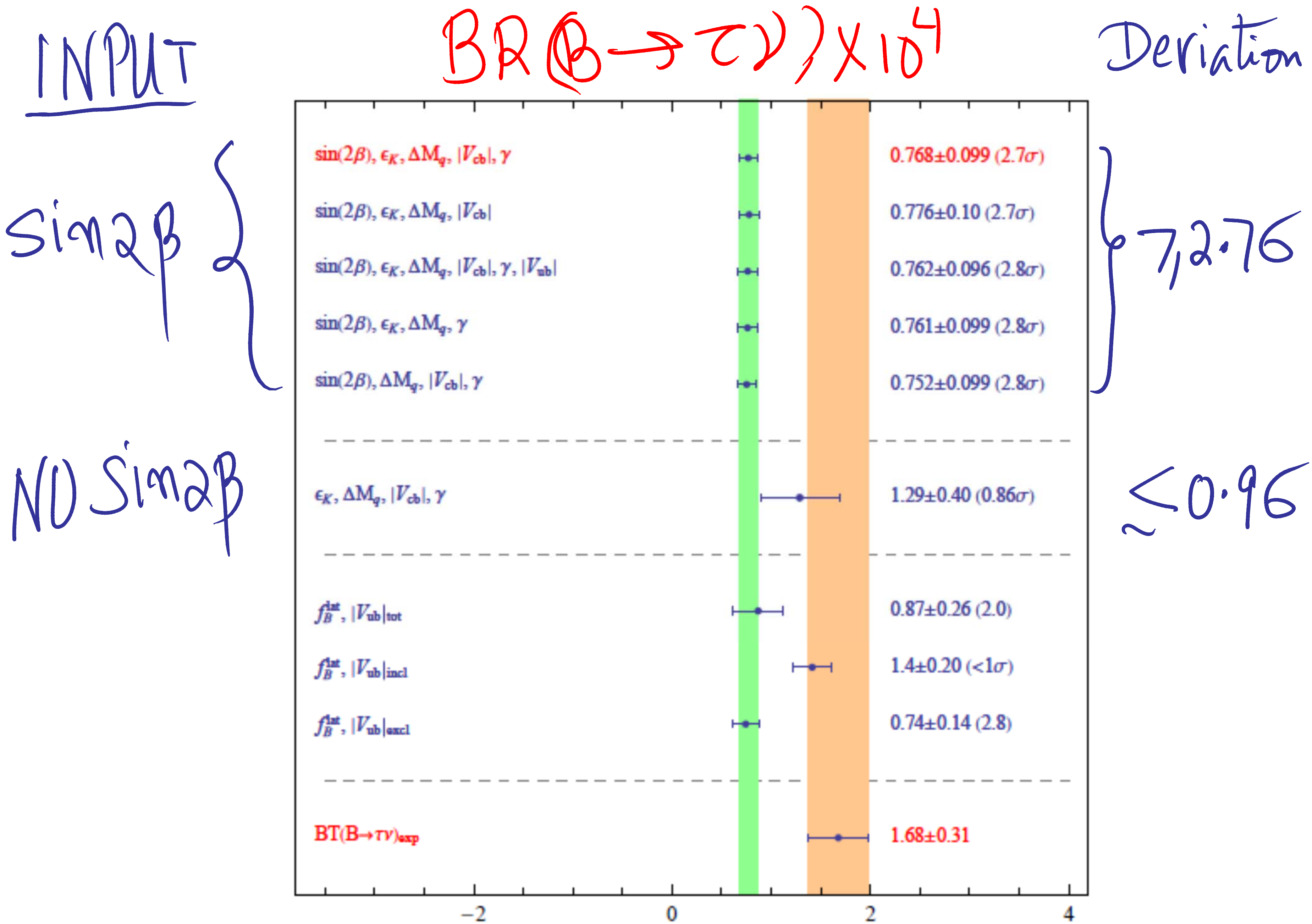
PREDICT



Predict sin2β & fB

LUNGHI+AS PLB'11


sin(2β)
f_B(MeV)
ε_K, ΔM_q, |V_cb|, γ, B→τν — 0.867±0.050 (3.2σ) — 200.3±9.3
ε_K, ΔM_q, |V_cb| — 0.827±0.083 (1.9σ) — 196.±11.
ε_K, ΔM_q, γ, B→τν — 0.905±0.047 (3.1σ) — 201.3±9.0
ΔM_q, |V_cb|, γ, B→τν — 0.889±0.055 (2.4σ) — 195.±11.
ε_K, ΔM_q, |V_cb|, B→τν — 0.870±0.049 (3.2σ) — 201.0±9.3
ε_K, ΔM_q, |V_cb|, γ, B→τν, |V_ub^tot| — 0.801±0.045 (2.4σ) — 200.±10.
ε_K, ΔM_q, |V_cb|, γ, B→τν, |V_ub^excl| — 0.712±0.037 (0.9σ) — 195.±11.
ε_K, ΔM_q, |V_cb|, γ, B→τν, |V_ub^incl| — 0.834±0.031 (3.9σ) — 200.3±9.7
ε_K, ΔM_q, |V_cb|, γ — 0.814±0.081 (1.8σ) — 194.±11.
[ε_K, ΔM_q, |V_cb|, γ, B→τν]*** — 0.859±0.055 (2.9σ) — 202.±13.
[ε_K, ΔM_q, |V_cb|, γ, B→τν]+++ — 0.867±0.050 (3.0σ) — 200.±9.3
b→ccs tree — 0.668±0.023
φK^0 — 0.44 +0.17 −0.18
η'K^0 penguin (clean) — 0.59±0.07
(φ,η')K — 0.57±0.065
K_SK_SK_S — 0.74±0.17
π^0K^0 — 0.57±0.17
ρ^0K_S — 0.54 +0.18 −0.21
ωK_S penguin (other) — 0.45±0.24
f_0K_S — 0.62 +0.11 −0.13
π^0π^0K_S — −0.72±0.71
φπ^0K_S — 0.97 +0.03 −0.52
K^+K^−K^0 — 0.82±0.07
−0.5
0.0
0.5
1.0
1.5
2.0
sin(2β)
"GOLD"
penguin dominated
LUNGHI + AS PLB 11


INPUT
BR(B→τν)×10^4
Deviation
sin2β
NO sin2β
sin(2β), ε_K, ΔM_q, |V_cb|, γ
sin(2β), ε_K, ΔM_q, |V_cb|
sin(2β), ε_K, ΔM_q, |V_cb|, γ, |V_ub|
sin(2β), ε_K, ΔM_q, γ
sin(2β), ΔM_q, |V_cb|, γ
ε_K, ΔM_q, |V_cb|, γ
f_B^lat, |V_ub|tot
f_B^lat, |V_ub|incl
f_B^lat, |V_ub|excl
BT(B→τν)exp
0.768±0.099 (2.7σ)
0.776±0.10 (2.7σ)
0.762±0.096 (2.8σ)
0.761±0.099 (2.8σ)
0.752±0.099 (2.8σ)
1.29±0.40 (0.86σ)
0.87±0.26 (2.0)
1.4±0.20 (<1σ)
0.74±0.14 (2.8)
1.68±0.31
≳ 2.76
≲ 0.96
−2
0
2
4

In a nutshell

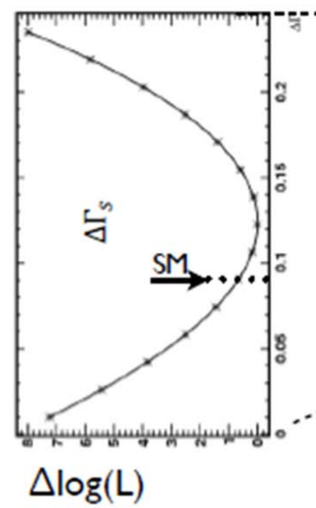
- **Bulk of NP effects is in Bd,Bs mixing & in sin2β {CONFIRMS our 2008 findings}**
- **Bulk of NP NOT in B->τν, or in ε_K [Presence of subdominant effects therein certainly possible]**
- **Many, many checks for robustness of the conclusions**
- **DIFFICULT to RECONCILE**

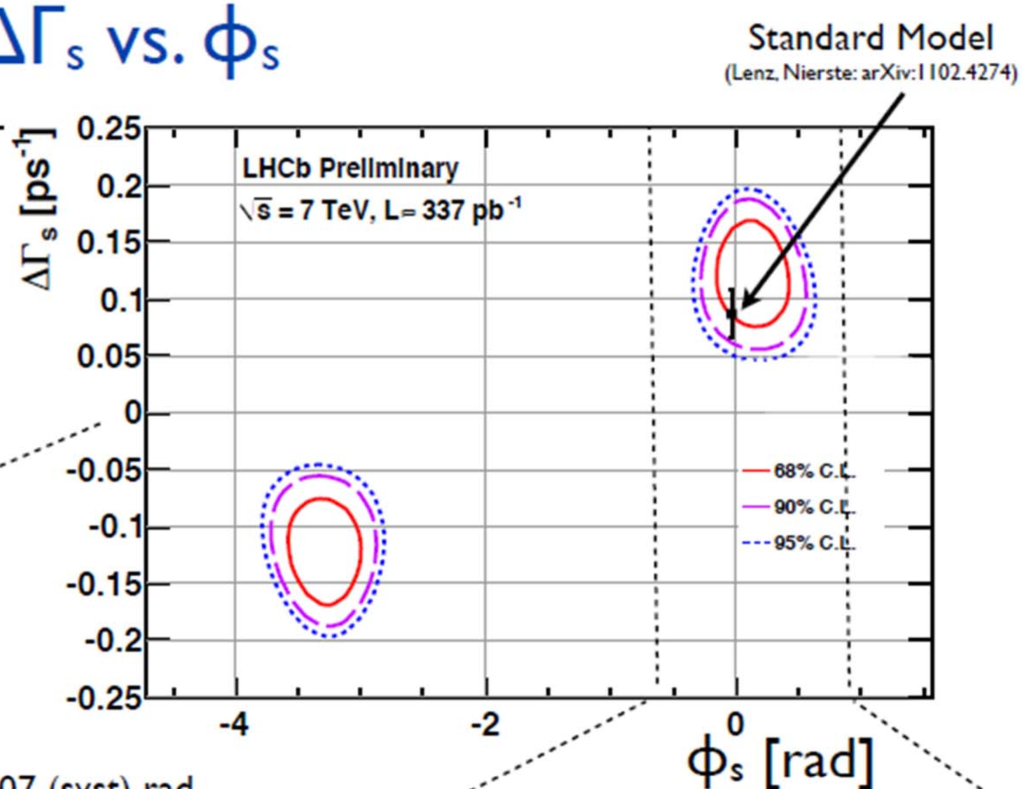
RESULTS with CKM-SM

G. Raven @ LP11

$B_s \to J/\psi\varphi$: $\Delta\Gamma_s$ vs. ϕ_s

LHCb-CONF-2011-49



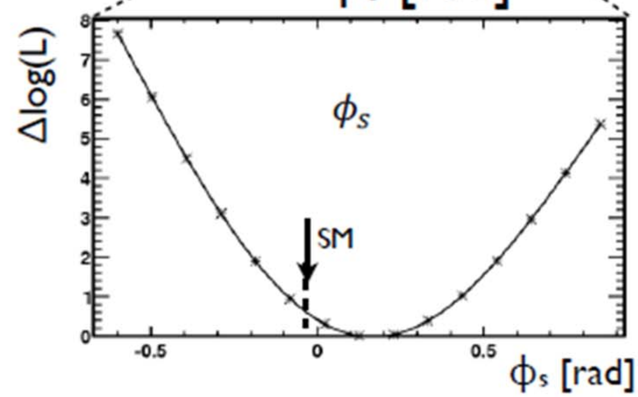


Most precise measurement of ϕ_s

- ϕ_s = 0.13 ± 0.18 (stat) ± 0.07 (syst) rad
- Consistent with SM

4 σ Evidence for $\Delta\Gamma_s \neq 0$:

- $\Delta\Gamma s$ = 0.123 ± 0.029 (stat) ± 0.008 (syst) ps^{-1}
- Γ_s = 0.656 ± 0.009 (stat) ± 0.008 (syst) ps^{-1}



31

(Sin2beta)tree vs (sin2beta)penguin

- The other hint is that b-> s penguin transitions have a non-vanishing BSM phase.
- Cleanest modes (eta' Ks, phi Ks) seem to show smaller value ~0.59 – 0.56
- Central value for several other modes is smaller than 0.68 [and of course practically all are well below the theory prediction ~0.85]

Note sin 42 deg = 0.67

sin 35 deg = 0.59 NEED TO TARGET such small deviation

~ 0.1 rad

SM: $\phi_s \sim -.04 \pm .02$

“…..but we have only just got started”, G Raven at LP11

A sentiment I enthusiastically share

Summary & Outlook

- Long & arduous effort; rather slow but steady progress….
- Simpler things like BK, fB, BB…now precision O(few%) already or very soon with important
  applications to UT & new physics search
- Most interesting K->pi pi, I=0 & epsilon' still
  not there yet but ReA0 ~O(15%),
  epsilon' ~O(30%) within sight
- QCDSP -> QCDOC -> QCDCQ , ~Dec'11 ->
- QCDCQ will tackle epsilon' first

Happy Birthday Alex!
We look forward to years of good physics from you!!