Three-quark systems in MA and MC projected QCD

Hideaki Iida (YITP, Kyoto U.)
in collaboration with
N. Sakumichi and H. Suganuma
(Department of Physics, Kyoto U.)

The XXVI International Symposium on Lattice Field Theory

College of William and Mary, Williamsburg, Virginia, USA

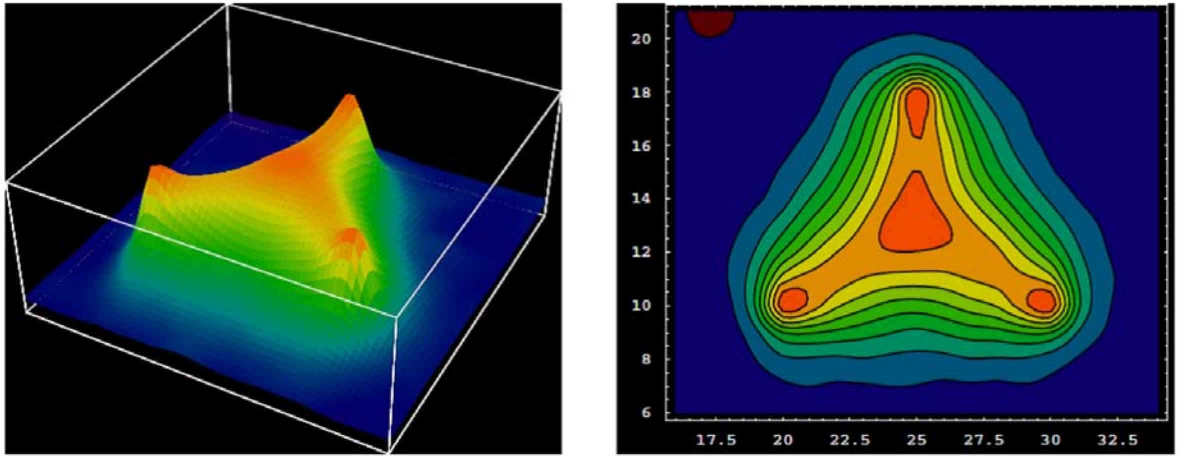
2008 July 14-19

'74～'76: Y.Nambu, G. 't Hooft , S.Mandelstam

Color confinement in QCD

…Most difficult and challenging problem in physics

One dimensional squeezing of color electric flux is
one of the keyword for color confinement.



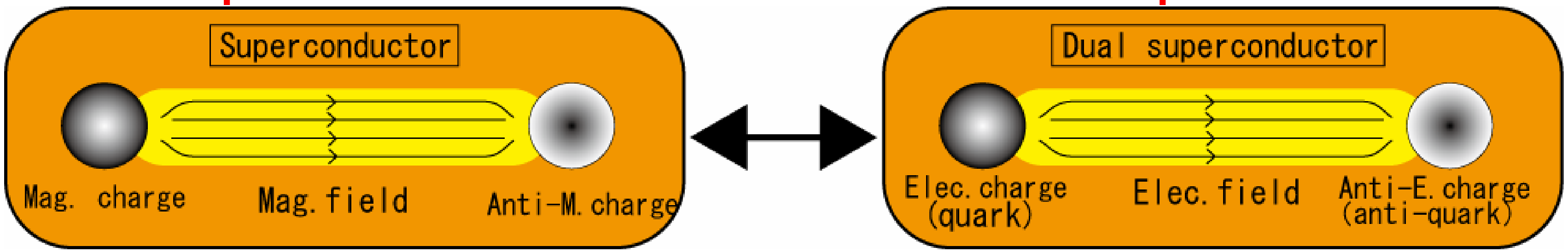
Action density in 3Q system in full QCD
[H.Ichie, V.Bornyakov, T.Streuer and G. Schierholtz, Nucl. Phys.A721(2003)]

Why is the color-electric flux squeezed?…Due to dual Meissner effect
⇒**Dual superconductor picture**

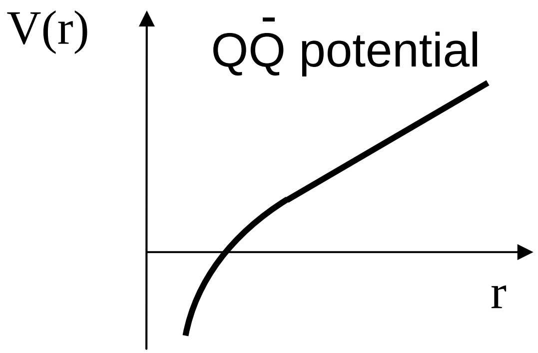
Dual superconductor picture

Due to the dual Meissner effect, the electric flux is squeezed into one dimensional flux tube in QCD vacuum. Therefore the potential between a quark and an anti-quark becomes linear at long distance.

Superconductor **Dual superconductor**



Actually, $Q\bar{Q}$ potential observed in lattice QCD shows linear potential at long distance.



Functional form:
Linear (+ Coulomb) potential

$$V(r) = \sigma r - \frac{A}{r} + C$$

Maximally Abelian (MA) gauge

G. 't Hooft, Nucl.Phys.**B190** (1981)
Z.Ezawa and A.Iwazaki, Phys.Rev.D**25** (1982); D**26** (1982)

However, there are two large gaps between dual superconducting theory and QCD:

(1) **Abelian ⇔ Non-Abelian**
The dual superconducting theory is based on the Abelian gauge theory subject to the Maxwell-type equations, where electo-magnetic duality is manifest, while QCD is a non-Abelian gauge theory.

(2) **Existence of a monopole as elementary degrees of freedom**
The dual superconducting theory requires condensation of color-magnetic monopoles as the key concept, while QCD does not have such a monopole as the elementary degrees of freedom.

Maximally Abelian (MA) gauge compensates these two gaps.

MA gauge on lattice: Gauge configurations are maximally Abelianized by gauge transformation.

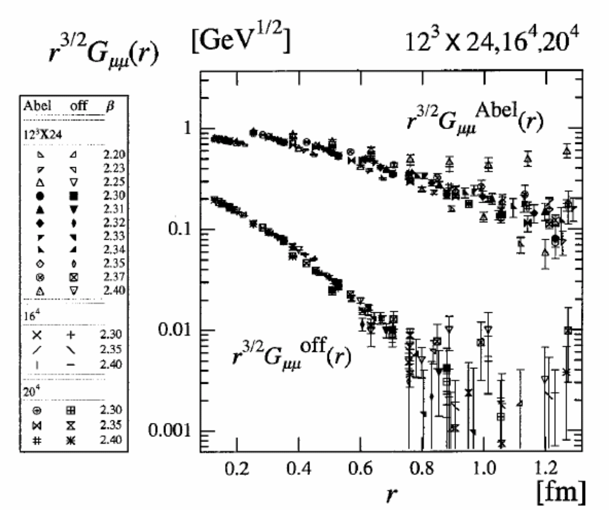
The following quantity, R_{MA}, is maximized by gauge transformation:

$$R_{\mathrm{MA}}[U_\mu(s)] \equiv \mathrm{Re} \sum_{s,\mu} \mathrm{Tr}\left(U_\mu^\dagger(s)\vec{H}U_\mu(s)\vec{H}\right)$$

($U_\mu(s)$: Link variable, $\vec{H}$: Cartan subalgebra of SU(3))

Maximally Abelian (MA) gauge

(1) Importance of Abelian gluons in MA gauge:



Off-diagonal gluon have large mass about 1GeV in MA gauge.
⇒ Off-diagonal gluon is inactive in infrared region.

Therefore, only the diagonal gluon is relevant in MA gauge for infrared region.

[K.Amemiya and H.Suganuma, Phys.Rev.D60, 114509 (1999)]

(2) Emergence of a monopole in MA gauge:

As a remarkable fact of MA gauge, **color-magnetic monopoles appear** as topological objects reflecting the nontrivial homotopy group,

$$\Pi_2(SU(N_c)/U(1)^{N_c-1}) = \mathbf{Z}_\infty^{N_c-1}$$

QCD is reduced to Abelian theory with monopole in MA gauge for infrared region.

Maximally Abelian (MA) gauge

There are so many studies on MA gauge:

(Germany) G.Schierholtz et al., M.Mueller-Preussker et al.
(USA) J.Stack et al., R.Haymaker et al.
(Italy) A. Di Giacomo et al., P.Cea et al.
(Russia) M.I.Polikarpov et al.
(Austria) H.Markum et al.
(Canada) R.Woloshyn et al.
(Japan) Kanazawa group (T.Suzuki et al.),
Hiroshima group (O.Miyamura et al.),
Osaka-Kyoto group (H.Suganuma et al.),
Chiba group (K.-I. Kondo et al.)

※I am very sorry if I do not list your name.

Maximally Abelian (MA) Projection

After the MA gauge fixing, we extract U(1) link variable u_μ^{Abel} from the SU(3) link variable U_μ^{MA} by maximizing the following quantity:

$$\mathrm{ReTr}\left(u_\mu^{\mathrm{Abel}}(s)^* U_\mu^{\mathrm{MA}}(s)\right)$$

where $U_\mu^{\mathrm{MA}} = \begin{pmatrix} \lambda^1 e^{i\varphi^1} & * & * \\ * & \lambda^2 e^{i\varphi^2} & * \\ * & * & \lambda^3 e^{i\varphi^3} \end{pmatrix}$ and $u_\mu^{\mathrm{Abel}}(s) = \begin{pmatrix} e^{i\theta_\mu^1(s)} & 0 & 0 \\ 0 & e^{i\theta_\mu^2(s)} & 0 \\ 0 & 0 & e^{i\theta_\mu^3(s)} \end{pmatrix}$

MA-gauge fixed SU(3) configuration

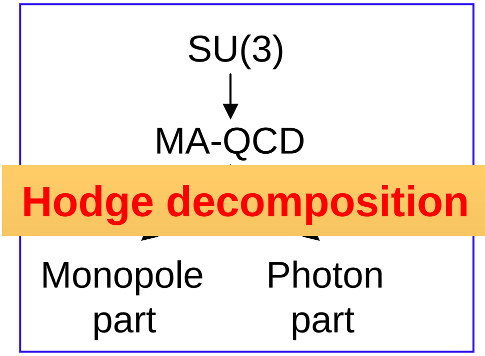
U(1) link variable
…close to U_μ^{MA}

$\left[\theta^1 + \theta^2 + \theta^3 = 0 \ (\mathrm{mod}\, 2\pi)\right]$

Hodge decomposition

In the Abelian theory, there appear not only the electric current but also the magnetic (monopole) current.

Decomposition of electric current (Photon part) and magnetic current (Monopole part) ⇒ Hodge decomposition



Decomposition: $\theta_\mu(s) = \theta_\mu^{\mathrm{Ph}}(s) + \theta_\mu^{\mathrm{Mo}}(s)$

$$\begin{cases} (\partial \wedge \theta^{\mathrm{Mo}})_{\mu\nu} \equiv \theta_{\mu\nu}^{\mathrm{Mo}} - 2\pi n_{\mu\nu}^{\mathrm{Mo}} \\ (\partial \wedge \theta^{\mathrm{Ph}})_{\mu\nu} \equiv \theta_{\mu\nu}^{\mathrm{Ph}} - 2\pi n_{\mu\nu}^{\mathrm{Ph}} \end{cases} \qquad \left(u_\mu^{\mathrm{Abel}}(s) = \begin{pmatrix} e^{i\theta_\mu^1(s)} & 0 & 0 \\ 0 & e^{i\theta_\mu^2(s)} & 0 \\ 0 & 0 & e^{i\theta_\mu^3(s)} \end{pmatrix} \right)$$

$$-\pi \le \theta_{\mu\nu}^{\mathrm{Ph(Mo)}} < \pi \quad n_{\mu\nu}^{\mathrm{Ph(Mo)}} = 0, \pm 1, \pm 2 \qquad (\partial \wedge \theta)_{\mu\nu} \equiv \partial_\mu \theta_\nu - \partial_\nu \theta_\mu$$ (-4π ~ 4π)

$$\begin{cases} j_\nu \equiv \partial_\mu \theta_{\mu\nu}, & \text{…electric current} \\ k_\nu \equiv \partial_\mu^* \theta_{\mu\nu} = 2\pi \partial_\mu^* n_{\mu\nu} & \text{…magnetic current} \end{cases} \qquad {}^*\theta_{\mu\nu} \equiv \epsilon_{\mu\nu\alpha\beta}\theta_{\alpha\beta}/2$$

We impose $j_\nu = \partial_\mu \theta_{\mu\nu}^{\mathrm{Ph}}, \quad \partial_\mu^* \theta_{\mu\nu}^{\mathrm{Ph}} = 2\pi \partial_\mu^* n_{\mu\nu}^{\mathrm{Ph}} = 0$ …Ph part includes only the electric current.

Landau gauge fixing for residual gauge symmetry: $\partial_\mu \theta_\mu^{\mathrm{Ph}}(s) = 0$

Hodge decomposition

Then $j_\nu(s) = \partial^2 \theta_\nu^{\mathrm{Ph}}(s)$ …4 dim. Poisson equation

The solution is given by

$$\begin{cases} \theta_\mu^{\mathrm{Ph}}(s) = \sum_s D(s-s')j_\mu(s'), \\ D(s) = -\frac{1}{N^4}\sum_{n_1=0}^{N-1}\cdots\sum_{n_4=0}^{N-1}\frac{e^{-2\pi i n\cdot s/N}}{4\sum_{\mu=1}^4 \sin^2(\pi n_\mu/N)} \end{cases}$$

with N^4 lattice and periodic boundary condition

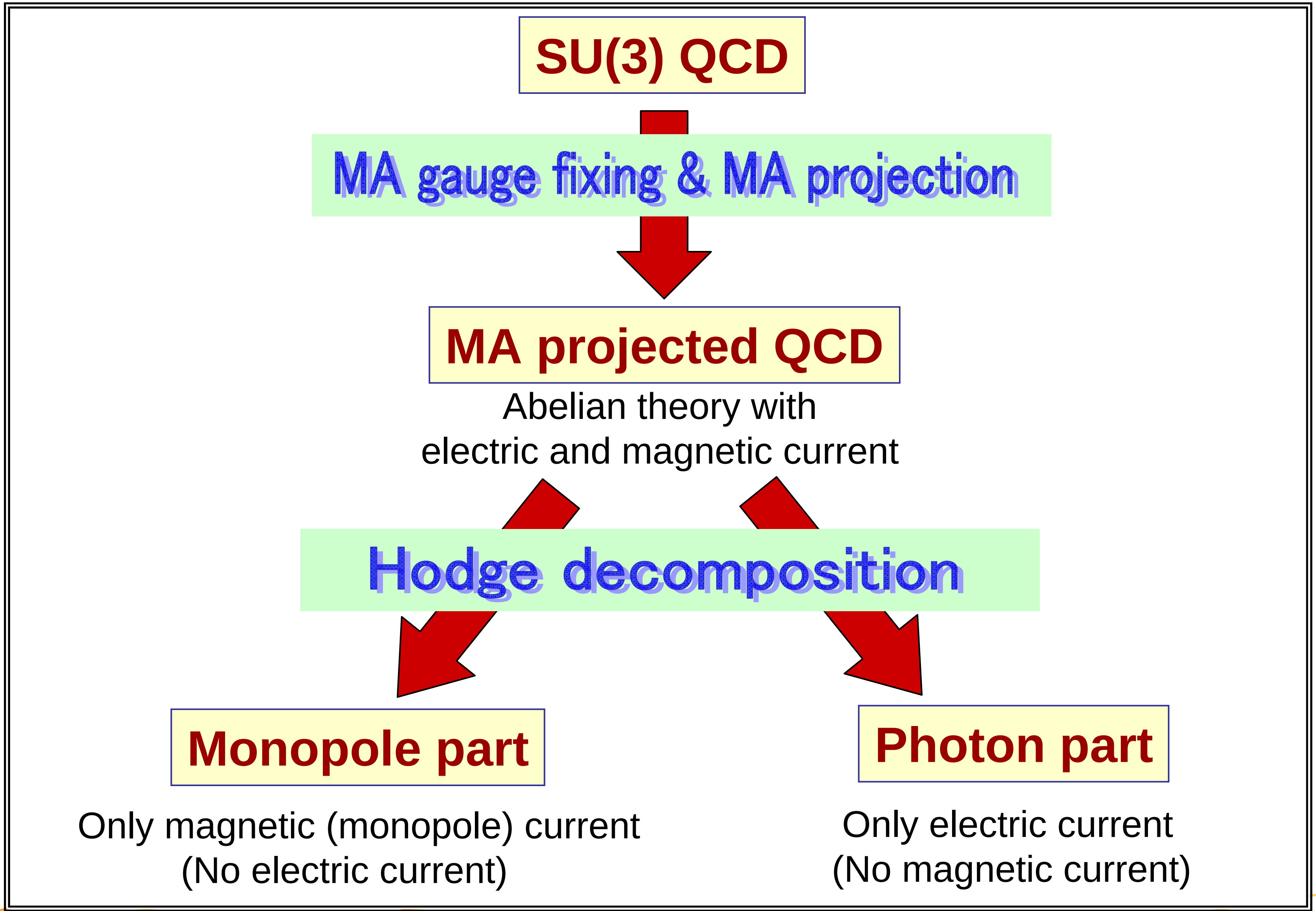
→We obtain $\boldsymbol{\theta_\mu^{\mathrm{Ph}}}$. Only include electric current

Monopole part: $\boldsymbol{\theta_\mu^{\mathrm{Mo}}(s) = \theta_\mu(s) - \theta_\mu^{\mathrm{Ph}}(s)}$ Only include magnetic current

In the continuum limit, $\partial_\mu \theta_{\mu\nu}^{\mathrm{Mo}} = 0,\, k_\nu = \partial_\mu^* \theta_{\mu\nu}^{\mathrm{Mo}}$

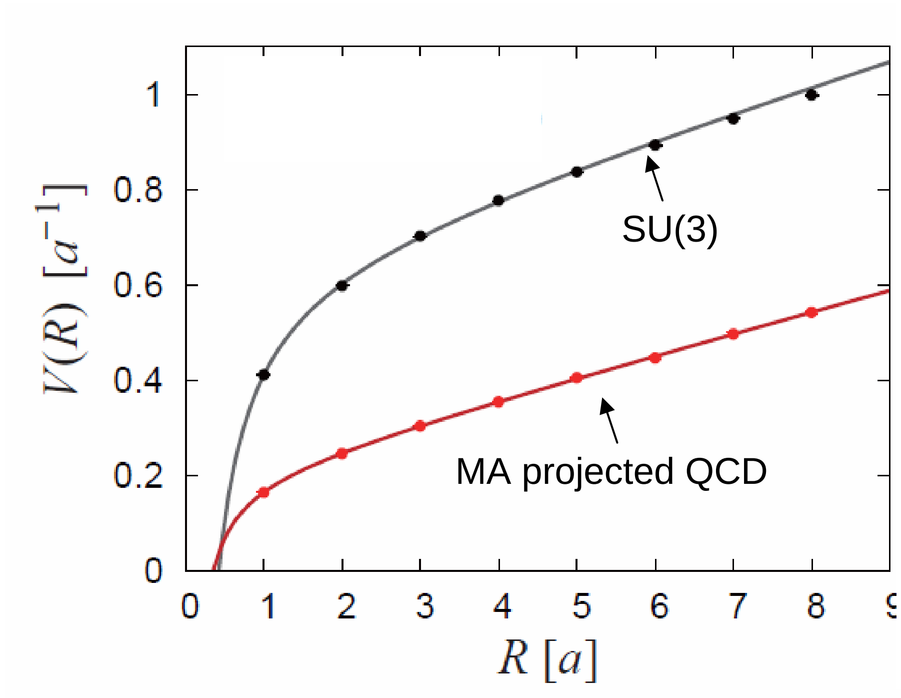
$$\left(\begin{array}{l} \theta_{\mu\nu} - 2\pi n_{\mu\nu} = \theta_{\mu\nu}^{\mathrm{Ph}} + \theta_{\mu\nu}^{\mathrm{Mo}} - 2\pi(n_{\mu\nu}^{\mathrm{Ph}} + n_{\mu\nu}^{\mathrm{Mo}}) \\ n_{\mu\nu} \simeq n_{\mu\nu}^{\mathrm{Mo}} \quad n_{\mu\nu}^{\mathrm{Ph}} \simeq 0 \quad |\theta_{\mu\nu}|, |\theta_{\mu\nu}^{\mathrm{Ph}}|, |\theta_{\mu\nu}^{\mathrm{Mo}}| \ll 1 \end{array} \right)$$

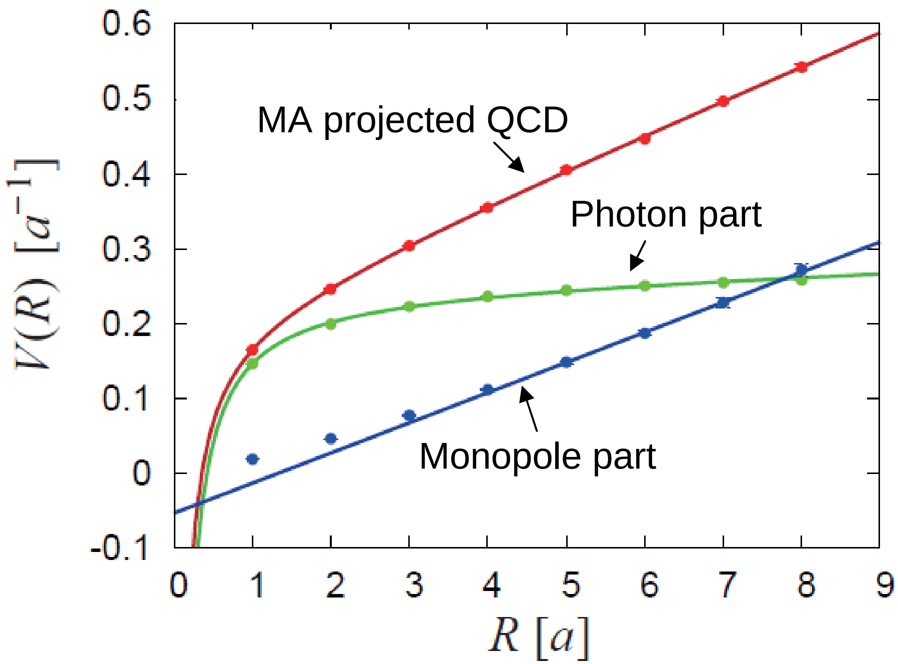
MA projection and Hodge decomposition



Abelian dominance & monopole dominance for quark confinement of $Q\bar{Q}$ system

$Q\bar{Q}$ potential for SU(3), MA, Mo and Ph QCD





$\sigma_{Q\bar{Q}}$ $[a^{-2}]$

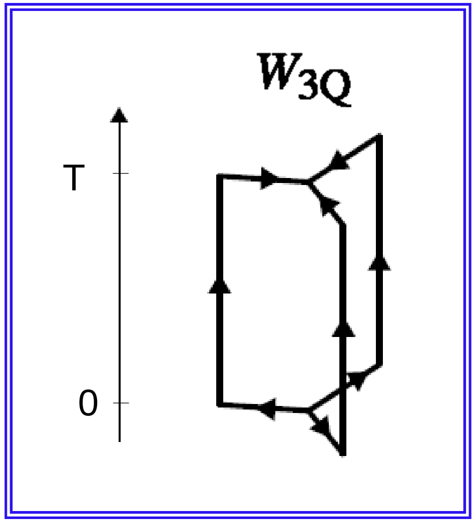
SU(3): 0.0506
MA: 0.0439
Mo: 0.0402
Ph: 0.0014

- $\sigma_{Q\bar{Q}}^{\mathrm{SU(3)}} \simeq \sigma_{Q\bar{Q}}^{\mathrm{MA}} \simeq \sigma_{Q\bar{Q}}^{\mathrm{Mo}}$
  …Abelian dominance and monopole dominance for quark confinement of $Q\bar{Q}$ system
- $\sigma_{Q\bar{Q}}^{\mathrm{Ph}} \simeq 0$ …No contribution to confinement

Three-quark potential in MA projected QCD

We study three-quark potential in MA projected QCD quantitatively.

[Ref.) H.Suganuma, A.Yamamoto, N.Sakumichi, T.T.Takahashi, H.Iida, F.Okiharu, Mod. Phys. Lett. **A** (2008).]



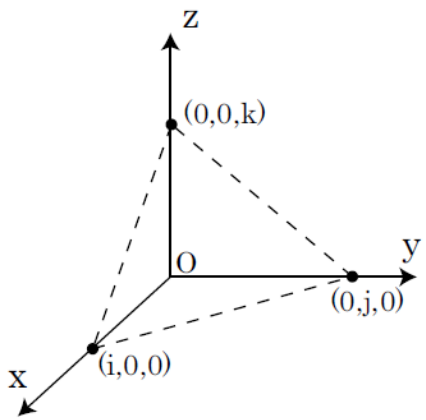
Three-quark potential V_{3Q} is extracted from 3Q Wilson loop W_{3Q}:

$$V_{3Q} = -\lim_{T\to\infty} \frac{1}{T} \ln \langle W_{3Q} \rangle$$

where $$W_{3Q} \equiv \frac{1}{3!} \epsilon_{abc}\epsilon_{a'b'c'} U_1^{aa'} U_2^{bb'} U_3^{cc'}$$

$$U_k \equiv P \exp\left\{ ig \int_{\Gamma_k} dx_\mu A^\mu(x) \right\} \quad (k = 1, 2, 3)$$

[Ref.) For example., T.T.Takahashi and H.Suganuma et al., Phys.Rev.Lett.**86** (2001); Phys.Rev.D**65** (2002).]

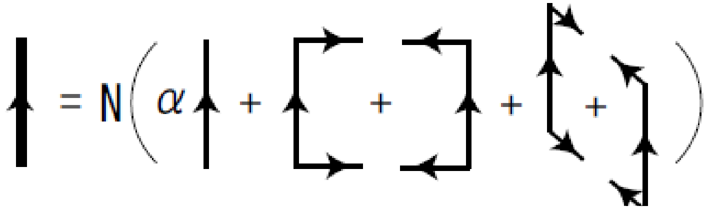


Quark sources are located at each axes.
We measure 120 different configurations of sources.

(different configurations of (i,j,k)=(1,1,1)-(8,8,8))

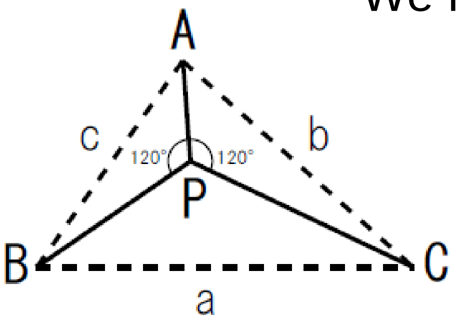
Three-quark potential in MA projected QCD

- **Gauge-invariant smearing** :
  The real ground state of flux tube is considered to be "fat".
  Therefore, a spatially extended operator has larger overlap to the ground state.



- Parameters:

β	a(fm)	Lattice size	N_{3Q}	N_{conf}	N_{therm}	N_{sep}	α	N_{smr}
6.0	0.10	$16^3 \times 32$	120	100	25,000	500	2.3	40



We fit the 3Q potential in each part by the linear +Coulomb potential:

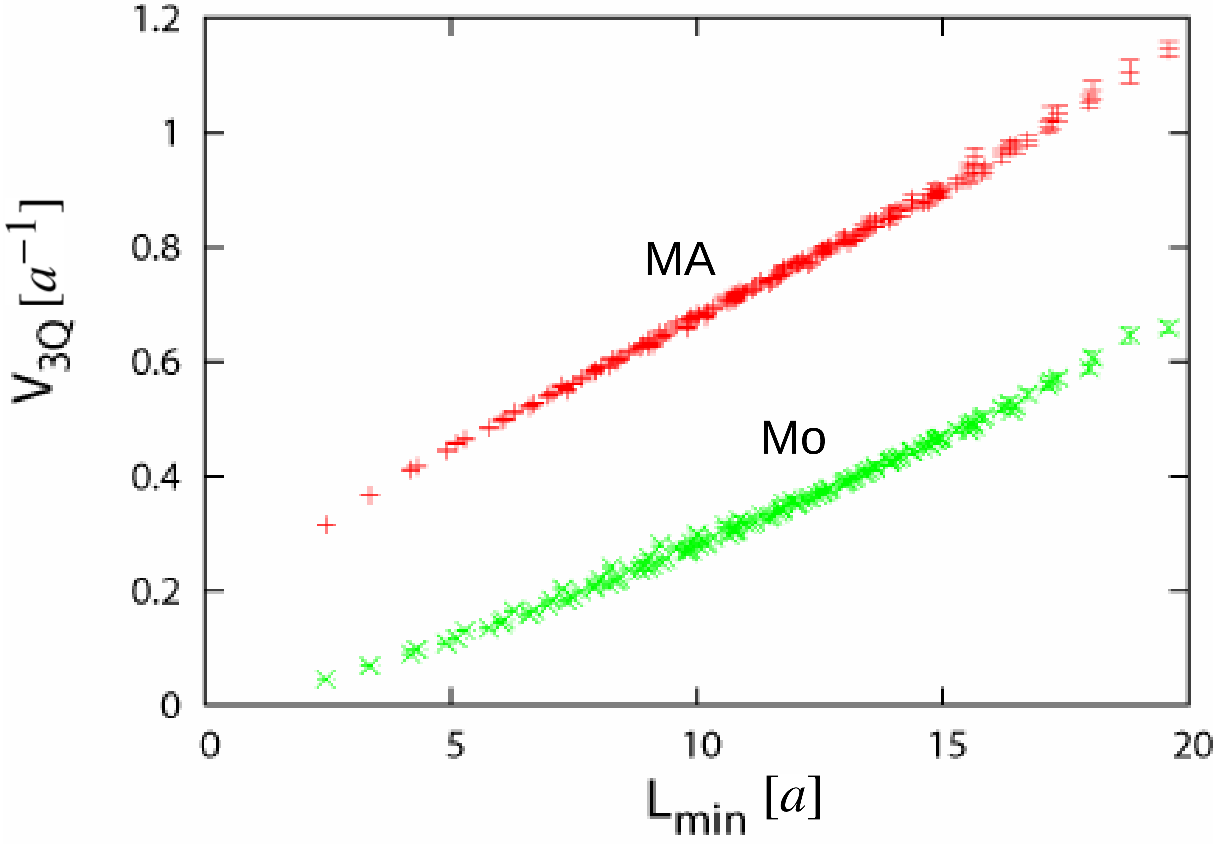
$$V_{3Q} = -A_{3Q} \sum_{i<j} \frac{1}{|\mathbf{r}_i - \mathbf{r}_j|} + \sigma_{3Q} L_{\min} + C_{3Q}$$

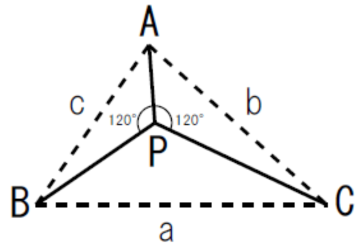
(r_i…position of the quark sources (= A, B,C))

$$L_{\min} = \mathrm{AP} + \mathrm{BP} + \mathrm{CP}$$ (∠ABC, ∠BCA, ∠CAB<120°)

Three-quark potential in MA projected QCD

3Q potential in MA and Mo QCD





$L_{\rm min} = \mathrm{AP} + \mathrm{BP} + \mathrm{CP}$

$\sigma_{3Q}\ [a^{-2}]$

MA: 0.0456 (99%)

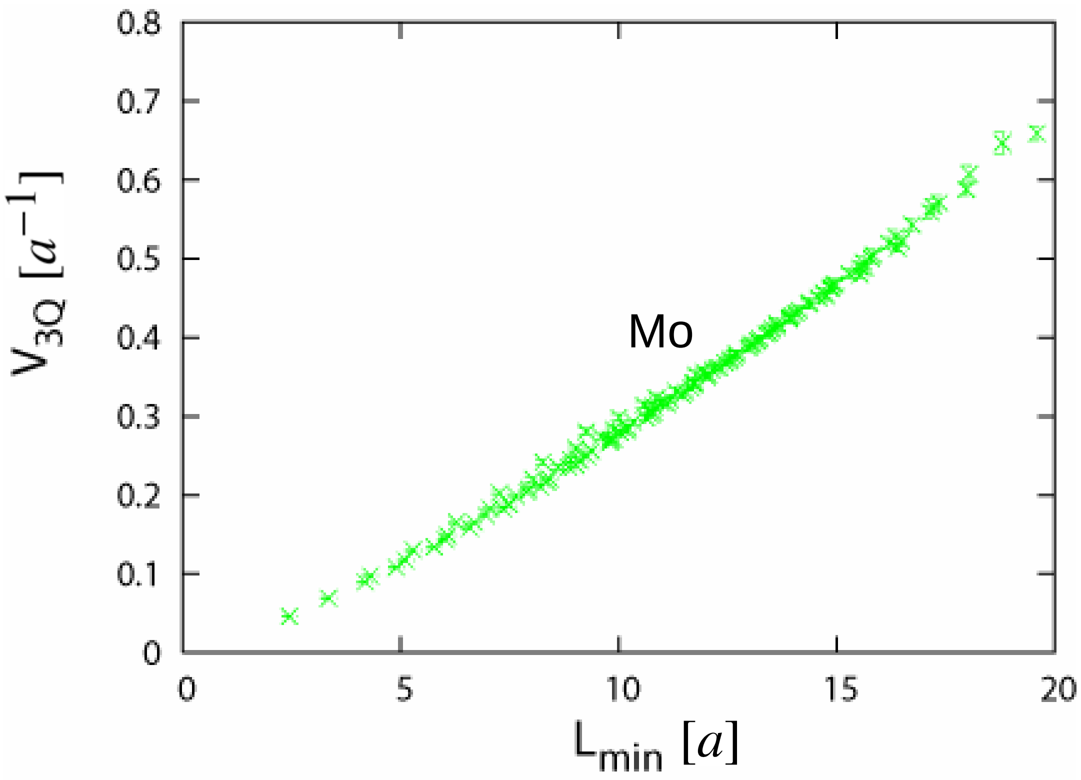
Mo: 0.0382 (83%)

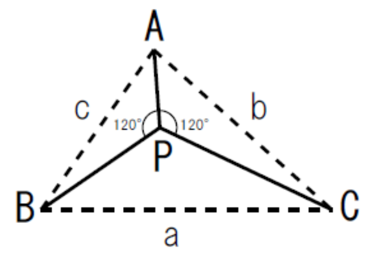
These potentials are well fitted by the potential form:

$$V_{3Q} = -A_{3Q} \sum_{i<j} \frac{1}{|\mathbf{r}_i - \mathbf{r}_j|} + \sigma_{3Q} L_{\rm min} + C_{3Q}$$

Three-quark potential in MA projected QCD

3Q potential in Mo QCD





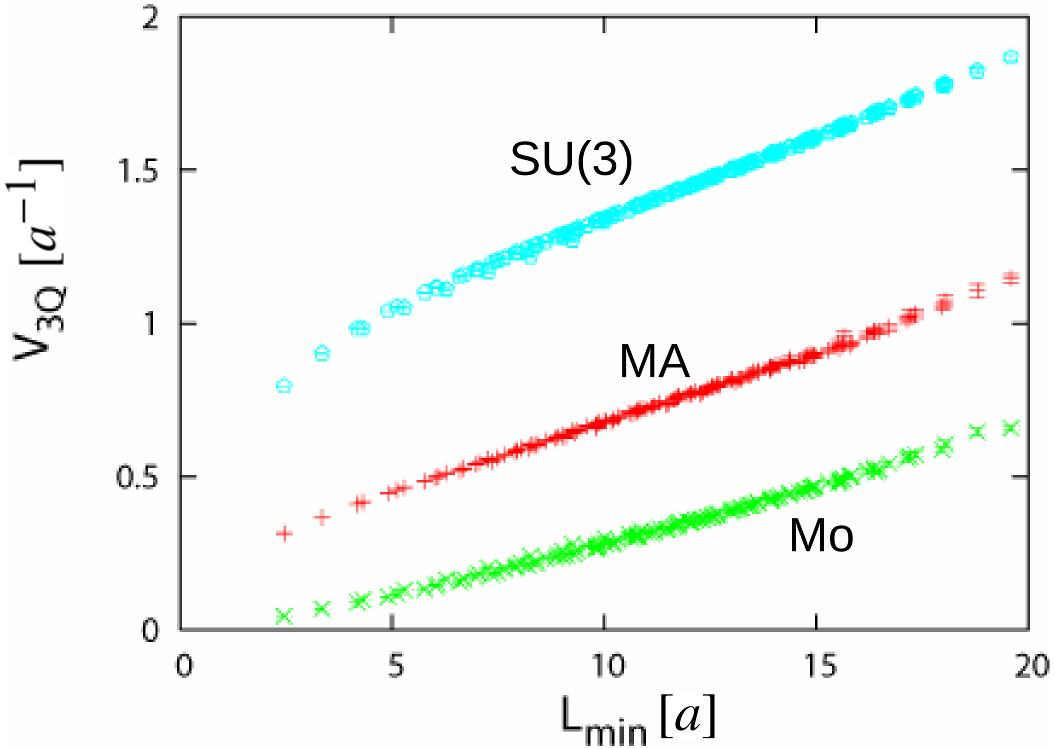
$$L_{min} = AP + BP + CP$$

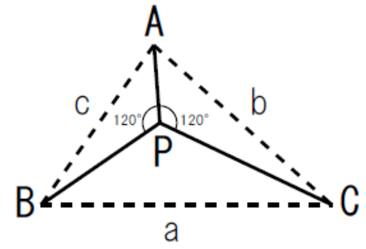
3Q potential in Mo QCD is approximately single-valued function of L_{min}

※This is non-trivial fact, because there are three parameters for the position of heavy quarks in 3Q system.

Three-quark potential in MA projected QCD

3Q potential in SU(3), MA and Mo QCD





$L_{\rm min} = \mathrm{AP} + \mathrm{BP} + \mathrm{CP}$

σ_{3Q}

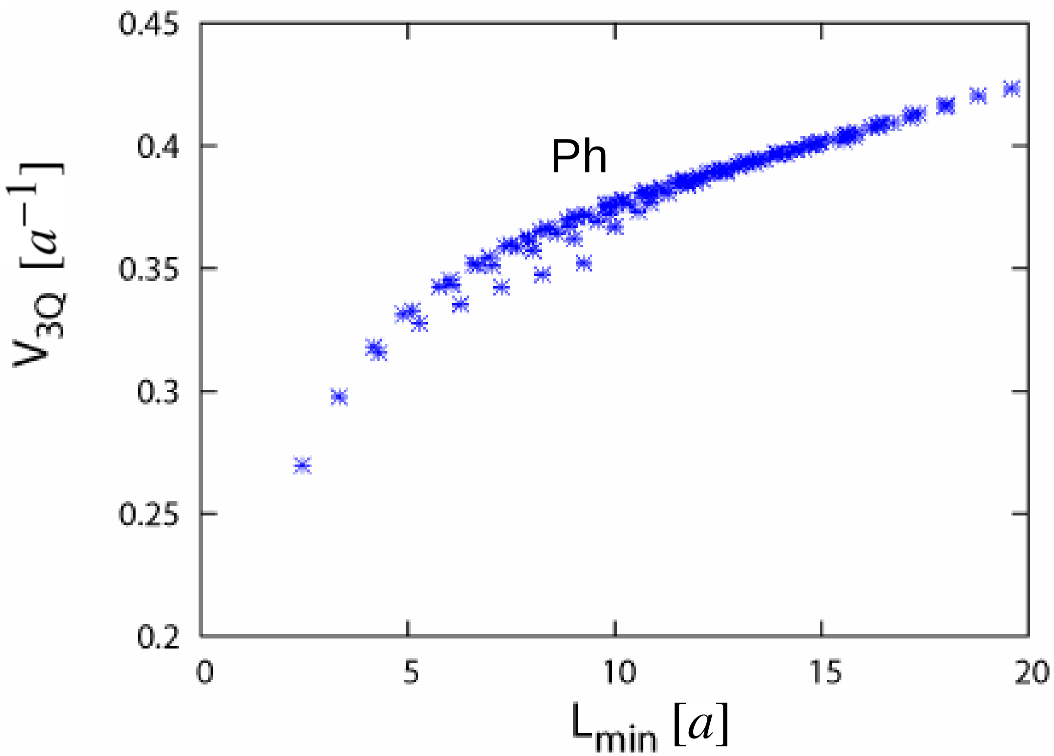
SU(3): 0.0460
MA: 0.0456 (99%)
Mo: 0.0382 (83%)

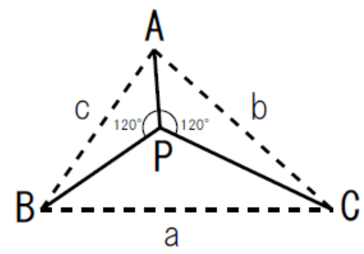
$$\sigma_{3Q}^{\rm MA} \simeq \sigma_{3Q}^{\rm Mo} \simeq \sigma_{3Q}^{\rm SU(3)}$$

We find the Abelian dominance and monopole dominance for quark confinement of 3Q system.

Three-quark potential in MA projected QCD

3Q potential in photon part plotted against L_{min}



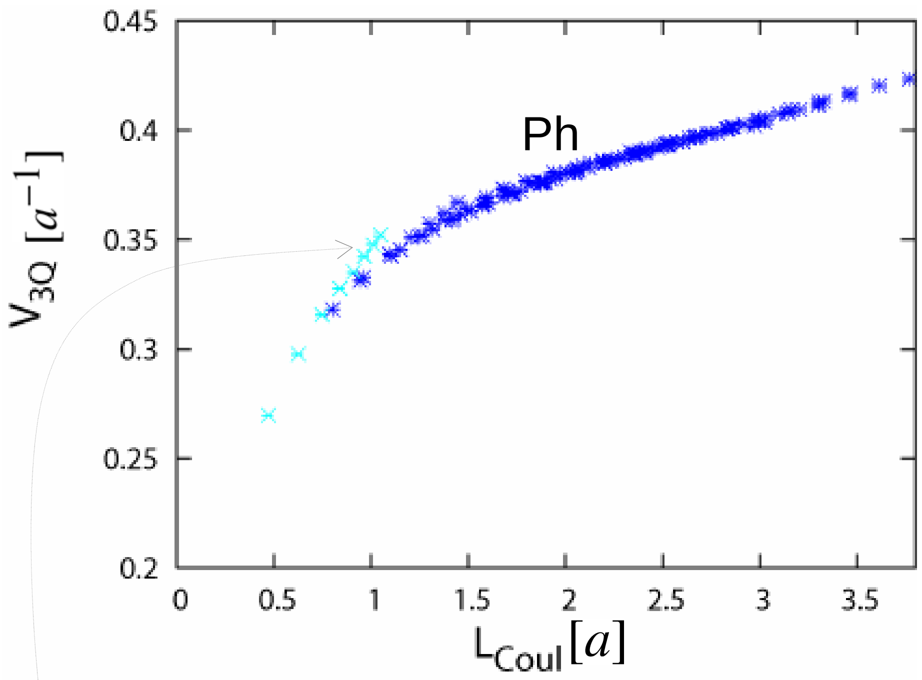


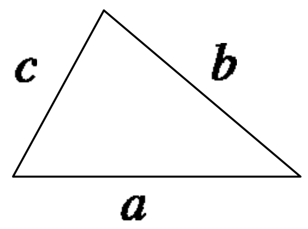
$L_{min} = AP + BP + CP$

3Q potential in Ph QCD is NOT a sing-valued function of L_{min}.

Three-quark potential in MA projected QCD

3Q potential in photon part plotted against L_{Coul}





$$L_{Coul} \equiv (1/a + 1/b + 1/c)^{-1}$$

3Q potential in Ph QCD is approximately a sing-valued function of L_{Coul}.
⇒ Photon part is pure Coulomb system.
(Only two-body Coulomb interaction)

$\sigma_{3Q}^{Ph} \simeq 0$ **... Absence of confinement force**

(× : data of $(a,b,c) = (1,1,\#)$ …These data largely suffer from lattice discretization error.)

MC projected QCD

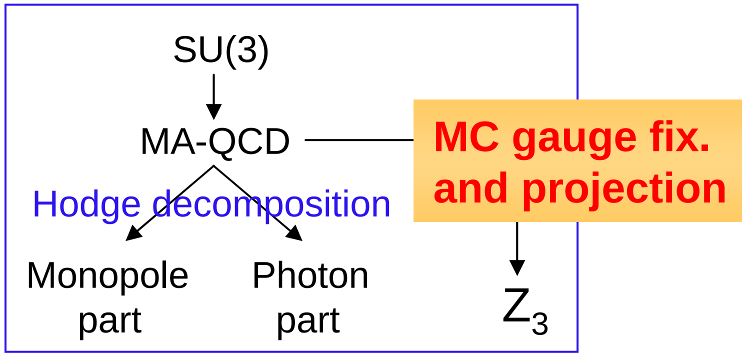
We study three-quark potential in Maximal Center (MC) projected QCD quantitatively.

- Maximal Center gauge is realized by maximizing the following quantity by gauge transformation:

[J.Greensite et al, Phys. Lett. B474 (2000).]

$$\sum_{s,\mu} |\mathrm{Tr}\, u_\mu(s)|^2$$

where $u_\mu(s) = \begin{pmatrix} e^{i\theta^1_\mu(s)} & 0 & 0 \\ 0 & e^{i\theta^2_\mu(s)} & 0 \\ 0 & 0 & e^{i\theta^3_\mu(s)} \end{pmatrix}$



※Here, we perform MC gauge fixing from MA projected QCD

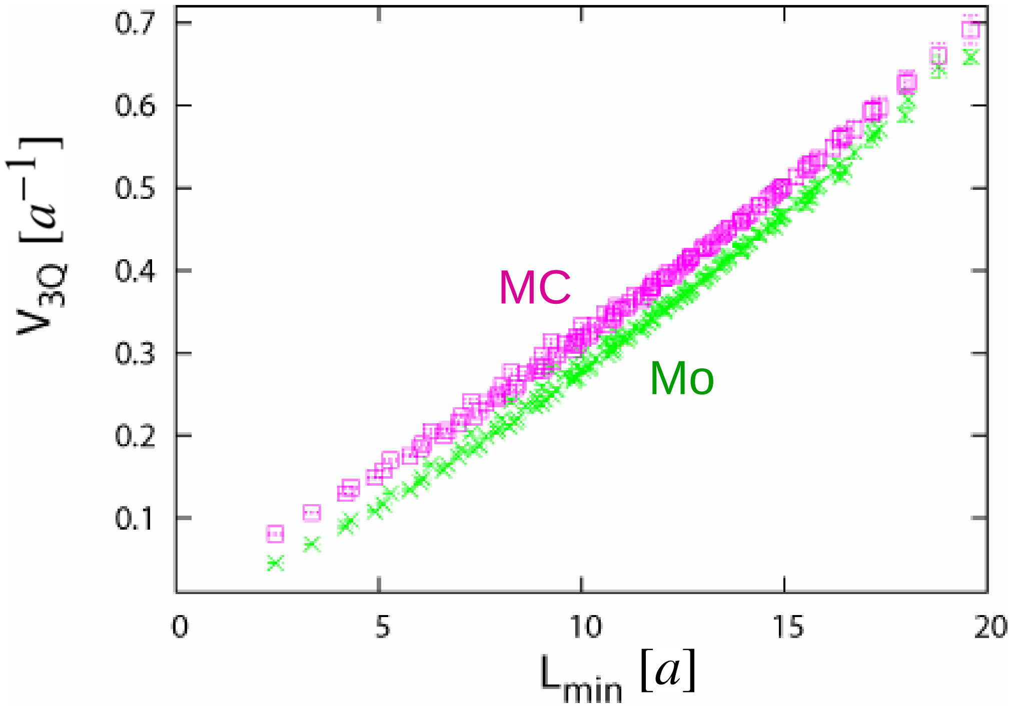
- MC projection is realized by maximizing $\mathrm{ReTr}(z^*_\mu(s) u_\mu(s))$

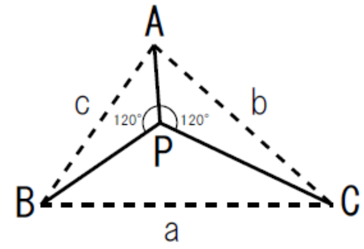
$$\begin{cases} z_\mu(s) = e^{2i\pi l/3} \cdot \mathbf{1} \ (l = 0, 1, 2) \\ z_\mu(s) \in Z_3 = \mathbf{1}, \omega \mathbf{1}, \omega^2 \mathbf{1} \end{cases}$$

… Center element of SU(3)

Three-quark potential in MC projected QCD

3Q potential in MC QCD





$L_{min} = AP + BP + CP$

3Q potential in MC QCD is approximately single-valued function of L_{min}

σ_{3Q}

SU(3): 0.0460

Mo: 0.0382 (75%)

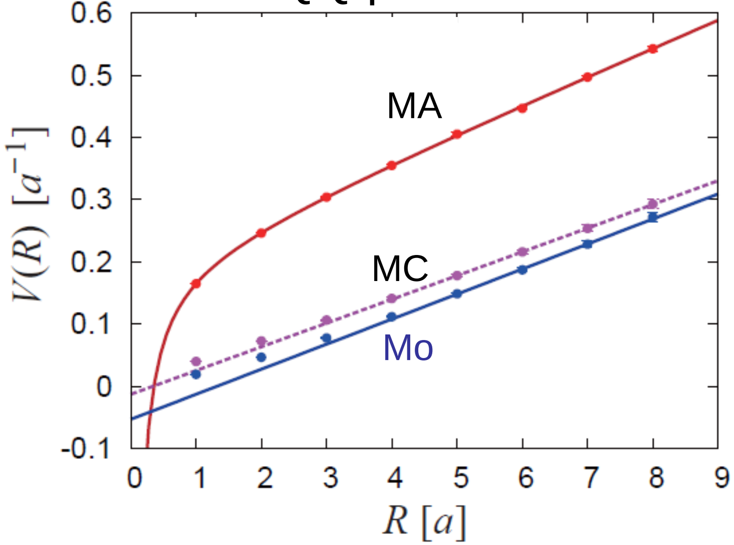
MC(Z_3): 0.0372 (73%)

$$\sigma_{3Q}^{MC} \simeq \sigma_{3Q}^{Mo} \simeq \sigma_{3Q}^{SU(3)} \simeq \sigma_{3Q}^{MA}$$

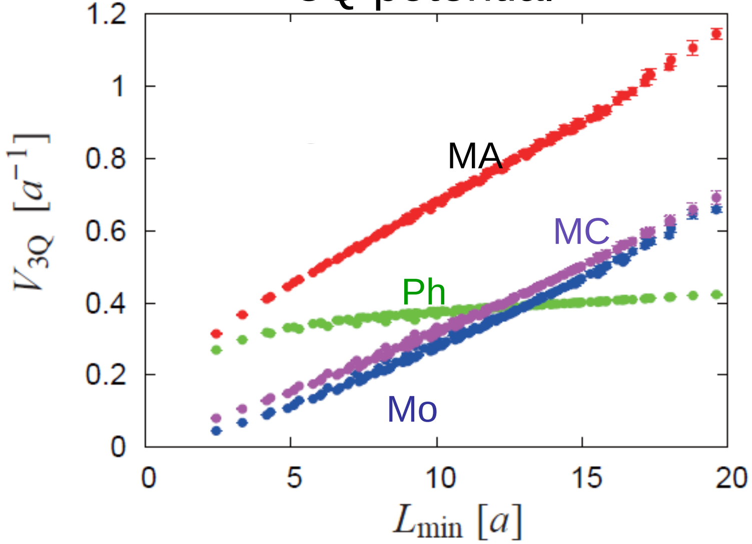
- We find the center dominance for quark confinement of 3Q system.
- We find strong similarity between Mo QCD and MC QCD.

$Q\bar{Q}$ and 3Q potential in MA and MC projected QCD

$Q\bar{Q}$ potential



3Q potential



$\sigma_{Q\bar{Q}}$

SU(3): 0.0506
MA: 0.0439 (87%)
Mo: 0.0402 (80%)
Ph: 0.0014 (∼0)
MC: 0.0361 (71%)

σ_{3Q}

SU(3): 0.0460
MA: 0.0456 (99%)
Mo: 0.0382 (75%)
Ph: 0.0021 (∼0)
MC: 0.0372 (73%)

For all part, i.e.,
SU(3), MA, Mo, Ph, and MC,

$$\sigma_{3Q} \simeq \sigma_{Q\bar{Q}}$$

is satisfied.

N-Δ mass splitting in MA projected QCD (preliminary)

Baryonic potential in MA projected QCD is investigated in the study.
Difference of 3Q potential between SU(3) QCD and MA projected QCD may affect the light hadron spectrum.
Therefore, **we study the light baryon mass spectrum in MA projected QCD.**
In this talk, we focus on N-Δ mass splitting.

Condition of numerical simulation

Quenched approximation

- **Fermion action:** Standard Wilson quark action

$$S_F \equiv \sum_{x,y} \bar{\psi}(x)K(x,y)\psi(y),$$

$$K(x,y) \equiv \delta_{x,y} - \kappa \sum_{\mu}\{(1-\gamma_\mu)U_\mu(x)\delta_{x+\hat{\mu},y} + (1+\gamma_\mu)U_\mu^\dagger(y)\delta_{x,y+\hat{\mu}}\}$$

$U_\mu(x)$: link-variable
κ : hopping parameter

- **Operators:** $N^\alpha(x) \equiv \epsilon_{cde} u_c^\alpha(x)(u_d(x)(C\gamma_5)d_e(x) - d_d(x)(C\gamma_5)u_e(x))$

$$\Delta_i^{++\alpha}(x) \equiv \epsilon_{cde} u_c^\alpha(x)(u_d(x)(C\gamma_i)u_e(x))$$

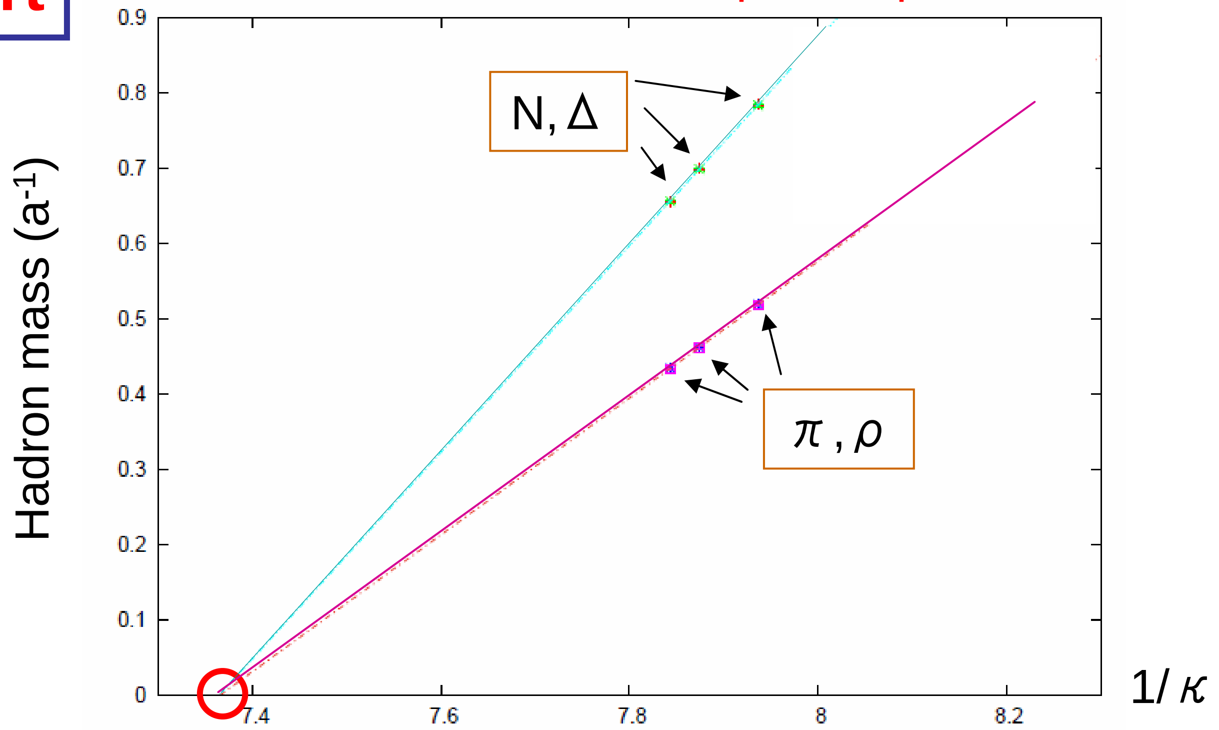
…temporal correlator $G(t) \equiv \frac{1}{V}\sum_{\vec{x}}\langle O(\vec{x},t)O^\dagger(\vec{0},0)\rangle$

- In the calculation, extended operators of Gaussian type (radius:0.4fm) are used for the enhancement of ground state overlap.

N-Δ mass splitting in MA projected QCD

Photon part

Hadron mass vs 1/κ in photon part



- **Mass: proportional to quark number**…N, Δ (π , ρ) are degenerate. (Ratio…3 : 2)
- **Massless at the same κ** …All the hadron masses is zero at the same κ where quark mass becomes zero → Trivial system

⇒ System consisting from three or two **quasi-free quarks.**

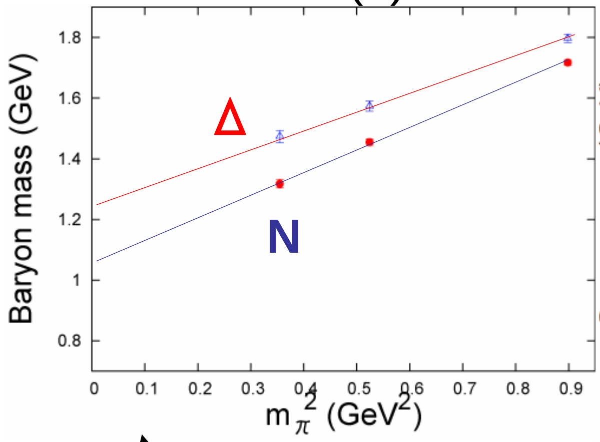
No compact bound state like hadrons in photon part

※However, photon part is different from no interacting case (U=1).

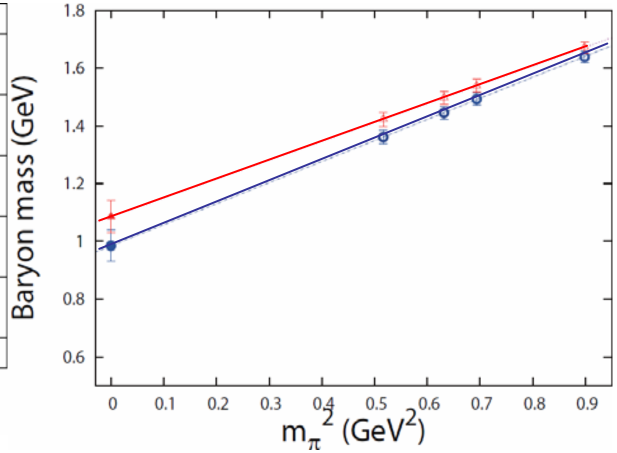
N-Δ mass splitting in MA projected QCD (preliminary)

Mass of N, Δ vs m_π^2

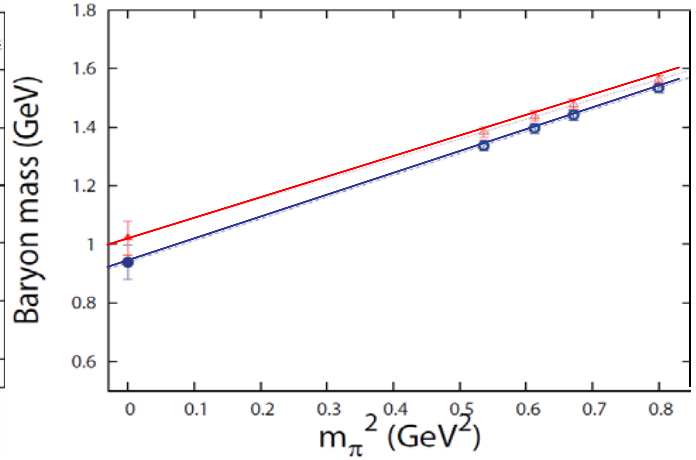
SU(3)



MA



Mo



↑ Chiral limit

	κ	κ_c
SU(3)	0.1520, 0.1540, 0.1550	0.1571
MA-QCD	0.1350, 0.1365, 0.1370, 0.1380	0.1422
Mo-QCD	0.1260, 0.1270, 0.1275, 0.1282	0.1329
Ph-QCD	0.1260, 0.1270, 0.1275	–

critical κ (chiral limit)

We find the significant change of critical κ (= κ in chiral limit) in each part, SU(3), MA and Mo.
It indicates that in different part, physical situation is not equivalent at the same κ.
Therefore, **we compare N-Δ mass splitting in chiral limit,** where the property of chiral symmetry is the same.
(Physical situation in different part is considered to be the same at κ_c)

N-Δ mass splitting in MA projected QCD (preliminary)

N-Δ mass splitting in chiral limit.

	SU(3) QCD	MA →	MA-QCD	Hodge →	Mo-QCD
N-Δ mass splitting	200MeV	projection	100MeV	decomposition	(smaller than) 80MeV

N-Δ mass splitting is significantly reduced in MA and Mo projected QCD.

N-Δ split. of **SU(3)** **>** N-Δ split. of **MA** **>** N-Δ split. of **Mo**

cf) Coulomb coefficient of $Q\bar{Q}$ is also reduced in MA and Mo projected QCD:

	SU(3) QCD	MA-QCD	Mo-QCD
$A_{Q\bar{Q}}$	0.277	0.083	~0

…Consistent with the N-Δ mass splitting in constituent quark model
(origin of the splitting…one-gluon exchange)

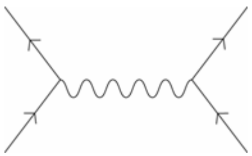
Reduction of one-gluon exchange → smaller Coulomb coefficient
Reduction of one-gluon exchange → smaller N-Δ splitting (in constituent quark model)

N-Δ mass splitting in MA projected QCD (preliminary)

Why does the Coulomb coefficient becomes small in MA projected QCD?

<u>One possibility</u>

SU(3) QCD

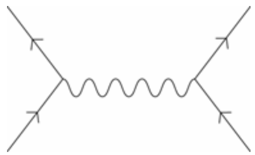


8 gluons

MA gauge fixing
& MA projection ⇨

→ **1/4**

MA QCD



2 gluons

Hodge
decomposition ⇨

Monopole part

No Coulomb potential

	SU(3) QCD	MA-QCD	Mo-QCD
$A_{Q\bar{Q}}$	0.277 →	0.083	∼0

⇧ **1/3∼1/4**

Summary

$Q\bar{Q}$ potential and 3Q potential are quantitatively studied in MA/MC projected QCD on SU(3) lattice.

- String tensions of $Q\bar{Q}$ potentials in SU(3), MA-QCD, Mo-QCD and MC-QCD are roughly equivalent (80～99%：MA･Mo, 70～80%: MC).

$$\sigma_{Q\bar{Q}}^{SU(3)} \simeq \sigma_{Q\bar{Q}}^{MA} \simeq \sigma_{Q\bar{Q}}^{Mo} \simeq \sigma_{Q\bar{Q}}^{MC}$$

- For 3Q potentials, string tensions in SU(3), MA-QCD, Mo-QCD and MC-QCD are roughly equivalent (75～99%：MA･Mo, 70～80%: MC).

$$\sigma_{3Q}^{SU(3)} \simeq \sigma_{3Q}^{MA} \simeq \sigma_{3Q}^{Mo} \simeq \sigma_{3Q}^{MC}$$

- String tensions of $Q\bar{Q}$ and 3Q in each part are almost equivalent (over 90%).
  ⇒ Universality of string tension: $\sigma_{3Q} \simeq \sigma_{Q\bar{Q}}$

- In photon part, there is almost no confinement force.

$$\sigma_{Q\bar{Q}}^{Ph} \simeq 0, \ \sigma_{3Q}^{Ph} \simeq 0$$

- Strong similarity between Mo and MC-QCD is observed.

Summary

N-Δ mass splitting in MA projected QCD is studied. (preliminary)

- **N-Δ mass splitting is significantly reduced in MA and Mo projected QCD.**
  → Consistent with the N-Δ mass splitting in constituent quark model
  (origin of the splitting in this model…one-gluon exchange)

N-Δ mass splitting in chiral limit

	SU(3) QCD	MA-QCD	Mo-QCD
N-Δ mass splitting	200MeV	100MeV	smaller than 80MeV

cf) Reduction of Coulomb coefficient in MA-QCD and Mo-QCD.

	SU(3) QCD	MA-QCD	Mo-QCD
$A_{Q\bar{Q}}$	0.277	0.083	∼0

Reduction of one-gluon exchange → smaller Coulomb coefficient
Reduction of one-gluon exchange → smaller N-Δ splitting (in constituent quark model)

- **In photon part, hadrons are not created and the system consists of quasi-free quarks.**

Backup slide

Back-up slide

- Y-Ansatz for confinement potential is almost established by not only our group but also many other groups.

Lattice:

H.Ichie et al., Phys. Rev. D**70**, 054506 (2004).
F.Okiharu et al., Eur.Phys.J.C**35**, 537 (2004).
F.Bissey et al., Phys.Rev.D**76**, 114512 (2007).
M.Chernodub et al.,
F.Karsch et al.,
Proceedings of "STRONG AND ELECTROWEAK MATTER 2004".
(hep-lat/0408031)

…

Other theories:

J.Cornwall, Phys.Rev.D**54**, 6527 (1996).
D.Kuzmenko and Y.Simonov, Phys.Atom.Nucl.**66**, 950 (2003).
O.Andreev, arXiv:0804.4756.

…

質問対策:

・市江さんのとなにがちがう？⇒MCが入っている、市江さんのはそんなに定量的でない（Mo等に関しては、弦定数の数値的な議論はしていなかった）、light-hadron spectrumも見ている。

・なぜphoton partでsplittingが見えない？⇒粒子が束縛されていないから（広がった状態）

・MoとMCが非常に似ている⇒閉じ込めの本質はmonopoleでなくてvortex?
Because we perform the MC projection from the MA projected QCD, we can not say strongly so.

・