Recent results of CKM physics, quark masses from RBC/UKQCD

Taku Izubuchi
for Riken-BNL-Columbia/UKQCD collaboration

BROOKHAVEN NATIONAL LABORATORY

RIKEN BNL Reserch Center

Deepest Condolences to those who suffer from Tohoku-Pacific Ocean Earthquake, and all my best wishes for their earliest recovery.

- Lattice QCD computation : ''Accelerator'' and ''Detector''
- CKM physics : continuum limit of B_K
- QCD+QED simulation : up, down and strange quark masses
- Conclusion
-
- (Current situation of Japanese community)

RBC/UKQCD collaboration

RIKEN-BNL Research Center (RBRC)

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S. Ohta, E. Shintani

BNL
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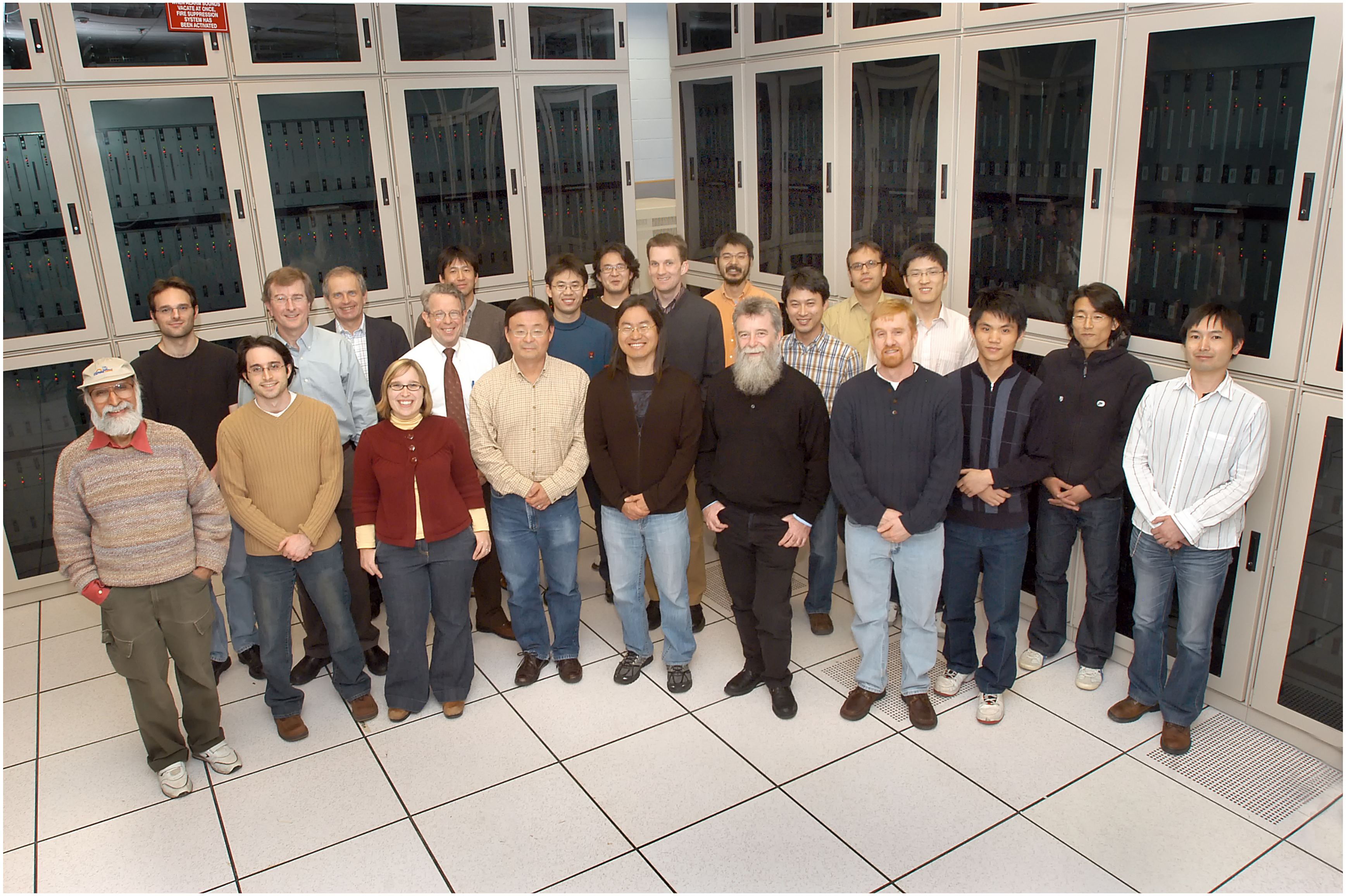
CERN A. Juttner

11 students, 18 PhD theses

RBC/UKQCD collaboration



Lattice QCD Advertisements

- Lattice QCD (LQCD, or LGT) is a perfect way to calculate physical quantities of QCD based on the first principle.
- Systematic errors could be, in principle, completely removable.

  - Perturbation theory is reliable for QED, and high energy QCD
  - Unknown truncation errors (α_s^n).
  - Non-perturbative effects of, $e.g.$ a form

    $$\exp[-1/\alpha_s^2] = 0 + 0\alpha_s^2 + 0\alpha_s^4 \cdots$$

    has no perturbative expansion in α_s, which could be important for QCD's phenomena : bound states (Hadron), spontaneously breaking chiral symmetry, confinement of colored,....

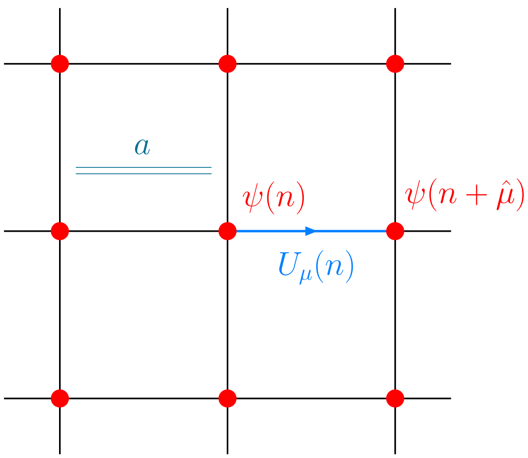
LGT computing has two ingredients :

- QCD vacuum ensemble generation $\sim$ Accelerator
- Physical observable measurements $\sim$ Detector

Lattice Gauge Theory

- Analysis of Quantum Field Theory such as Quantum Chromo Dynamics, needs non-perturbative calculation.

  $\Psi(x), A_\mu(x), x \in \mathcal{R}^4$: *continuous infinity*
  quantum divergences: needs regularization and renormalization



- Discretized Euclidean space-time
- lattice spacing $a \sim 0.1$ fm
  (UV cut-off $|p| \leq \pi/a$)

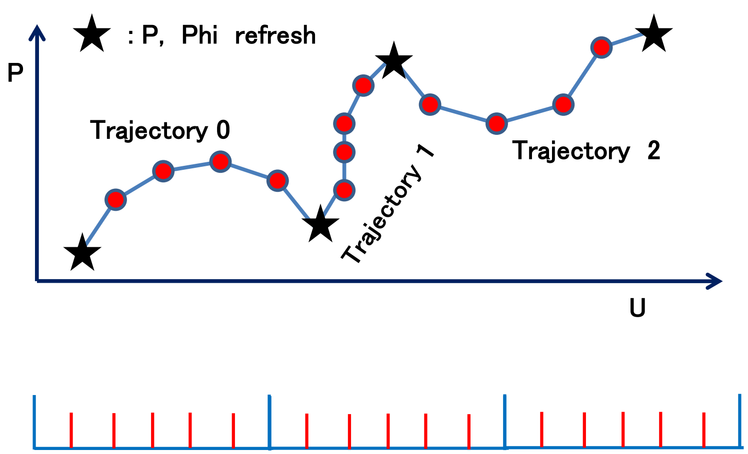
- $\psi(n)$: Fermion field (Grassmann number)
- $U_\mu(n)$: Gauge field

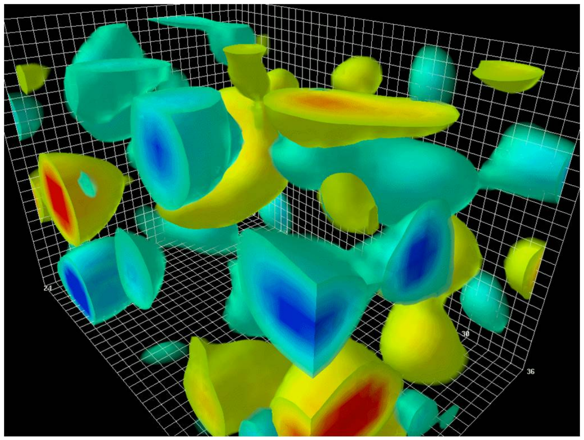
- Feynman's path integral for Huge dimensional variables $32^3 \times 64 \sim 150$M
  Number of states (for simplest 4^4 Ising) $2^{4^4} \sim 10^{77}$ needs more than 10^{35} years !

Hybrid Monte Carlo (LGT's "Accelerator")

- Monte Carlo to Sample Important configurations of QCD action $e^{-S_{\rm QCD}}$
- Accumulate samples of QCD vacuum, typically $\mathcal{O}(100) \sim \mathcal{O}(1,000)$ files of gauge configuration $U_\mu(n)$ on disk (1 $\sim$ 10 GB/conf).
- By solving a classical QCD, with an occasional stochastic "hit": exactly $\propto e^{-S_{\rm QCD}}$
- Must generate sequentially $\{U_\mu^{(0)} \to U_\mu^{(1)} \to \cdots\}$, which needs capable machines.

$$\text{Prob}(U_\mu) \propto \det D_{u,d,s}[U] e^{-S_g}$$





[D. Leinweber]

- RHMC for odd flavor [Clark Kennedy]
- Solve short (long) modes more (less) frequently [Hasenbush's trick]

Domain Wall Quarks (for up, down, and strange)

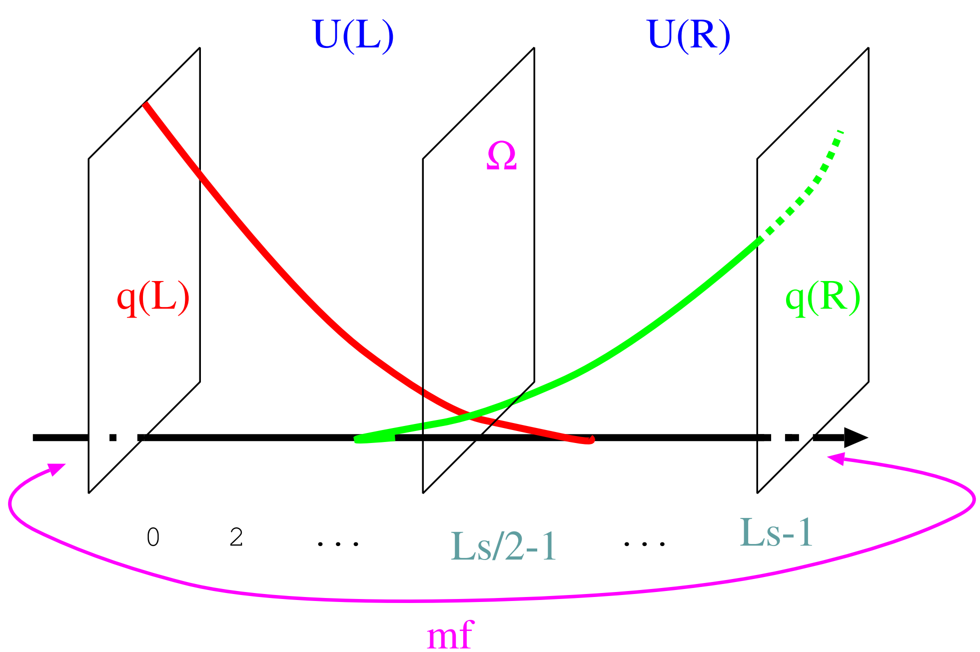
[Kaplan, Shamir, Blum & Soni]

- 4D lattice quark utilizing an ''extra dimension'', L_s. (expensive)
- Almost perfect chiral symmetry

  Small unphysical mixing for the Weak Matrix Elements

  Error from discretization is small $\mathcal{O}(a^2\Lambda^2_{QCD}) \sim$ a few %.

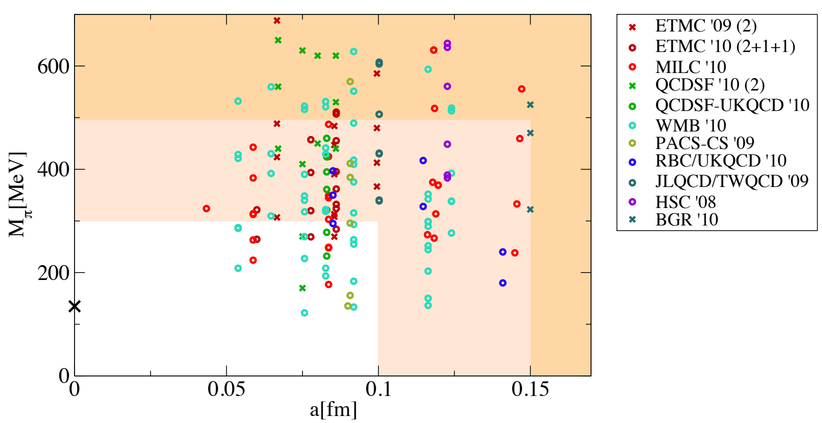
  Chiral extrapolation is simpler, continuum like.
- Unitary theory (at long distance).

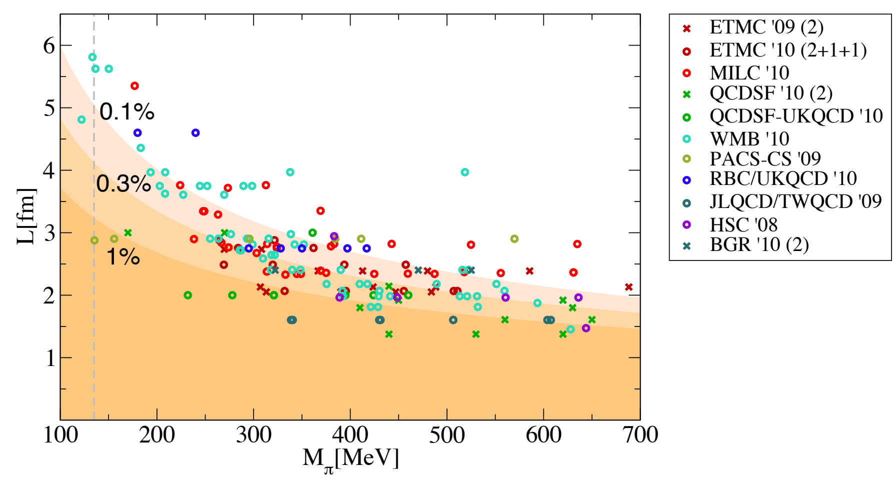


Parameters of "Accelerator" (HMC)

- Number of QCD vacuum ensembles, controls statistical accuracies ("Luminosity"). $N_{\text{conf}} \sim \mathcal{O}(100 - 1,000)$,
- lattice spacings a controls discretization errors $a \sim$ 0.05-0.15 fm
- up, down, and strange ($N_F = 2+1$) quark masses : $\underline{m_u, m_d, m_s} < \Lambda_{\text{QCD}} < m_c, m_b, m_t$ lighter the more computationally demanding $\propto m_q^{-3}$. M_π : 190 $\sim$ 500 MeV
- lattice volume V : $(2 \sim 6\text{fm})^3$

[C. Hoelbling, Lattice 2010]





Physics measurements "Detectors"

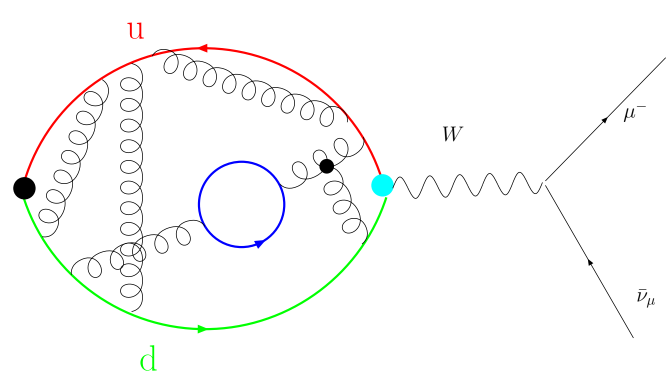
- Measurements physical observables on the vacuum ensemble.

$$\langle \mathcal{O} \rangle = \int \underline{\mathcal{D}U_\mu \, \text{Prob}[U_\mu]} \times \mathcal{O}[U_\mu]$$

- Could do Analysis on many configurations independently (trivial parallel jobs) $\longrightarrow$ could also use PC Clusters

- We made hadron operator (EW operators) from quark, and let the quark propagates on each of the generated QCD configuration (by solving the Dirac Eq)

- Obtain hadron mass or QCD matrix elements of operators



$\langle 0|\bar{d}\gamma_5 u(0)|\pi\rangle \frac{e^{ipx}}{\sqrt{2E}} \langle \pi|\bar{u}\gamma_m u\gamma_5 d|0\rangle \times G_F V_{ud} m_\mu \bar{\nu}(1-\gamma_5)\mu$

$$\mathcal{M}(\pi \to \mu\overline{\nu}) \sim i f_\pi q_\mu \times G_F V_{ud} m_\mu (\overline{\nu}\mu)_L$$

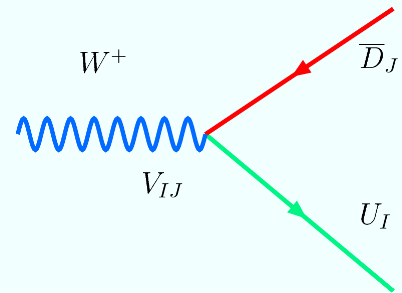
$$= \langle \pi(q)|\bar{u}\gamma_\mu\gamma_5 d(0)|0\rangle \times G_F V_{ud} m_\mu (\overline{\nu}\mu)_L$$

CKM physics on DWQCD

[Ruth Van de Water lat09]

- In 1963, N. Cabbibo, then M. Kobayashi and T. Maskawa in 1973 introduced a mixing between quark flavors.

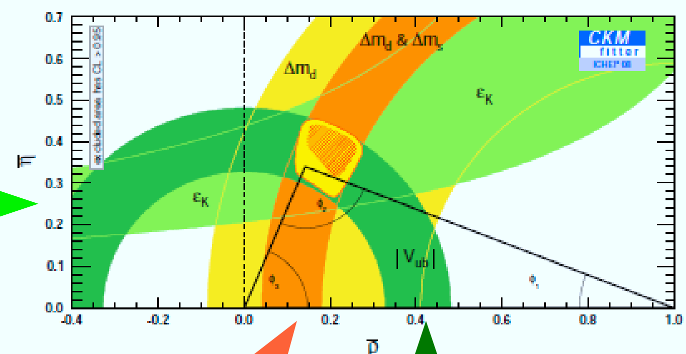
$$V_{CKM} = \begin{bmatrix} V_{ud}, V_{us}, V_{ub} \\ V_{cd}, V_{cs}, V_{cb} \\ V_{td}, V_{ts}, V_{tb} \end{bmatrix} \approx \begin{bmatrix} 1-\lambda^2/2, & \lambda, & A\lambda^3(\rho - i\eta) \\ -\lambda, & 1-\lambda^2/2, & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta), & -A\lambda^2, & 1 \end{bmatrix}$$



- Unitary condition CKM matrix includes: the unitarity triangle

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

K_0-$\overline{K}_0$ B_K



- To pin down the CKM, and to search for the new physics, the Hadron matrix elements is needed: EXPT. = CKM x LATTICE

B decay, B_0-$\overline{B}_0$

$B \rightarrow \pi$ l nu

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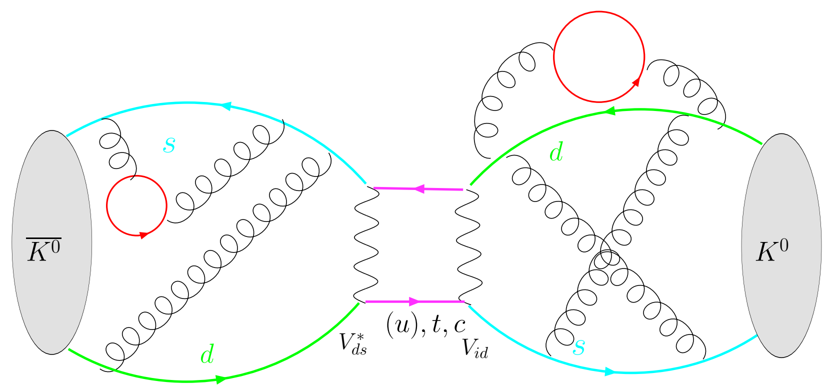
$K^0 - \overline{K^0}$ mixing, Indirect CP violation

- $K^0_{L,S}$ are the superpositions of CP eigen states $|K^0_\pm\rangle$
  $|K_{L,S}\rangle \sim \frac{1}{\sqrt{1+\epsilon_K^2}}\left(|K^0_\mp\rangle + \epsilon_K|K^0_\pm\rangle\right)$

- To compared with experimentally measured ϵ_K, one needs to evaluate the matrix elements of EW Hamiltonian



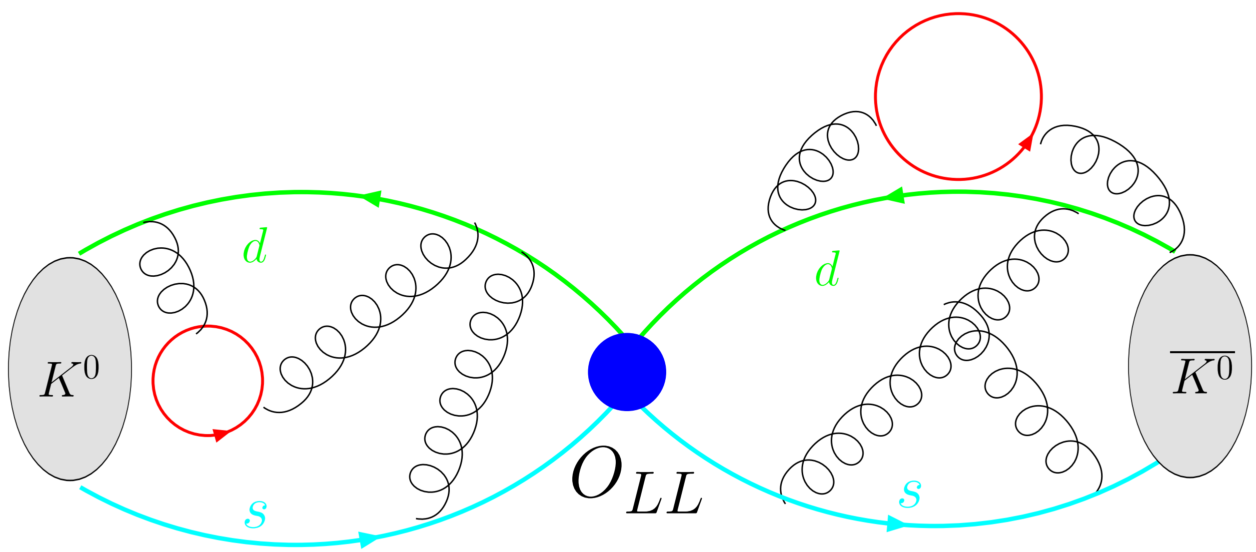
$$H^{\Delta S=2} = \frac{G_F^2 M_W^2}{16\pi^2}\left[\,(V^*_{cd}V_{cs})^2 F(x_c) + (V^*_{td}V_{ts})^2 F(x_t)\right.$$
$$\left. + \quad 2(V^*_{td}V_{ts}V^*_{cd}V_{cs})\bar{F}(x_c, x_t)\,\right] O_{LL}$$

Besides known perturbative functions, this leads to Kaon's bag parameter B_K

$$O_{LL} = \bar{s}\gamma_\mu(1-\gamma_5)d\bar{s}\gamma_\mu(1-\gamma_5)d$$

$$\epsilon_K = \mathcal{A} - \mathcal{B}\eta\rho\hat{B}_K$$

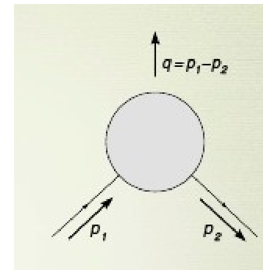
$$B_K = \frac{\hat{B}_K}{\alpha(\mu)^{-\gamma_0/(2\beta_0)}} = \frac{\langle\bar{K}|O_{LL}|K\rangle}{\langle\bar{K}|O_{LL}|K\rangle_{VS}} = \frac{\langle\bar{K}|O_{LL}|K\rangle}{\frac{8}{3}f_K^2 M_K^2}$$



Calibration of "Detector"

New Renormalization Schemes

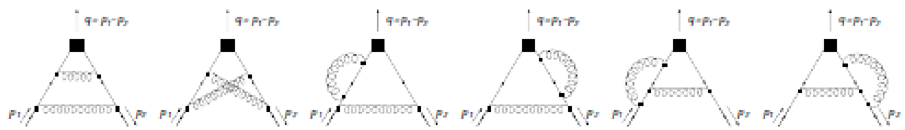
[09 C. Sturm, Y. Aoki, N. Christ, TI, C. Sachrajda, A. Soni]
[10 L. Almeida, C. Sturm]



$(q^2 = p_1^2 = p_2^2)$

- Match the normalization of operator on lattice and in continuum theory (MS) via RI/SMOM schemes

  calculate the 3 pt amplitudes for a momentum configuration (SMOM) on lattice non-perturbatively, and in continuum theories.



- We find symmetric momentum (SMOM) configuration is useful to reduce one of the dominant systematic errors due to IR effects.

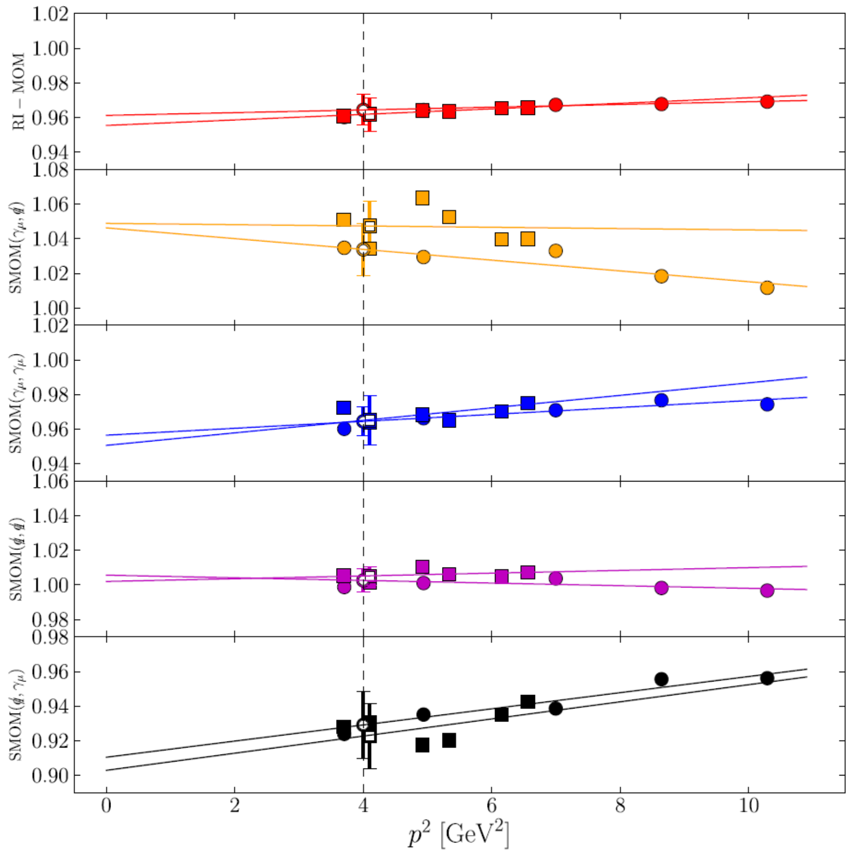
- Quark mass renormalization error

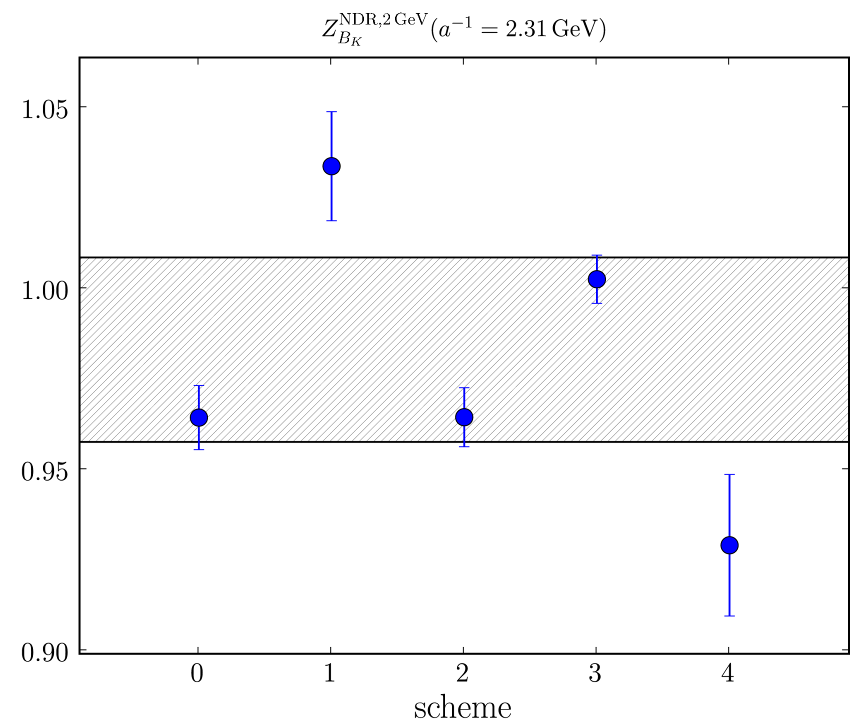
  ~10% (MOM) → ~ 5% (SMOM) → ~ 2% (SMOM 2loop) ,

- Using different RI/SMOM schemes (using various spinor projections) to check the systematic errors

- Four quark operator for B_K

Z(BK) systematic errors

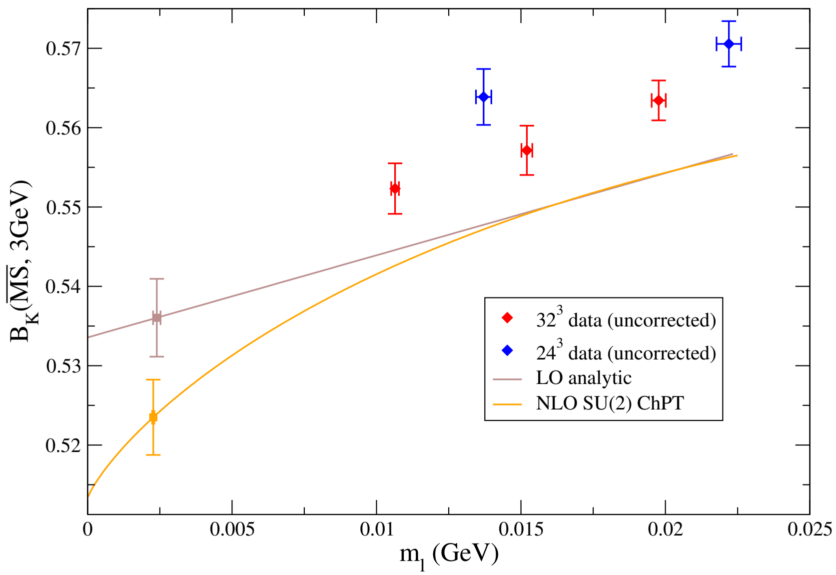


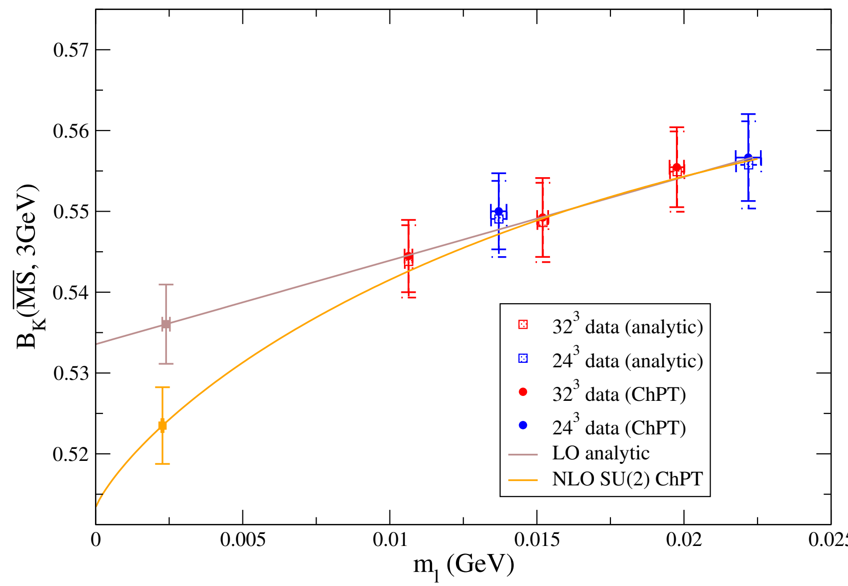


$$Z_{B_K}^{NDR}(\mu = 2\mathrm{GeV}, a^{-1} = 2.31\mathrm{GeV}) = 0.964(25)[2.6\%]$$

$$Z_{B_K}^{NDR}(\mu = 2\mathrm{GeV}, a^{-1} = 1.73\mathrm{GeV}) = 0.936(30)$$

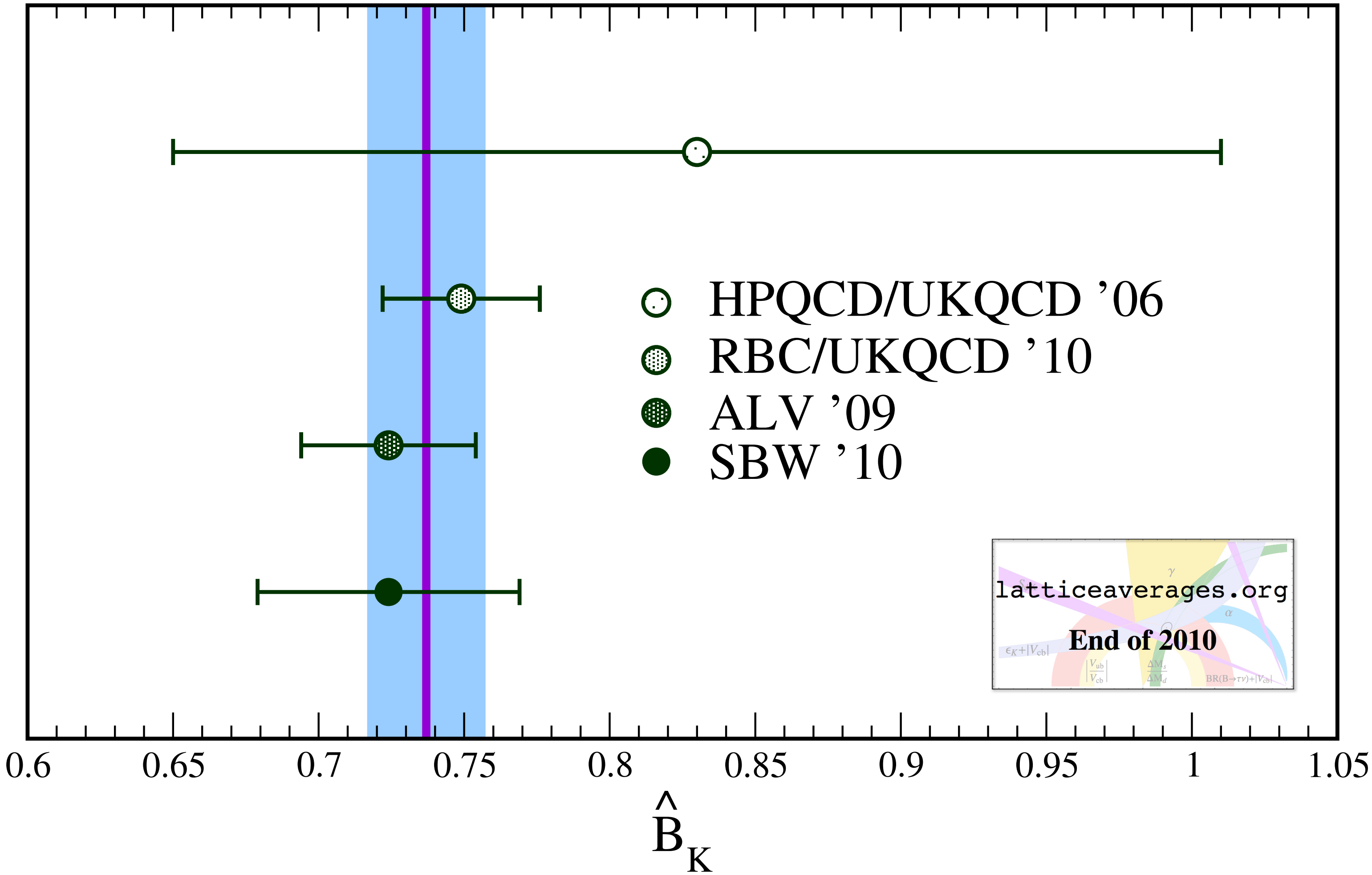
a^2 correction of B_K





- a^{-1} =1.73(3) GeV and 2.28(3) GeV.
- $\mathcal{O}(a^2)$ correction is done to data point in right plot
- Two extrapolations: SU(2)+Kaon ChPT and the linear.

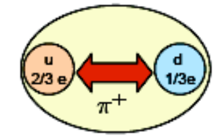
Comparison with other results



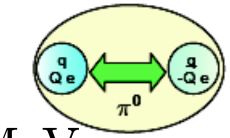
- $\hat{B}_K = 0.749(7)_{stat}(21)_{\chi}(3)_{FV}(15)_{NPR}$ [RBC/UKQCD10 arXiv:1012.4178]
- (Laiho, Lunghi, & Van de Water, `http://latticeaverages.org/`

QCD+QED simulation

[R. Zhou, S. Uno, T. Blum, T. Doi, M. Hayakawa. TI, N. Yamada,]



- Up down quark has different electric charge and masses
  → Breaking of isospin symmetry



- Isospin breaking effects are accurately measured experimentally

$$\Delta m_\pi = m_{\pi^\pm} - m_{\pi^0} = 4.5936(5)\text{MeV}, \quad m_N - m_P = 1.2933317(5)\text{MeV}$$

- Quark masses. (Strong CP problem)

- Compute Pion/Kaon using Nf=2+1 DWF QCD + QED

  Requiring m_q < 40 MeV (70MeV), 48 (120) partially quenched data points for PS meson survive

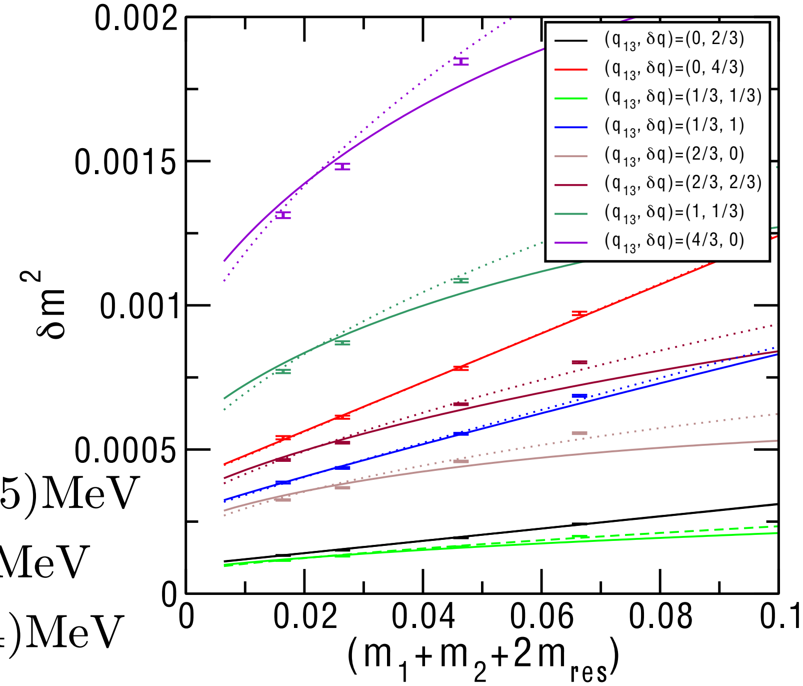
- Fit to chiral perturbation theory with EM (SU(3)+EM and SU(2)+Kaon+EM) to extract quark masses.

- Chiral symmetry is essential to define quark massless points.

- Input:

$$M_{\rm PS}(m_u, 2/3, m_d, -1/3) = 139.57018(35)\text{MeV}$$
$$M_{\rm PS}(m_u, 2/3, m_s, -1/3) = 493.673(14)\text{MeV}$$
$$M_{\rm PS}(m_d, -1/3, m_s, -1/3) = 493.673(14)\text{MeV}$$

24^3 m_l = 0.01



Quark mass from QCD+QED simulation

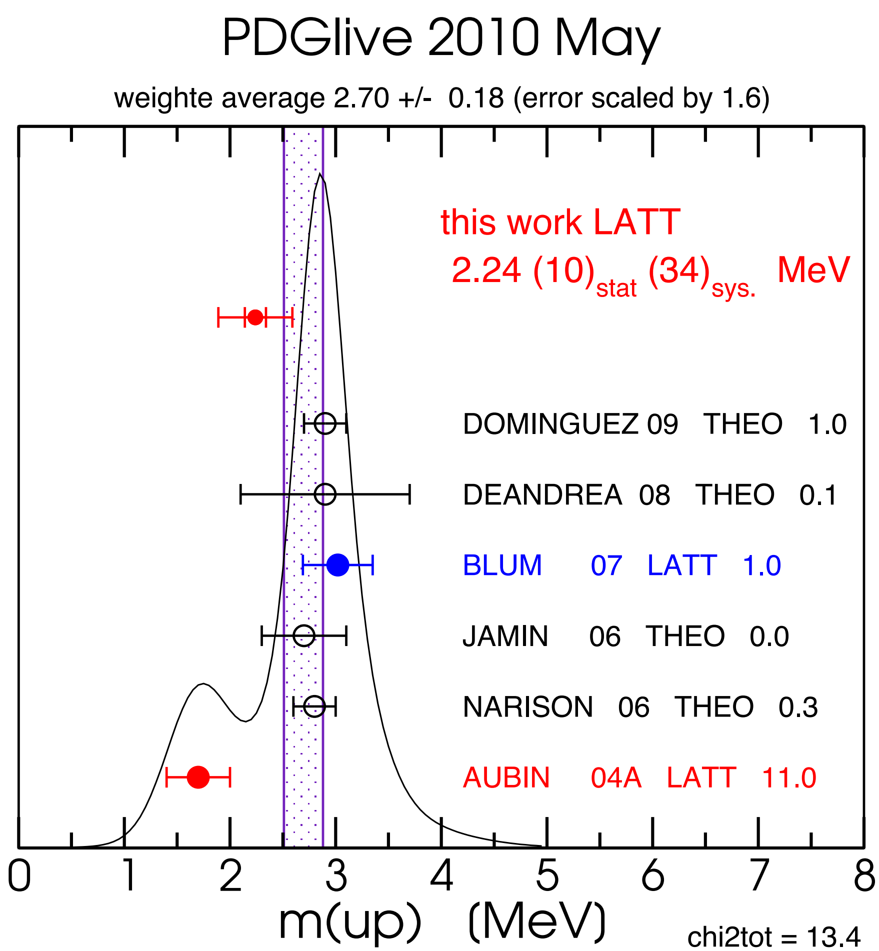
[PRD82 (2010) 094508 [47pages]]

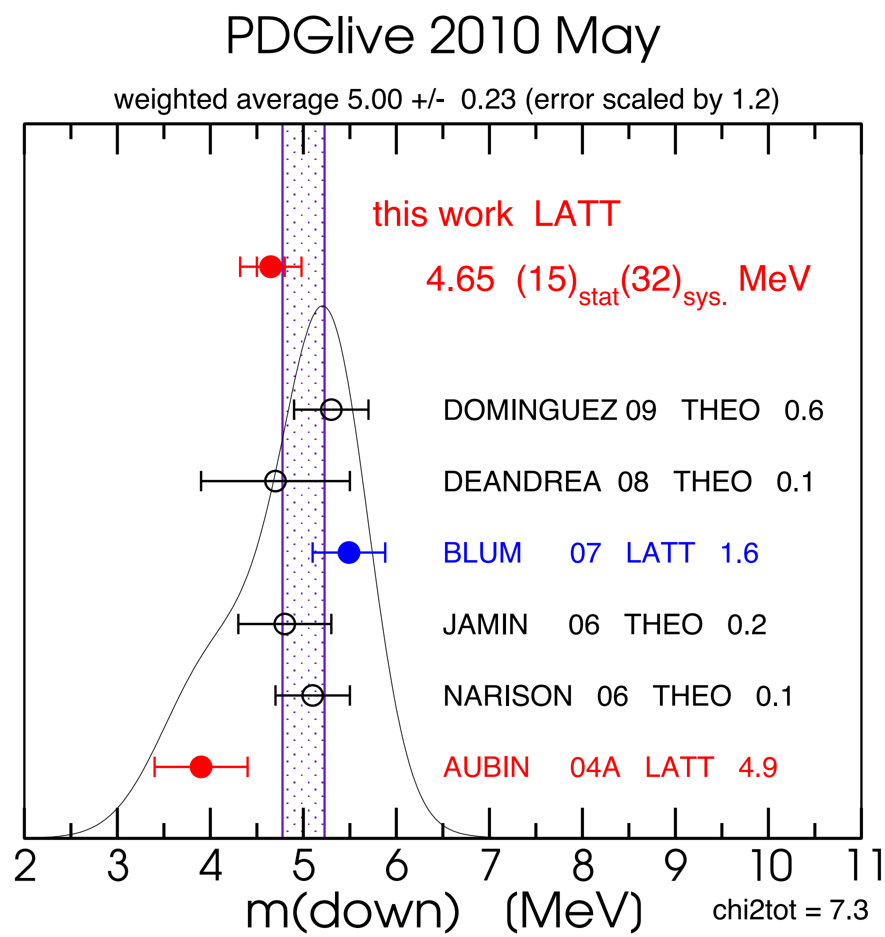
$$
\begin{aligned}
m_u &= 2.24 \pm 0.10 \pm 0.34 \ \text{MeV} \\
m_d &= 4.65 \pm 0.15 \pm 0.32 \ \text{MeV} \\
m_s &= 97.6 \pm 2.9 \pm 5.5 \ \text{MeV} \\
m_d - m_u &= 2.411 \pm 0.065 \pm 0.476 \ \text{MeV} \\
m_{ud} &= 3.44 \pm 0.12 \pm 0.22 \ \text{MeV} \\
m_u/m_d &= 0.4818 \pm 0.0096 \pm 0.0860 \\
m_s/m_{ud} &= 28.31 \pm 0.29 \pm 1.77,
\end{aligned}
$$

- $\overline{\text{MS}}$ at 2 GeV using NPR/SMOM scheme.
- Particular to QCD+QED, finite volume error is large: 14% and 2% for m_u and m_d.
- This would be due to photon's non-confining feature (vs gluon).
- Volume, a^2, chiral extrapolation errors are being removed.
- Applications for Hadronic contribution to $(g-2)_\mu$ in progress.

Comparison with u,d masses in PDG

red $N_F = 2+1$ staggered, DWF blue N_F=2 DWF (2.7 fm)^3





Taku Izubuchi, The Ohio State University, November 29, 2010 42

Conclusions

- Progress in Theory, Algorithm, and Hardware are finally bringing us the opportunity to calculate physics quantities [A. Juttner's talk]

$$\underline{m_u}, \underline{m_d}, \underline{m_s}, \underline{f_\pi, f_K}, \underline{B_K}, \underline{f_+(q^2)}, f_B, B_B, \cdots$$

  which are highly relevant to our understanding of the fundamental constituents of matter and the forces between them with fully controlled systematic errors.

- Continuum limit of B_K is taken.

- One step towards QCD+QED computation that fully includes isospin breaking effects (quark mass and charge).

- Future prospects :
  - $K \to \pi\pi$ decay, ϵ'/ϵ. $\Delta I = 3/2$ is under control, $\Delta I = 1/2$ is begin challenged.
  - Eliminates three sources of systematic errors on the next generation machines.
  - Other applications of QCD+QED including $(g-2)_\mu$ Hadronic light-by-light diagram.

2011 Tohoku-Pacific Ocean Earthquake

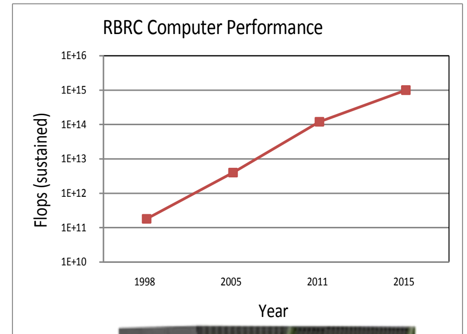
- Friday, March 11th 14:46 (JST) M9.0 + many smaller but still significant earth quakes.
- Among many other bad damages, KEK, J-PARC, RIBF, were shutdown after the earthquake.
- Monday, March 14th 22:50 (JST) A roll call (head count) for members of national-wide Particle & Nuclear Theory Group (Soryushi-Ron Group; SG), who belong to the institutes located in Tohoku-Kantou-Koushinetsu region, announced on the mailing list.
- Some colleagues may be staying in shelters.

- As of 19:00 (JST) yesterday, approximately after 43 hours from the call, 387 names, from 45 institutes are reported to be safe on the wik. It's been rapidly growing.
  [Koji Hahsimoto (RIKEN), Tetsuji Kimura (KEK), Yuji Tachikawa (IPMU), TI]
  (Note this is NOT 100 % confirmed results (PRELIMINARY)).
- No seriously injured person from SG are known to us so far.
- Computers, such as RICC, are still working ! (suffering once a day shutdown due to the scheduled power outage, RIBF as well).
- Some colleagues, from affected institutes, already started looking for places to continue their studies. Some already moved and started to work.
- I belive many experimentalists at KEK, RIKEN, Univ. of Tokyo and very many others are monitoring the radioactive levels of the nation.
- RIBF at RIKEN, already restarted from Monday, KEK and J-PARC will start to recover as soon as next week.

QCD* machines

[Columbia Univ, RBRC, Univ. of Edinburgh]

- QCDSP(48GF/rackpeak),TIDSPC31(1993-1998)
  12 racks at RBRC, 600GF
- QCDOC(0.8TF/rack)180nmASIC(2003-2005)
  1 core, System on Chip, 12 racks at RBRC, 10TF, $1/Mflops(sustained)
- QCDCQ(205TF/rack)45nm(2007-2011)
  2 racks at RBRC/BNL, 400 TF



- Low power consumptions −→ large number of nodes (1,024) per rack
- High memory/interconnect Bandwidth
- Gives efficient performance for lattice QCD

Other machines

Argonne, (IBM BG/P 557 TF peak)

RIKEN/Japan RICC (Cluster, 100 TF peak)

Via USQCD collaboration, als Clusters @ J-Lab, FNAL

Origins of Isospin breaking in Kaon

- Reason why the iso doublet, (K^+, K^0), has the mass splitting

$$M_{K^\pm} - M_{K^0} = -3.937(29) \quad \text{MeV}, \qquad \text{[PDG]}$$

  - ▷ $(m_{\text{dwn}} - m_{\text{up}})$: *makes $M_{K^+} - M_{K^0}$ negative.*
  - ▷ $(q_u - q_d)$: *makes $M_{K^+} - M_{K^0}$ positive.*

- Using the determined quark masses and SU(3) LEC, we could isolate (to $\mathcal{O}((m_{\text{up}} - m_{\text{dwn}})\alpha))$ each of contributions,

$$\begin{aligned} & M^2_{\text{PS}}(m_{\text{up}}, 2/3, m_{\text{str}}, -1/3) - M^2_{\text{PS}}(m_{\text{dwn}}, -1/3, m_{\text{str}}, -1/3) \\ \simeq & M^2_{\text{PS}}(m_{\text{up}}, 0, m_{\text{str}}, 0) - M^2_{\text{PS}}(m_{\text{dwn}}, 0, m_{\text{str}}, 0) \qquad [\Delta M(m_{\text{up}} - m_{\text{dwn}})] \\ + & M^2_{\text{PS}}(\bar{m}_{ud}, 2/3, \bar{m}_{ud}, -1/3) - M^2_{\text{PS}}(\bar{m}_{ud}, -1/3, m_{\text{str}}, -1/3) \qquad [\Delta M(q_u - q_d)] \end{aligned}$$

- ▷ *$\Delta M(m_{\text{up}} - m_{\text{dwn}})$ = -5.23 (14) MeV [133(4)% in $\Delta M^2(m_{\text{up}} - m_{\text{dwn}})$]*
  ▷ *$\Delta M(q_u - q_d)$ = 1.327(37) MeV [-34(1)% in $\Delta M^2(q_u - q_d)$]*

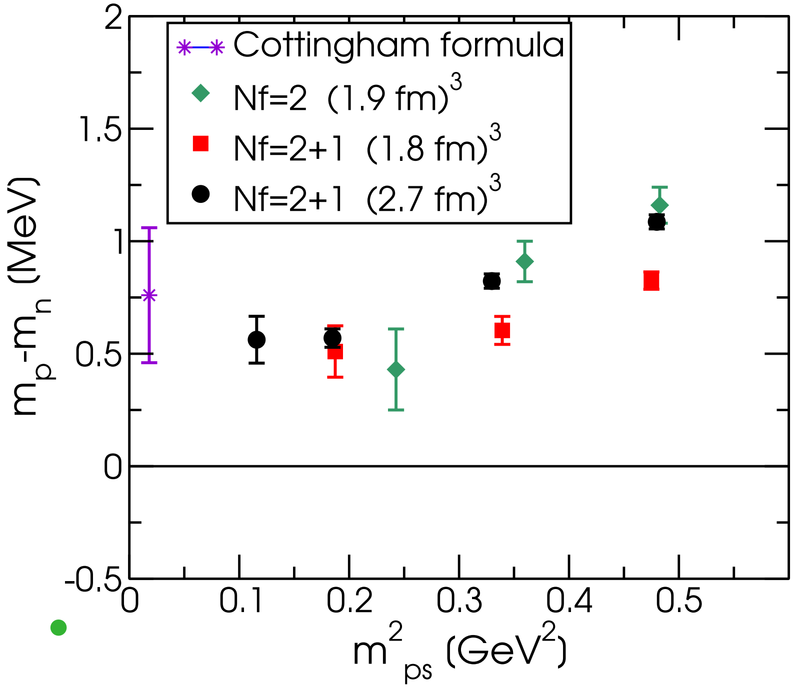
  Also SU(3) ChPT, $\Delta M(m_{\text{up}} - m_{\text{dwn}})$=-5.7(1) MeV and $\Delta M(q_u - q_d)$=1.8(1) MeV.

- Similar analysis for π is possible, but facing a difficulty of isolating sea strange quark terms. $m_{\pi^\pm} - m_{``\pi^0"} = 4.50(23)$ MeV

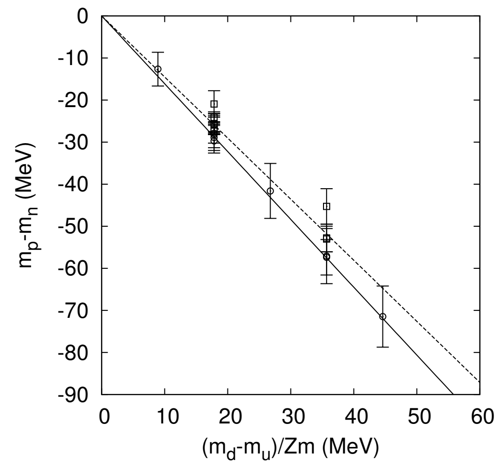
Nucleon mass splitting in $N_F = 2, 2+1$

[R.Zhou, T.Doi]

$(q_u - q_d)$ effect



$(m_{\text{up}} - m_{\text{dwn}})$ effect



$$M_N - M_p|_{\text{QED}} = 0.383(68) \text{ MeV}$$

$$M_N - M_p|_{\text{quark mass}} = -2.24(12) \text{ MeV}$$

$$\Longrightarrow M_N - M_p| = -1.86(14)(47)_{\text{FV,fit}} \text{ MeV}$$