Recent progress in $B_K$ and $\varepsilon_K$ in lattice QCD

Weonjong Lee
on behalf of the SWME Collaboration

Lattice Gauge Theory Research Center
Department of Physics and Astronomy
Seoul National University

KIAS PPC Workshop, 11/12/2013
1. Testing the Standard Model
   - Indirect CP violation and $B_K$

2. $B_K$
   - $B_K$ on the lattice
   - Data Analysis for $B_K$
   - Continuum extrapolation of $B_K$

3. Conclusion and Future Plan

CP Violation and $B_K$
Kaon Eigenstates and $\varepsilon$

- Flavor eigenstates, $K^0 = (\bar{s}d)$ and $\bar{K}^0 = (s\bar{d})$ mix via box diagrams.

\[ K_1 = \frac{1}{\sqrt{2}}(K_0 - \bar{K}_0) \]
\[ K_2 = \frac{1}{\sqrt{2}}(K_0 + \bar{K}_0) \]

Neutral Kaon eigenstates $K_S$ and $K_L$.

\[ K_S = \frac{1}{\sqrt{1 + |\varepsilon|^2}}(K_1 + \varepsilon K_2) \]
\[ K_L = \frac{1}{\sqrt{1 + |\varepsilon|^2}}(K_2 + \varepsilon K_1) \]
Kaon Eigenstates and $\varepsilon$

- **Flavor eigenstates**, $K^0 = (s\bar{d})$ and $\bar{K}^0 = (s\bar{d})$ mix via box diagrams.

- **CP eigenstates** $K_1$(even) and $K_2$(odd).

\[
K_1 = \frac{1}{\sqrt{2}}(K^0 - \bar{K}^0) \quad K_2 = \frac{1}{\sqrt{2}}(K^0 + \bar{K}^0)
\]
Kaon Eigenstates and $\varepsilon$

- **Flavor eigenstates**, $K^0 = (\bar{s}d)$ and $\bar{K}^0 = (s\bar{d})$ mix via box diagrams.

- **CP eigenstates** $K_1$(even) and $K_2$(odd).

  $$K_1 = \frac{1}{\sqrt{2}}(K^0 - \bar{K}^0) \quad K_2 = \frac{1}{\sqrt{2}}(K^0 + \bar{K}^0)$$

- **Neutral Kaon eigenstates** $K_S$ and $K_L$.

  $$K_S = \frac{1}{\sqrt{1 + |\varepsilon|^2}}(K_1 + \bar{\varepsilon}K_2) \quad K_L = \frac{1}{\sqrt{1 + |\varepsilon|^2}}(K_2 + \bar{\varepsilon}K_1)$$
Indirect CP violation and direct CP violation

\[ K_L \propto K_2 + \bar{\varepsilon} K_1 \]

- Indirect: \( \varepsilon \)
- Direct: \( \varepsilon' \)
$\varepsilon$ and $\hat{B}_K$

- **Experiment**: $\varepsilon = (2.228 \pm 0.011) \times 10^{-3} \times e^{i\phi_{\varepsilon}}$, $\phi_{\varepsilon} = 43.52(5)^\circ$. 
\( \varepsilon \) and \( \hat{B}_K \)

- **Experiment:** \( \varepsilon = (2.228 \pm 0.011) \times 10^{-3} \times e^{i\phi_{\varepsilon}}, \quad \phi_{\varepsilon} = 43.52(5)^\circ. \)
- **Relation between \( \varepsilon \) and \( \hat{B}_K \) in standard model.**

\[
\varepsilon = \exp(i\phi_{\varepsilon}) \sqrt{2} \sin(\phi_{\varepsilon}) C_\varepsilon \text{Im}_t X \hat{B}_K + \xi + \xi_{LD}
\]

\[
X = \text{Re}_c[\eta_1 S_0(x_c) - \eta_3 S_3(x_c, x_t)] - \text{Re}_t \eta_2 S_0(x_t)
\]

\[
\lambda_i = V_{is}^* V_{id}, \quad x_i = m_i^2/M_W^2, \quad C_\varepsilon = \frac{G_F^2 F_K^2 m_K M_W^2}{6\sqrt{2}\pi^2 \Delta M_K}
\]

\[
\xi = \exp(i\phi_{\varepsilon}) \sin(\phi_{\varepsilon}) \frac{\text{Im} A_0}{\text{Re} A_0}
\]

\[
\xi_{LD} = \text{Long Distance Effect} \approx 2\%
\]
**Testing the Standard Model**

**Indirect CP violation and $B_K$**

### $\varepsilon$ and $\hat{B}_K$

- **Experiment:** $\varepsilon = (2.228 \pm 0.011) \times 10^{-3} \times e^{i\phi_\varepsilon}$, $\phi_\varepsilon = 43.52(5)^\circ$.

- **Relation between $\varepsilon$ and $\hat{B}_K$ in standard model.**

\[
\varepsilon = \exp(i\phi_\varepsilon) \sqrt{2} \sin(\phi_\varepsilon) C_\varepsilon \text{ Im}\lambda_t X \hat{B}_K + \xi + \xi_{LD}
\]

\[
X = \text{ Re}\lambda_c [\eta_1 S_0(x_c) - \eta_3 S_3(x_c, x_t)] - \text{ Re}\lambda_t \eta_2 S_0(x_t)
\]

\[
\lambda_i = V_{is}^* V_{id}, \quad x_i = m_i^2/M_W^2, \quad C_\varepsilon = \frac{G_F^2 F_K^2 m_K M_W^2}{6\sqrt{2}\pi^2 \Delta M_K}
\]

\[
\xi = \exp(i\phi_\varepsilon) \sin(\phi_\varepsilon) \frac{\text{ Im}A_0}{\text{ Re}A_0}
\]

\[
\xi_{LD} = \text{ Long Distance Effect} \approx 2\%
\]

- **Definition of $B_K$ in standard model.**

\[
B_K = \frac{\langle \bar{K}_0 | [\bar{s}\gamma_\mu (1 - \gamma_5) d] [\bar{s}\gamma_\mu (1 - \gamma_5) d] | K_0 \rangle}{\frac{8}{3} \langle \bar{K}_0 | \bar{s}\gamma_\mu \gamma_5 d | 0 \rangle \langle 0 | \bar{s}\gamma_\mu \gamma_5 d | K_0 \rangle}
\]

\[
\hat{B}_K = C(\mu) B_K(\mu), \quad C(\mu) = \alpha_s(\mu)^{-\frac{\gamma_0}{2\beta_0}} [1 + \alpha_s(\mu) J_3]
\]
$B_K$ definition in standard model

\[
B_K = \frac{\langle \bar{K}_0 | [\bar{s}\gamma_\mu (1 - \gamma_5) d] [\bar{s}\gamma_\mu (1 - \gamma_5) d] | K_0 \rangle}{\frac{8}{3} \langle \bar{K}_0 | \bar{s}\gamma_\mu \gamma_5 d | 0 \rangle \langle 0 | \bar{s}\gamma_\mu \gamma_5 d | K_0 \rangle}
\]

\[
\hat{B}_K = C(\mu) B_K(\mu),
\]

\[
C(\mu) = \alpha_s(\mu)^{-\frac{\gamma_0}{2b_0}} [1 + \alpha_s(\mu)J_3]
\]
What do we calculate on the lattice?
Data Analysis for $B_K$
Data for $B_K$ with $am_d = am_s = 0.025 (20^3 \times 64)$
\[ N_f = 2 + 1 \] QCD: MILC coarse lattices

<table>
<thead>
<tr>
<th>( a ) (fm)</th>
<th>( a m_l / a m_s )</th>
<th>geometry</th>
<th>ens ( \times ) meas</th>
<th>production</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12</td>
<td>0.03/0.05</td>
<td>20(^3) \times 64</td>
<td>564 ( \times ) 9</td>
<td>done (SNU)</td>
</tr>
<tr>
<td>0.12</td>
<td>0.02/0.05</td>
<td>20(^3) \times 64</td>
<td>486 ( \times ) 9</td>
<td>done (SNU)</td>
</tr>
<tr>
<td>0.12</td>
<td>0.01/0.05</td>
<td>20(^3) \times 64</td>
<td>671 ( \times ) 9</td>
<td>done (SNU)</td>
</tr>
<tr>
<td>0.12</td>
<td>0.01/0.05</td>
<td>28(^3) \times 64</td>
<td>274 ( \times ) 8</td>
<td>done (BNL)</td>
</tr>
<tr>
<td>0.12</td>
<td>0.007/0.05</td>
<td>20(^3) \times 64</td>
<td>651 ( \times ) 10</td>
<td>done (SNU)</td>
</tr>
<tr>
<td>0.12</td>
<td>0.005/0.05</td>
<td>24(^3) \times 64</td>
<td>509 ( \times ) 9</td>
<td>done (SNU)</td>
</tr>
</tbody>
</table>
\(N_f = 2 + 1\) QCD: MILC fine lattices

<table>
<thead>
<tr>
<th>(a) (fm)</th>
<th>(am_l/am_s)</th>
<th>geometry</th>
<th>ens x meas</th>
<th>production</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09</td>
<td>0.0062/0.0310</td>
<td>28^3 \times 96</td>
<td>995 \times 9</td>
<td>done (SNU)</td>
</tr>
<tr>
<td>0.09</td>
<td>0.0031/0.0310</td>
<td>40^3 \times 96</td>
<td>959 \times 9</td>
<td>done (SNU)</td>
</tr>
<tr>
<td>0.09</td>
<td>0.0093/0.0310</td>
<td>28^3 \times 96</td>
<td>950 \times 9</td>
<td>done (SNU)</td>
</tr>
<tr>
<td>0.09</td>
<td>0.0124/0.0310</td>
<td>28^3 \times 96</td>
<td>1996 \times 9</td>
<td>done (SNU)</td>
</tr>
<tr>
<td>0.09</td>
<td>0.00465/0.0310</td>
<td>32^3 \times 96</td>
<td>665 \times 9</td>
<td>done (SNU)</td>
</tr>
<tr>
<td>0.09</td>
<td>0.0062/0.0186</td>
<td>28^3 \times 96</td>
<td>950 \times 9</td>
<td>done (KISTI)</td>
</tr>
<tr>
<td>0.09</td>
<td>0.0031/0.0186</td>
<td>40^3 \times 96</td>
<td>701 \times 9</td>
<td>done (SNU)</td>
</tr>
<tr>
<td>0.09</td>
<td>0.0031/0.0031</td>
<td>40^3 \times 96</td>
<td>576 \times 9</td>
<td>done (KISTI)</td>
</tr>
<tr>
<td>0.09</td>
<td>0.00155/0.0310</td>
<td>64^3 \times 96</td>
<td>790 \times 9</td>
<td>done (KISTI)</td>
</tr>
</tbody>
</table>
$N_f = 2 + 1$ QCD: MILC superfine/ultrafine lattice

<table>
<thead>
<tr>
<th>$a$ (fm)</th>
<th>$am_l/am_s$</th>
<th>geometry</th>
<th>ens $\times$ meas</th>
<th>production</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td>0.0036/0.018</td>
<td>$48^3 \times 144$</td>
<td>744 $\times$ 9</td>
<td>done (SNU)</td>
</tr>
<tr>
<td>0.06</td>
<td>0.0025/0.018</td>
<td>$56^3 \times 144$</td>
<td>799 $\times$ 9</td>
<td>done (KISTI)</td>
</tr>
<tr>
<td>0.06</td>
<td>0.0072/0.018</td>
<td>$48^3 \times 144$</td>
<td>593 $\times$ 9</td>
<td>done (KISTI)</td>
</tr>
<tr>
<td>0.06</td>
<td>0.0054/0.018</td>
<td>$48^3 \times 144$</td>
<td>617 $\times$ 9</td>
<td>done (SNU)</td>
</tr>
<tr>
<td>0.06</td>
<td>0.0018/0.018</td>
<td>$64^3 \times 144$</td>
<td>826 $\times$ 6.6</td>
<td>(*KISTI)</td>
</tr>
<tr>
<td>0.06</td>
<td>0.0036/0.0108</td>
<td>$64^3 \times 144$</td>
<td>600 $\times$ 0.1</td>
<td>(*SNU)</td>
</tr>
<tr>
<td>0.045</td>
<td>0.0030/0.015</td>
<td>$64^3 \times 192$</td>
<td>747 $\times$ 1</td>
<td>(BNL)</td>
</tr>
</tbody>
</table>
Correlated Bayesian Fitting with SU(2) SChPT

(a) X-fit

(b) Y-fit

- MILC, $48^3 \times 144$, 642 cnfs, 9 meas at $a = 0.06$ fm.
Sea quarks and valence quarks
Continuum extrapolation of $B_K$ (1)

- Fitting functional form:

$$f_1 = c_1 + c_2 (a \Lambda_Q)^2 + c_3 \frac{L_P}{\Lambda_X^2} + c_4 \frac{S_P}{\Lambda_X^2}$$

$$f_2 = f_1 + c_5 (a \Lambda_Q)^2 \frac{L_P}{\Lambda_X^2} + c_6 (a \Lambda_Q)^2 \frac{S_P}{\Lambda_X^2}$$

$$f_3 = f_1 + c_5 \alpha_s^2 + c_6 (a \Lambda_Q)^2 \alpha_s + c_7 (a \Lambda_Q)^4$$

$$f_4 = f_2 + c_7 \alpha_s^2 + c_8 (a \Lambda_Q)^2 \alpha_s + c_9 (a \Lambda_Q)^4$$

- Bayesian constraint = prior information:

$$\Lambda_Q = 0.3 \text{ GeV}$$
$$\Lambda_X = 1.0 \text{ GeV}$$
$$c_i = 0 \pm 2 \text{ for } i \geq 2$$
Continuum extrapolation of $B_K$ (2)

- Bayesian Fit to $f_1$

(c) $B_K$ vs. $L_P$

(d) $B_K$ vs. $S_P$

- We exclude the MILC coarse ensembles in this fit.
Continuum extrapolation of $B_K$ (3)

- Bayesian Fit to $f_4$

(e) $B_K$ vs. $L_P$

(f) $B_K$ vs. $S_P$

- We exclude the MILC coarse ensembles in this fit.
Continuum extrapolation of $B_K$ (4)

<table>
<thead>
<tr>
<th>fit func</th>
<th>$f_1$</th>
<th>$f_2$</th>
<th>$f_3$</th>
<th>$f_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$/dof</td>
<td>1.38</td>
<td>1.38</td>
<td>1.37</td>
<td>1.37</td>
</tr>
</tbody>
</table>

Fitting quality of the Bayesian fits
### Error Budget of $B_K$ [ SU(2), 4X3Y, NNNLO]

<table>
<thead>
<tr>
<th>cause</th>
<th>error (%)</th>
<th>memo</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistics</td>
<td>0.62</td>
<td>see text</td>
</tr>
<tr>
<td>matching factor</td>
<td>4.4</td>
<td>$\Delta B_K^{(2)}$ (U1)</td>
</tr>
<tr>
<td>discretization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$am_\ell$ extrap</td>
<td>0.78</td>
<td>diff. of B1 and B4 fits</td>
</tr>
<tr>
<td>$am_s$ extrap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X-fits</td>
<td>0.33</td>
<td>varying Bayesian priors (S1)</td>
</tr>
<tr>
<td>Y-fits</td>
<td>0.53</td>
<td>diff. of linear and quad. (F1)</td>
</tr>
<tr>
<td>finite volume</td>
<td>0.5</td>
<td>diff. of $V = \infty$ and FV fit</td>
</tr>
<tr>
<td>$r_1$</td>
<td>0.27</td>
<td>$r_1$ error propagation (F1)</td>
</tr>
<tr>
<td>$f_\pi$</td>
<td>0.4</td>
<td>132 MeV vs. 124.4 MeV</td>
</tr>
</tbody>
</table>
Current Status of $B_K$ (1)

- SWME: 2011 (PRL):

  $$B_K(\text{RGI}) = \hat{B}_K = 0.727 \pm 0.004(\text{stat}) \pm 0.038(\text{sys})$$

- SWME: Lattice 2013

  $$B_K(\text{RGI}) = \hat{B}_K = 0.7377 \pm 0.0046(\text{stat}) \pm 0.0337(\text{sys})$$

- The statistical error remains approximately the same.
- The systematic error decreases slightly.
Current Status of $\varepsilon_K$

- SWME 2013: (in units of $1.0 \times 10^{-3}$)
  
  $\varepsilon_K = 1.51 \pm 0.18$ for Exclusive $V_{cb}$
  
  $\varepsilon_K = 1.91 \pm 0.21$ for Inclusive $V_{cb}$

- Experiments:
  
  $\varepsilon_K = 2.228 \pm 0.011$

- Hence, we observe $4.0/1.5 \sigma$ difference between the SM theory and experiments (exclusive/inclusive process).

- What does this mean? $\rightarrow$ Breakdown of SM ???
### Error Budget of Exclusive $\varepsilon_K$

<table>
<thead>
<tr>
<th>cause</th>
<th>error (%)</th>
<th>memo</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{cb}$</td>
<td>51.6</td>
<td>Exclusive (FNAL/MILC)</td>
</tr>
<tr>
<td>$B_K$</td>
<td>14.4</td>
<td>SWME</td>
</tr>
<tr>
<td>$\bar{\eta}$</td>
<td>9.7</td>
<td>Wolfenstein</td>
</tr>
<tr>
<td>$\eta_3$</td>
<td>8.1</td>
<td>$\eta_{ct}$</td>
</tr>
<tr>
<td>$m_c$</td>
<td>6.9</td>
<td>Charm quark mass</td>
</tr>
<tr>
<td>:</td>
<td>:</td>
<td>:</td>
</tr>
</tbody>
</table>
Current status of $B_K$ on the lattice

- SWME (this work)
- RBC-UKQCD (2011)
- BMW (2011)
NPR (Current Focus)

- Non-perturbative Renormalization (Jangho Kim): Matching factor error: 4.4% → 2.0∼3.0%
- Exceptional Momentum: 2.0∼3.0%
- Non-exceptional Momentum: 2.0∼2.5%
- Basically, we want to trade the truncation error with the statistical error.
Two-loop Perturbation (Current Focus)

- Two-loop Perturbation: (Jongjeong Kim and Kwangwoo Kim)
  Matching factor error: $4.4\% \rightarrow 0.92\%$

- Automated Feynman Rule Generation.

- Automated Feynman Diagram Generation.

- Basically, we use non-zero quark masses to regulate the IR divergences.
Grand Challenges in the front
**Tentative Goals (1)**

1. $V_{cb}$, we need to calculate the following semi-leptonic form factors:

   \[
   B \rightarrow D\ell\nu \quad (1) \\
   B \rightarrow D^*\ell\nu \quad (2)
   \]
Tentative Goals (1)

1. $V_{cb}$, we need to calculate the following semi-leptonic form factors:

$$B \rightarrow D\ell\nu$$
$$B \rightarrow D^*\ell\nu$$

2. We have already implemented a GPU version of the OK action inverter (Yong-Chull Jang).
Conclusion and Future Plan

Tentative Goals (1)

1. $V_{cb}$, we need to calculate the following semi-leptonic form factors:

\[ B \rightarrow D\ell\nu \quad \text{(1)} \]
\[ B \rightarrow D^*\ell\nu \quad \text{(2)} \]

2. We have already implemented a GPU version of the OK action inverter (Yong-Chull Jang).

3. We need to improve the vector and axial current in the same level as the OK action (Yong-Chull Jang, and Jon Bailey).
Conclusion and Future Plan

Tentative Goals (1)

1. $V_{cb}$, we need to calculate the following semi-leptonic form factors:

   \[ B \to D\ell\nu \]
   \[ B \to D^*\ell\nu \] (1) (2)

2. We have already implemented a GPU version of the OK action inverter (Yong-Chull Jang).

3. We need to improve the vector and axial current in the same level as the OK action (Yong-Chull Jang, and Jon Bailey).

4. We plan to work on this issue using the OK heavy quark action in collaboration with FNAL and MILC.
Conclusion and Future Plan

Tentative Goals (2)

1. We would like to determine $B_K$ directly from the standard model with its systematic and statistical error $\leq 2\%$. 

2. We expect to achieve this goal in a few years using the SNU GPU cluster: David 1, 2, 3 (∼100 Tera Flops), Jlab GPU cluster, and KISTI supercomputers.

3. Basically, we need to accumulate at least 9 times more statistics using the SNU GPU cluster machine. 

4. In addition, we need to obtain the matching factor using NPR (Jangho Kim) and using the two-loop perturbation theory (Kwangwoo Kim). 

Weonjong Lee on behalf of the SWME Collaboration (SNU)

KIAS PPC 2013
Conclusion and Future Plan

Tentative Goals (2)

1. We would like to determine $B_K$ directly from the standard model with its systematic and statistical error $\leq 2\%$.

2. We expect to achieve this goal in a few years using the SNU GPU cluster: David 1, 2, 3 ($\sim 100$ Tera Flops), Jlab GPU cluster, and KISTI supercomputers.
Tentative Goals (2)

1. We would like to determine $B_K$ directly from the standard model with its systematic and statistical error $\leq 2\%$.

2. We expect to achieve this goal in a few years using the SNU GPU cluster: David 1, 2, 3 ($\sim 100$ Tera Flops), Jlab GPU cluster, and KISTI supercomputers.

3. Basically, we need to accumulate at least 9 times more statistics using the SNU GPU cluster machine.
   ※ statistical error $< 1.0\%$
Tentative Goals (2)

1. We would like to determine $B_K$ directly from the standard model with its systematic and statistical error $\leq 2\%$.

2. We expect to achieve this goal in a few years using the SNU GPU cluster: David 1, 2, 3 ($\sim 100$ Tera Flops), Jlab GPU cluster, and KISTI supercomputers.

3. Basically, we need to accumulate at least 9 times more statistics using the SNU GPU cluster machine.
   ※ statistical error $< 1.0\%$

4. In addition, we need to obtain the matching factor using NPR (Jangho Kim) and using the two-loop perturbation theory (Kwangwoo Kim).
   ※ matching error $< 1.0\%$
Tentative Goals (3)

1. Long-Distance Effect $\xi_{LD} \approx 2\%$:
Tentative Goals (3)

1. Long-Distance Effect $\xi_{LD} \approx 2\%$:

2. Here, the precision goal is only $\approx 10\%$. 
Tentative Goals (3)

1. Long-Distance Effect $\xi_{LD} \approx 2\%$:

2. Here, the precision goal is only $\approx 10\%$.

3. We need $N_f = 2 + 1 + 1$ calculation on the lattice. MILC provides HISQ ensembles with $N_f = 2 + 1 + 1$. 

Weonjong Lee on behalf of the SWME Collaboration (SNU)

KIAS PPC 2013
Tentative Goals (3)

1. Long-Distance Effect $\xi_{LD} \approx 2\%$:

2. Here, the precision goal is only $\approx 10\%$.

3. We need $N_f = 2 + 1 + 1$ calculation on the lattice. MILC provides HISQ ensembles with $N_f = 2 + 1 + 1$.

4. As a by-product, a substantial gain is that the charm quark mass dependence might be under control in this way. (Brod and Gorbahn)
As a result, we hope to discover a breakdown of the standard model in the level of $5\sigma$ or higher precision.
Ultimate Goals

1. As a result, we hope to discover a breakdown of the standard model in the level of $5\sigma$ or higher precision.

2. As a result, we would like to provide a crucial clue to the physics beyond the standard model.
Ultimate Goals

1. As a result, we hope to discover a breakdown of the standard model in the level of $5\sigma$ or higher precision.

2. As a result, we would like to provide a crucial clue to the physics beyond the standard model.

3. As a result, we would like to guide the whole particle physics community into a new world beyond the standard model.
Thank God for your help !!!
SWME Collaboration
1998 — Present
SWME Collaboration

- Seoul National University (SNU):
  Prof. Weonjong Lee
  Dr. Jon Bailey and Dr. Nigel Cundy (RA Prof.)
  Dr. Jongjeong Kim (Postdoc) and Dr. Taegil Bae (Staff)
  10 + 1 graduate students.

- Brookhaven National Laboratory (BNL):
  Dr. Chulwoo Jung
  Dr. Hyung-Jin Kim (Postdoc)

- Los Alamos National Laboratory (LANL):
  Dr. Boram Yoon (Postdoc)

- University of Washington, Seattle (UW):
  Prof. Stephen R. Sharpe.
Lattice Gauge Theory Research Center (SNU)

- Center Leader: Prof. Weonjong Lee.
- Research Assistant Prof.: Dr. Jon Bailey
- Research Assistant Prof.: Dr. Nigel Cundy
- Postdoctoral Fellow: Dr. Jongjeong Kim
- 10 + 1 graduate students
- Secretary: Ms. Sora Park.
- more details on http://lgt.snu.ac.kr/.
Group Photo (2011)
Group Photo (2013)