Lattice @ BNL

- Lattice has always been very special @ BNL due in particular to Creutz's original work over 25 years ago.
- Mike continues to be active in basic issues in LFT:
  Strong CP, SM on the lattice, chiral symmetry; rooting issues pertaining to staggered etc.
  For the past year Mike has a student Stanislav Srednyack from SB
- My focus :WME on the Lattice for long time now
- WME effort continues on with RBC; RBC + UKQCD collaborations
- Recent addition of Karsch (separate group) complements a very strong finite temp. aspect to Lattice@BNL.
- Also RBRC has its own QCDOC [and UKQCD has large fraction of another QCDOC at Edinburgh]
- DOE-National Infrastructure for LGC: QCDOC @BNL
- *Each QCDOC is ~5 sustained Tf (+ newest arrival due NYS is a BG/L but..)making BNL world class facility for Lattice gauge computations*.

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Brookhaven Installation

RBRC (right) and DOE (left) 12K-node QCDOC machines

Christ@scidac,jlab

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UKQCD Machine (12,288 nodes/10 Tflops)

Christ@scidac,jlab

Issues with staggered fermions and "rooting" M.C.

Staggered fermions come with four "tastes"

- one exact flavored chiral symmetry
- two "tastes" of each chirality
- 't Hooft vertex strongly couples tastes $\prod_{t=1}^{4}(\overline{\psi}_t\psi_t)$

"Rooting" replaces fermion determinant $|D|$ with $|D|^{1/4}$

- maintains the exact chiral symmetry
- rank of chiral symmetry group larger than desired

Rooting averages even and odd chirality

- desired target 't Hooft vertex $(\overline{\psi}\psi)$ forbidden by extra symmetry

Lattice Phenomenology with domain wall quarks:

Hunting New Physics with the Lattice

Outline

- Why lattice is needed
- Exact chiral symmetry on the Lattice
- Illustrative applications
- Relevance of lattice to the LHC era
- Summary, outlook & concerns

Why Lattice is Needed

Due to the non-perturbative nature of low energy QCD, many experimental results, often attained at enormous cost cannot be used effectively to test the Standard Model unless accurate values of hadronic matrix elements are known; lattice is the only reliable tool for such calculations

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

$|\varepsilon_K|$ (BNL '64; Christenson et al), provides a CLASSIC EXAMPLE.

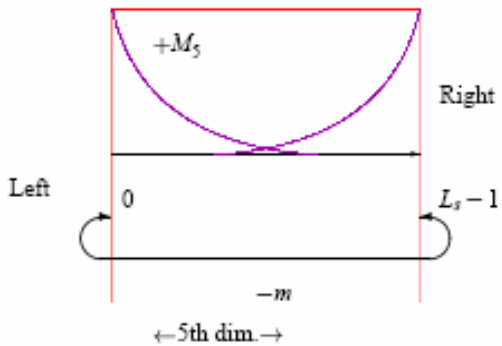
$$|\varepsilon_K| = \hat{B}_K C_K \lambda^6 A^2 \bar{\eta} \{\eta_1 S(x_c) + \eta_2 S(x_t)[A^2\lambda^4(1-\bar{\rho})] + \eta_3 S(x_c, x_t)\} \qquad C_K = \frac{G_F^2 f_K^2 m_K m_W^2}{6\sqrt{2}\pi^2 \Delta m_K}$$

The experimentally known value $|\varepsilon_K| = 2.27 \times 10^{-3}$ can be used to extract information on the poorly known SM parameters $\bar{\rho}$ and $\bar{\eta}$, once the non-perurbative quantity, B_K becomes known, as everything else on the RHS is known quite well.

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

Domain Wall Fermions at Ten Years

RIKEN BNL Research Center Workshop & Symposium...

March 15-17, 2007 at Brookhaven National Laboratory

Workshop On:

Domain Wall Fermions at Ten Years

The Workshop & Symposium Talks are now available online...

Date:	March 15-17, 2007
Location:	Brookhaven National Laboratory (BNL) Physics Department, Bldg 510, Large Seminar Room
Organizers:	Thomas Blum (BNL), Amarjit Soni (BNL)
Sponsors:	Brookhaven National Laboratory

- **Today is:** Friday, April 6, 2007
- Workshop Registration by Invitation Only (**Closed:** February 1, 2007)
- Additional GIS Registration for Non-U.S. Citizens (**Closed:** February 2, 2007) - If you are a Non-U.S. Citizen, you must complete a Guest Registration Form in addition to the Workshop Registration. Due to a required review process, **ALL** Foreign National attendees **must** be registered and approved in the BNL Guest Information System (GIS) before they will be allowed access to the site. The link to GIS will be provided to you after you have registered for this event.

Motivation & Plans

This workshop marks the 10th anniversary of domain wall fermion simulations in lattice QCD. It seems like a good idea to take stock of how far we have come and where we are headed with chirally symmetric lattice QCD calculations.

Today, continual improvements in massively parallel computers have made large scale dynamical simulations using chirally symmetric fermions become a reality. New algorithms and improved lattice actions are also becoming increasingly important to leverage these powerful machines. Even greater computing resources are expected in the near future and with exciting experiments at RHIC, JLab, J-PARC, (Super-)B factories and the LHC underway or coming soon, it is a crucial time for the lattice community to assess where we can make a large impact.

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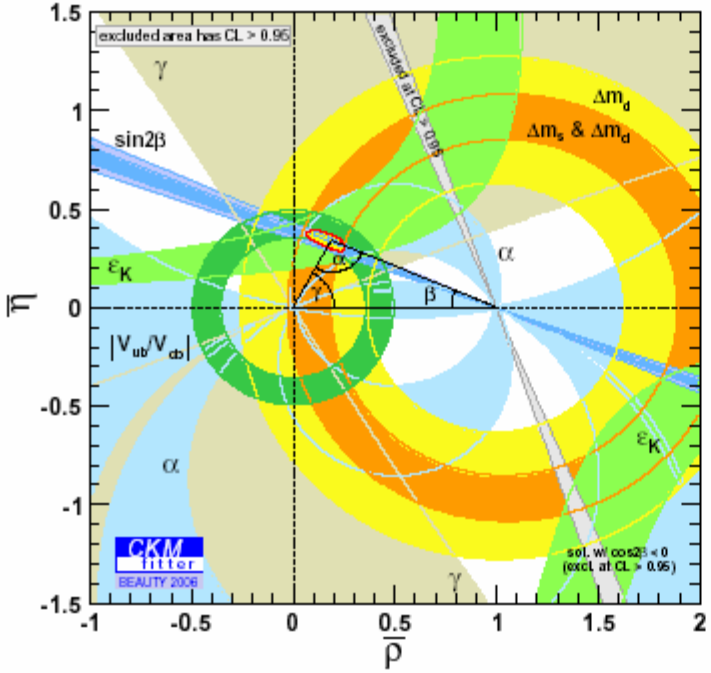
Kaon Bag Parameter

- Important theoretical input to the ϵ_K band which constrains the CKM unitary triangle.
- Lattice calculation is the only known first-principles calculation for B_K

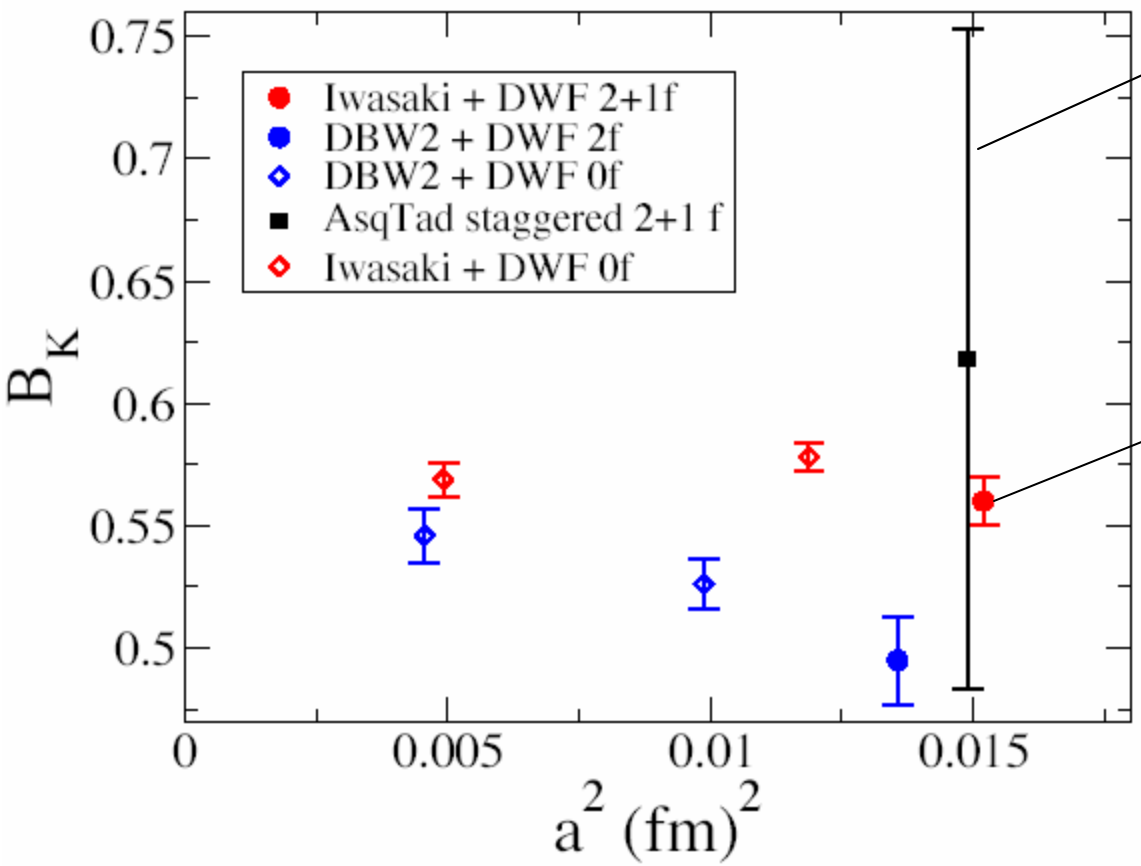


$$B_K = \frac{\langle \bar{K}_0 | \mathcal{O}_{LL}^{\Delta S=2} | K_0 \rangle}{\frac{8}{3} f_K^2 M_K^2}$$

On the lattice,

$$B_P = \frac{\langle \bar{K}_0 | \mathcal{O}_{LL}^{\Delta S=2} | K_0 \rangle}{\frac{8}{3} f_P^2 M_P^2}$$

Evaluate at $m_f = m_s^{phys}$ to get B_K.



Gimenez et al(HPQCD)
(staggered; 2+1)
PRD, 73,1145029(06)

RBC-UKQCD(DW;2+1);
hep-ph/0702042

Brief (~25 years) History of B_K

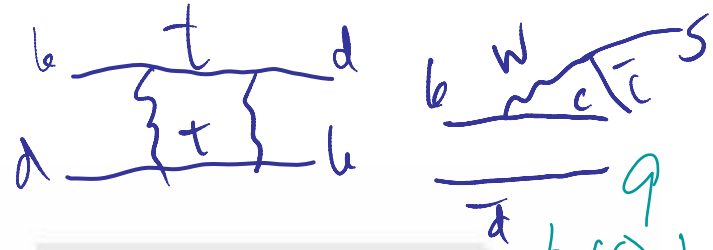
, ~'83 DGH use K^+ lifetime + LOChPT + SU(3)->
B_K ~0.33… no error estimate, no scale dependence… UNCONTROLLABLE APPROXIMATION

~'84 Lattice method for WME born…many attempts
& improvements for B_K evaluations

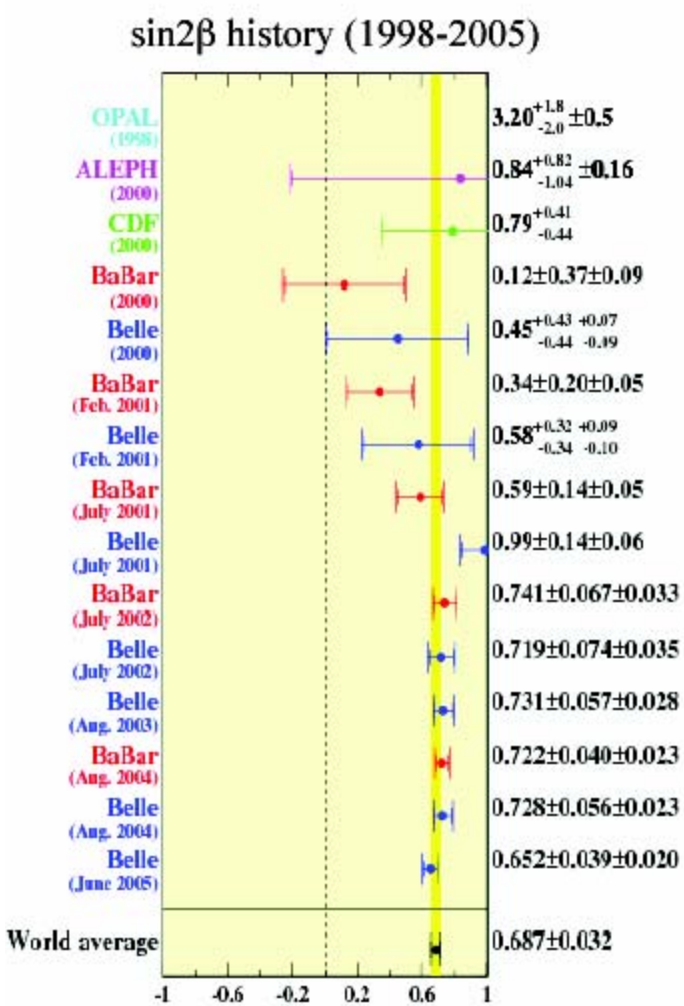
~'98 JLQCDstaggered B_K (2GeV)= 0.628(42)quenched(~110).
~'97 1st B_K with DWQ(T.Blum&A.S),0.628(47) quenched.
~'01 RBC B_K with DWQ, quenched=0.532(11) quenched

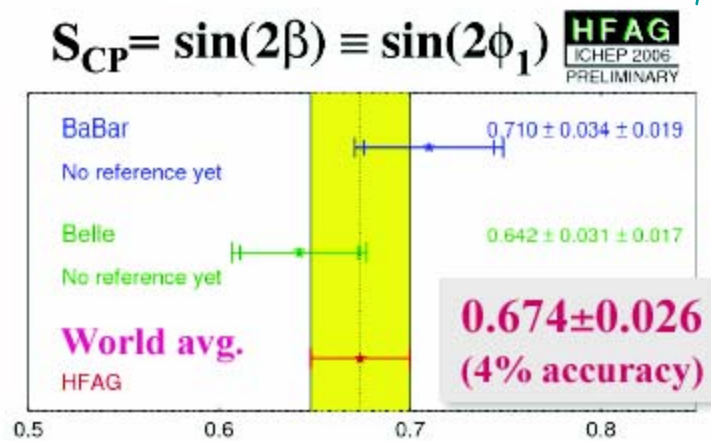
~'05 RBC , nf=2, dyn. DWQ, B_K =0.563(21)(39)(30)
~'06 Gimnez et al (HPQCD; stagg.) 2+1, B_K =0.618(18)(19)(30)(130)
~07,RBC-UKQCD DWQ 2+1 …..0.557(12)(29)
DWQ lower B_K -> requiring larger CKM-phase
~'08 Target 2+1 dyn. DWQ, B_K with total error 5%

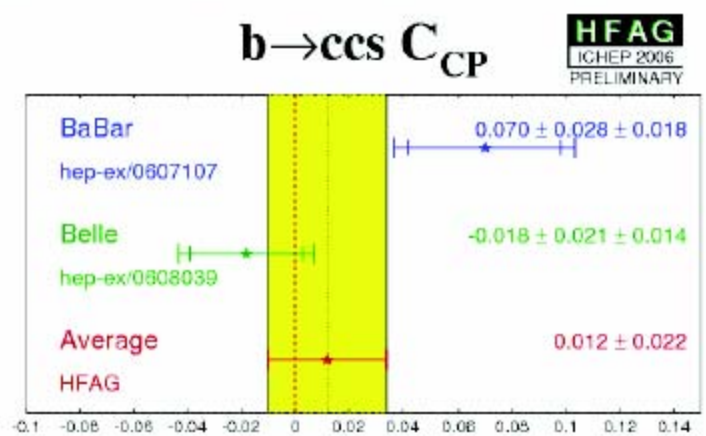
MEASUREMENT of $\beta(\phi_1)$



$10+5K
M-Y







SM $\sin 2\beta = .79 \pm .10$

Youngjoon Kwon@TC6,KEK,feb'07

B-factories & the lattice WME accomplish an important milestone!

- Phenomenal success of B-factories at a cost of ~$\$10^9$ produced a "clean" measurement
- Existing experimental info + Lattice WM's produced SM prediction
- Given the essential non-perturbative character of LEQCD and the only reliable method for handling that is the lattice, had it not been for the Lattice WM, B-factory clean #s could have turned into another ε'…
- This success though does not mean it should now be abandoned as further accuracy may well reveal the precious gem of New Physics….

. It is important to note that agreement of the SM-CKM paradigm and experimental measurements is only at the level of 15-20%.....

(Remember $\varepsilon_K \sim 10^{-3}$ so) plenty of BSM effects may be hiding within these errors….

Further improvement in accuracy in lattice calculations and experiments is highly desirable:

Target factor 2-3 reduction of theory error in sin 2β in 3-5 years!

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Motivation

- $K \to \pi l \nu$ (K_{l3}) decay leads to determination of $|V_{us}|$

$$decayrate \propto |V_{us}|^2 |f_+(q^2 = 0)|^2$$

- Require precise theoretical determination $f_+(0)$
- Current conservation $\Longrightarrow$ $f_+(0) = 1\Big|_{su(3)\ flavour\ limit}$
- Ademollo-Gatto Theorem -> second order SU(3) breaking effects in $f_+(0)$

$$f_+(0) = 1 + f_2 + f_4 + \cdots$$
$$\Rightarrow \Delta f = 1 + f_2 - f_+(0)$$

- [Leutwyler & Roos: $f_2 = -0.023$]

MODEL DEPENDENT

$$\Delta f = 1 + f_2 - f_+(0)$$

$$\Delta f = \begin{array}{ll} -0.016(8) & \text{(Leutwyler \& Roos, 1984)} \\ -0.017(5)(7) & \text{(Bećirević et al., quenched)} \\ -0.009(9) & \text{(Dawson et al., } N_f = 2 \text{ DWF)} \\ -0.025(4) & \text{(Tsutsui et al., } N_f = 2 \text{ Clover)} \\ -0.016(5) & \text{(Preliminary RBC/UKQCD)} \end{array}$$

WORK IN PROGRESS

Improve on earlier studies by:

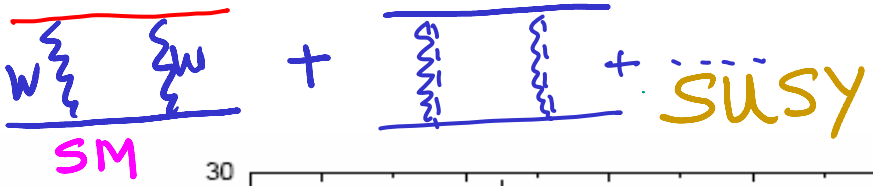
- Using $N_f = 2 + 1$ flavours of dynamical fermions
- Probing light quark masses
- Checking finite size effects

Relevance of Lattice to the LHC era

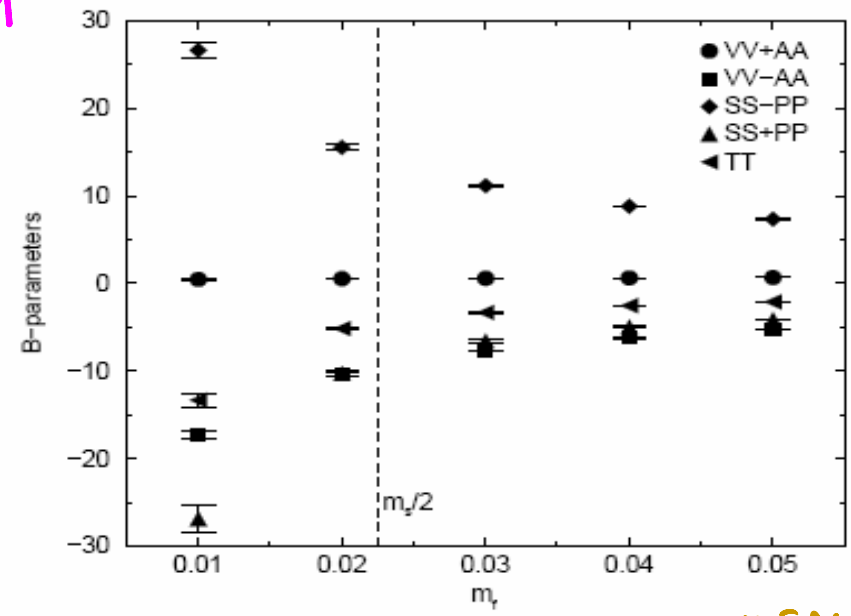
- QCD will be an integral part of any BSM scenario -> need ability for non-perturbative calculations.
- Two illustrations
- a) B_K
- b) proton lifetime
- See also Brower & Creutz write-up for SCIDAC (role of lattice for studying new strong dynamics that LHC may reveal)

Relevance of LQCD to the LHC era.

e.g. B_K (say due SUSY)



Y.Aoki et al (RBC) '05



SM

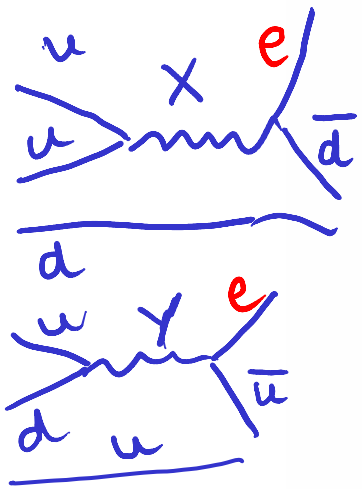
SUSY

FIG. 31: B-parameters for $\mathcal{O}_{VV+AA}$ (circle), $\mathcal{O}_{VV-AA}$ (square), $\mathcal{O}_{SS-PP}$ (diamond), $\mathcal{O}_{SS+PP}$ (triangle) and $\mathcal{O}_{TT}$ (left-triangle) for DBW2 $\beta = 1.04$ as a function of m_f.

Results for LEC's for proton decay

TABLE VI: Comparison of the low energy parameter of the nucleon decay chiral Lagrangian α and β among various QCD model calculation, lattice results in the literatures and the results from this work. Results with QCD model calculations are taken from the compilation by Brodsky et al. [15] In lattice QCD calculations, WF and DWF mean Wilson and domain-wall fermions. Our quenched results are shown with the total error consisting of statistical and systematic errors on the bare matrix elemnt, renormalization constant and scale. The unquenched errors are only statistical.

		$\lvert\alpha\rvert$ [GeV^3]	$\lvert\beta\rvert$ [GeV^3]	
QCD model calculation	Donoghue and Goldwich [10]	0.003		Bag model
	Thomas and McKellar [13]	0.02		Bag model
	Meljanac et al. [11]	0.005		Bag model
	Ioffe [8]	0.009		Sum rule
	Krasnikov et al. [12]	0.006		Sum rule
	Ioffe and Smilga [14]	0.006		Sum rule
	Tomozawa [9]	0.006		Quark model
	Brodsky et al. [15]	0.03		
Lattice QCD $N_f = 0$	Hara et al. [16]	0.03		WF, $a^{-1} = 1.8$ GeV
	Bowler et al. [17]	0.013	0.010	WF, $a^{-1} = 0.9$ GeV
	Gavela et al. [18]	0.0056(8)	$\simeq \lvert\alpha\rvert$	WF, $a^{-1} = 2$ GeV
	JLQCD [19]	0.015(1)	0.014(1)	WF, $a^{-1} = 2.3$ GeV
	CP-PACS & JLQCD [20]	$0.0090(09)(^{+5}_{-19})$	$0.0096(09)(^{+6}_{-20})$	WF, continuum limit
	This work	0.0100(19)	0.0108(21)	DWF, $a^{-1} = 1.3$ GeV
Lattice QCD $N_f = 2$	This work	0.0117(21)	0.0117(21)	DWF, $a^{-1} = 1.7$ GeV



WITH DYN. 2+1 NOW IN PROGRESS

Near future (lattice) outlook

- RBC -> [RBC + UKQCD] DWF project
- Due to the QCDOC machines @BNL and @ Edinburgh, factor of ~20 more computing power over '98-'04(QCDSP)…full QCD dynamical domain wall simulations in progress since ~05…many quantities relevant to phenomenology being computed.
- Look forward to improved calculations of B_K , ε'/ε, K_{l3}, p->eπ and many other quantities of physical interest.

. Note: Lattice will be relevant even in the LHC era

HET Group Publications 2006-Present

Creutz, Michael:

The Evil that is rooting.
Michael Creutz (Brookhaven). Jan 2007. 10pp.
e-Print Archive: hep-lat/0701018

So you want to be a lattice theorist?
Michael Creutz (Brookhaven). Oct 2006. 6pp.
Talk given at Quark Confinement and the Hadron Spectrum 7, Ponta Delgada, Azores, Portugal, 2-7 Sep 2006.
e-Print Archive: hep-lat/0610067

One flavor QCD.
Michael Creutz (Brookhaven). Sep 2006. 29pp.
e-Print Archive: hep-th/0609187

Diseases with rooted staggered quarks.
Michael Creutz (Brookhaven). Aug 2006. 5pp.
Contributed to 24th International Symposium on Lattice Field Theory (Lattice 2006), Tucson, Arizona, 23-28 Jul 2006.
e-Print Archive: hep-lat/0608020

Flavor extrapolations and staggered fermions.
Michael Creutz (Brookhaven). Mar 2006. 8pp.
e-Print Archive: hep-lat/0603020

Davoudiasl, Hooman:

Signatures of Spherical Compactification at the LHC.
Hooman Davoudiasl (Brookhaven), Thomas G. Rizzo (SLAC). SLAC-PUB-12327, BNL-HET-07-4, Feb 2007. 21pp. Submitted to JHEP.
e-Print Archive: hep-ph/0702078

Warped Gravitons at the LHC and Beyond.
Kaustubh Agashe (Syracuse U.), Hooman Davoudiasl (Brookhaven), Gilad Perez (YITP, Stony Brook), Amarjit Soni (Brookhaven). SU-4252-843, BNL-HET-07-3, YITP-SB-07-02, Jan 2007. 9pp.
e-Print Archive: hep-ph/0701186

Tevatron for LHC report: Higgs.
U. Aglietti *et al.* FERMILAB-CONF-06-467-E-T, Dec 2006. 138pp.
e-Print Archive: hep-ph/0612172

Quantum sampling in the landscape during inflation.
Hooman Davoudiasl (Brookhaven & Wisconsin U., Madison), Sash Sarangi (Columbia U.), Gary Shiu (Wisconsin U., Madison). BNL-HET-06-16, MAD-TH-06-10, MADPH-06-1469,

CU-TP-1165, Nov 2006. 5pp.
e-Print Archive: hep-th/0611232

Cosmology with Light Axions from Technicolor.
Hooman Davoudiasl (Wisconsin U., Madison). MADPH-06-1468, Jul 2006. 4pp.
e-Print Archive: hep-ph/0607111

Dawson, Sally:

Chiral-logarithmic Corrections to the S and T Parameters in Higgsless Models.
S. Dawson, C.B. Jackson. Mar 2007. 45pp.
e-Print Archive: hep-ph/0703299

PANIC international forum: Physics at high energies - vision for the future.
S. Dawson, S. Aronson, P. Oddone, F. Takasaki, A. Wagner (Brookhaven & Fermilab & KEK, Tsukuba & DESY). 2006. 1pp. Prepared for Particles and Nuclei International Conference (PANIC 05), Santa Fe, New Mexico, 24-28 Oct 2005. Published in AIP Conf.Proc.842:1109-1109,2006. Also in "Santa Fe 2005, Particles and nuclei" 1109-1109.

Tevatron for LHC report: Higgs.
U. Aglietti *et al.* FERMILAB-CONF-06-467-E-T, Dec 2006. 138pp.
e-Print Archive: hep-ph/0612172

QCD Corrections to Higgs Pair Production in Bottom Quark Fusion.
Sally Dawson (Brookhaven), Chung Kao (Fermilab & Oklahoma U.), Yili Wang, Peter Williams (Oklahoma U.). FERMILAB-PUB-06-378-T, Oct 2006. 23pp.
Published in Phys.Rev.D75:013007,2007.
e-Print Archive: hep-ph/0610284

Higgs triplets and limits from precision measurements.
Mu-Chun Chen (Fermilab), Sally Dawson, Tadas Krupovnickas (Brookhaven). FERMILAB-PUB-06-065-T, BNL-06-2, Apr 2006. 4pp.
Published in Phys.Rev.D74:035001,2006.
e-Print Archive: hep-ph/0604102

Chris Jackson:

Tevatron for LHC report: Higgs.
U. Aglietti *et al.* FERMILAB-CONF-06-467-E-T, Dec 2006. 138pp.
e-Print Archive: hep-ph/0612172

Shrihari Gopalakrishna:

Stop Decay into Right-handed S neutrino LSP at Hadron Colliders.
Andre de Gouvea, Shrihari Gopalakrishna (Northwestern U.), Werner Porod (Valencia U., IFIC). NUHEP-TH-06-05, Jun 2006. 24pp. Published in JHEP 0611:050,2006.
e-Print Archive: hep-ph/0606296

Exclusive Drell-Yan production at next-to-next-to-leading order.
W.B. Kilgore (Brookhaven). 2006. 5pp.
Prepared for 8th DESY Workshop on Elementary Particle Theory: Loops and Legs in Quantum Field Theory, Eisenach, Germany, 23-28 Apr 2006.
Published in Nucl.Phys.Proc.Suppl.160: 12-16,2006. Also in "Eisenach 2006, Elementary particle theory" 12-16.

Tevatron-for-LHC Report of the QCD Working Group.
TeV4LHC QCD Working Group *et al.* FERMILAB-CONF-06-359, Oct 2006. 156pp.
e-Print Archive: hep-ph/0610012

Les houches physics at TeV colliders 2005, standard model and Higgs working group: Summary report.
C. Buttar *et al.* Apr 2006. 234pp.
Contributed to Les Houches Workshop on Physics at TeV Colliders, Les Houches, France, 2-20 May 2005.
e-Print Archive: hep-ph/0604120

Tadas Krupovnickas:

LHC Signals from Warped Extra Dimensions.
Kaustubh Agashe (Syracuse U.), Alexander Belyaev (Michigan State U.), Tadas Krupovnickas (Brookhaven), Gilad Perez (YITP, Stony Brook), Joseph Virzi (LBL, Berkeley).
BNL-HET-06-13, MSUHEP-060915, SU-4252-838, YITP-SB-06-43, Dec 2006. 11pp.
e-Print Archive: hep-ph/0612015

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Mu-Chun Chen (Fermilab), Sally Dawson, Tadas Krupovnickas (Brookhaven). FERMILAB-PUB-06-065-T, BNL-06-2, Apr 2006. 4pp. Published in Phys.Rev.D74:035001,2006.
e-Print Archive: hep-ph/0604102

William Marciano:

The weak mixing angle and new physics (a tale of two numbers).
W.J. Marciano (Brookhaven). 2006. 4pp.
Prepared for CIPANP 2006: 9th Conference on the Intersections of Particle and Nuclear Physics, Westin Rio Mar Beach, Puerto Rico, 30 May - 3 Jun 2006.
Published in AIP Conf.Proc.870:236-239,2006. Also in "Rio Grande 2006, Intersections of particle and nuclear physics" 236-239.

Electroweak physics: Precision studies.
W.J. Marciano (Brookhaven). 2006. 10pp.
Prepared for Particles and Nuclei International Conference (PANIC 05), Santa Fe, New Mexico, 24-28 Oct 2005.

Published in AIP Conf.Proc.842:651-660,2006. Also in "Santa Fe 2005, Particles and nuclei" 651-660.

Intense neutrino beams and leptonic CP violation.
William Marciano, Zohreh Parsa (Brookhaven). BNL-HET-06-14, Oct 2006. 7pp.
Contributed to 22nd International Conference on Neutrino Physics and Astrophysics (Neutrino 2006), Santa Fe, New Mexico, 13-19 Jun 2006.
e-Print Archive: hep-ph/0610258

Review of Particle Physics.
By Particle Data Group (W.M. Yao *et al.*). 2006. Published in J.Phys.G33:1-1232,2006.

Proposal for an Experimental Program in Neutrino Physics and Proton Decay in the Homestake Laboratory.
M. Diwan *et al.* BNL-76798-2006-IR, Aug 2006. 47pp.
e-Print Archive: hep-ex/0608023

Amarjit Soni:

K(l3) form factor with N(f) = 2+1 dynamical domain wall fermions: A Progress report.
D.J. Antonio, P.A. Boyle, C. Dawson, T. Izubuchi, A. Juttner, C. Sachrajda, S. Sasaki, A. Soni, R.J. Tweedie, J.M. Zanotti (Edinburgh U. & RIKEN BNL & Kanazawa U., Inst. Theor. Phys. & Southampton U. & Tokyo U. & Brookhaven). EDINBURGH-2007-4, SHEP-0706, Feb 2007. 4pp.
Talk given at 4th International Workshop on the CKM Unitarity Triangle (CKM 2006), Nagoya, Japan, 12-16 Dec 2006.
e-Print Archive: hep-lat/0702026

Future prospects for heavy flavor physics: Round table.
A. Masiero (Padua U. & INFN, Padua), F. Ferroni (Rome U. & INFN, Rome), T.E. Browder (Hawaii U.), M. Ciuchini (INFN, Rome3 & Rome III U.), S. Playfer (Edinburgh U.), A. Soni (Brookhaven). 2007. 5pp.
Prepared for Workshop on Theory, Phenomenology and Experiments in Heavy Flavor Physics, Capri, Italy, 29-31 May 2006. Published in Nucl.Phys.Proc.Suppl.163:198-202,2007. Also in "Capri 2006, Theory, phenomenology and experiment in heavy flavor physics" 198-202.

Warped Gravitons at the LHC and Beyond.
Kaustubh Agashe (Syracuse U.), Hooman Davoudiasl (Brookhaven), Gilad Perez (YITP, Stony Brook), Amarjit Soni (Brookhaven). SU-4252-843, BNL-HET-07-3, YITP-SB-07-02, Jan 2007. 9pp.
e-Print Archive: hep-ph/0701186

2+1 flavor domain wall QCD on a (2 fm)^3 lattice: Light meson spectroscopy with L(s) = 16.
By RBC Collaboration and UKQCD Collaboration (C. Allton *et al.*). BNL-HET-07-1, CU-TP-1175, EDINBURGH-2007-1, KEK-TH-1132, RBRC-637, SHEP-0701, SWAT-07-502, Jan 2007. 17pp.
e-Print Archive: hep-lat/0701013

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Clean Signals of CP-violating and CP-conserving New Physics in B ---> P V gamma Decays at B Factories and Hadron Colliders.
David Atwood (Iowa State U.), Tim Gershon (Warwick U.), Masashi Hazumi (KEK, Tsukuba), Amarjit Soni (Brookhaven). BNL-HET-06-15, Jan 2007. 16pp.
e-Print Archive: hep-ph/0701021

A Striking signature of heavy Majorana neutrinos in charged Higgs pair production at the ILC.
David Atwood (Iowa State U.), Shaouly Bar-Shalom (Technion), Amarjit Soni (Brookhaven). BNL-HET-06-19, Jan 2007. 5pp.
e-Print Archive: hep-ph/0701005

First results from 2+1-Flavor Domain Wall QCD: Mass Spectrum, Topology Change and Chiral Symmetry with L_s=8.
D.J. Antonio *et al.* Dec 2006. 82pp.
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Summary, Outlook & Concerns

I. HET group has expertise & interests in diverse areas of HEP, precision EW, flavor, collider,LHC & RHIC phenomenology and is also very strong in its lattice gauge effort .

2. We thank the reviewers & the DOE for adding one PD so now total is four: should help in capitalizing advent of LHC era in light of group's Interest & expertise given also that BNL is a major player of ATLAS in the US

3. Unfortunately for past 3-4 years 0 lattice PD in HET. This is a concern given the continuing importance of the subject…Note also BNL(RBC) lattice PD's : Blum('04), Orginos('05), Wingate('06) & now Dawson('07) promotion to junior faculty positions in the last 4 years.

4. *Having said all that must also emphasize that addition to lattice at the expense of phenomenology not desirable in this era*