Bulk and finite-temperature transitions in SU(3) gauge theories with many light fermions

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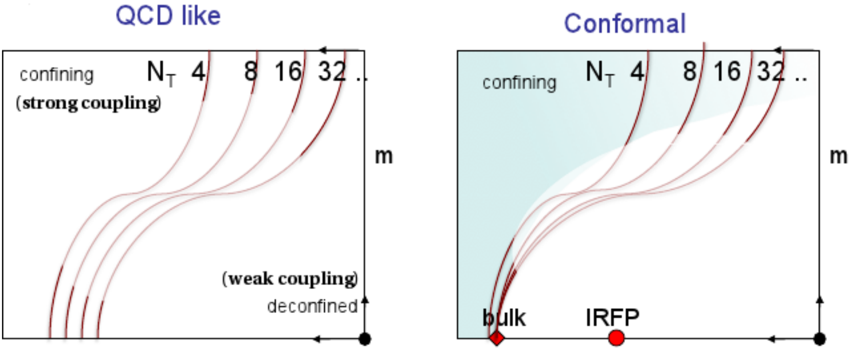
PRD **85**:094509 (2012) [arXiv:1111.2317**v2**] and work in progress
with Anqi Cheng, Anna Hasenfratz and Greg Petropolous

Motivation for studying finite-temperature transitions



$\beta_c \to \infty$ as $N_T \to \infty$ $\qquad$ $\beta_c \to \beta_{bulk}$ as $N_T \to \infty$

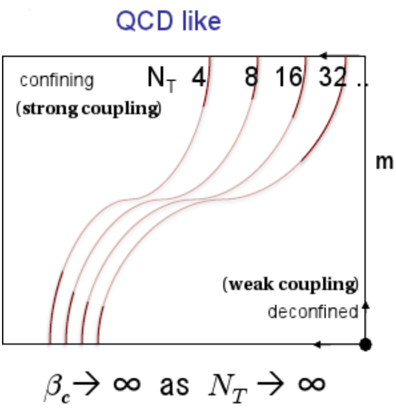
Hope for contrast between confining vs. IR-conformal systems

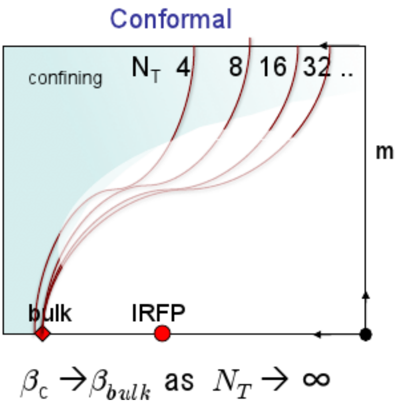
Previous work: Groningen–INFN; Lattice Higgs Collaboration

$\longrightarrow$ Explore with action that showed $N_F = 12$ IR fixed point via MCRG

(For more on MCRG: Greg Petropoulos, Thursday 14:30)

Motivation for studying finite-temperature transitions

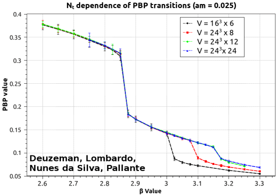


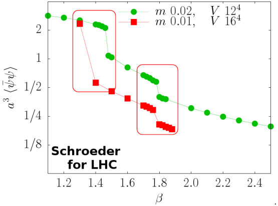


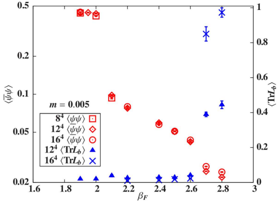
- nHYP smeared action with adjoint plaquette term $\beta_A = -0.25\beta_F$
- $N_F = 8$ and 12 staggered fermions in fundamental rep.
- $T > 0$ volumes up to $40^3 \times 20$, as well $T = 0$ up to $32^3 \times 64$ (large-volume runs still in progress $\longrightarrow$ results preliminary)

For $N_F = 12$ we observe **two** bulk transitions

Strange behavior in $\langle\overline{\psi}\psi\rangle$ observed using three staggered actions







Our observations (may not yet be consensus)

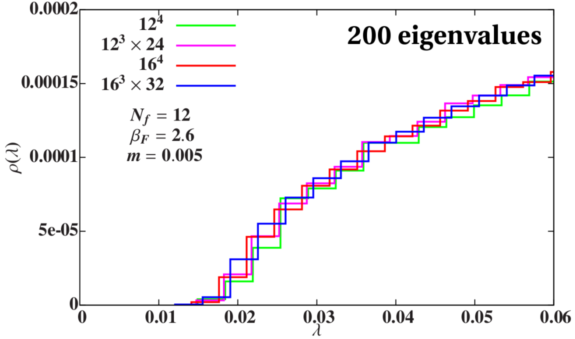
- Large jump in $\langle\overline{\psi}\psi\rangle$ at stronger coupling
- Large jump in RG-blocked Polyakov loop at weaker coupling

Suggest a confined but chirally symmetric phase

Study through low-lying eigenvalues, and new order parameters. . .
(and spectrum and static potential, omitted from this talk)

Eigenvalue density $\rho(\lambda)$ in intermediate phase

Good observable for exploring chiral properties



$$\langle \overline{\psi}\psi \rangle \propto m \int \frac{\rho(\lambda) d\lambda}{\lambda^2 + m^2}$$

$$\omega \equiv \chi_P - \chi_S$$
$$= 4m^2 \int \frac{\rho(\lambda) d\lambda}{(\lambda^2 + m^2)^2}$$

"Soft edge": $\lim_{V\to\infty} \rho(\lambda) \propto (\lambda - \lambda_0)^\alpha$ with $\lambda_0 > 0$ $\quad (\alpha \approx 0.5)$

Gap in infinite-volume extrapolation of eigenvalue density
$\Longrightarrow \langle \overline{\psi}\psi \rangle = 0$ and $\chi_S = \chi_P$ (axial $U(1)_A$ restored) in chiral limit

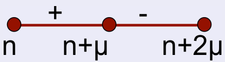
(For more on eigenvalues at weak coupling: A. Hasenfratz, Tuesday 14:50)

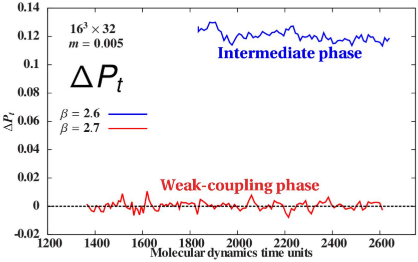
Novel behavior: single-site shift symmetry breaking

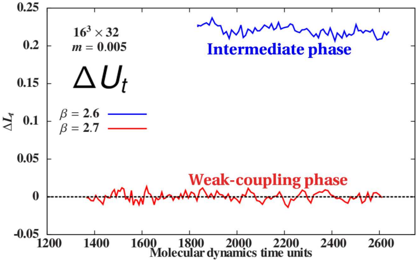
Order parameters: differences of plaquettes $\Box$ or links $\overline{\chi}U\chi$

$$\Delta P_\mu = \langle \mathrm{ReTr}\,\Box_{n,\mu} - \mathrm{ReTr}\,\Box_{n+\mu,\mu} \rangle_{n_\mu \text{ even}}$$

$$\Delta U_\mu = \langle \alpha_{\mu,n}\overline{\chi}_n U_{\mu,n}\chi_{n+\mu} - \alpha_{\mu,n+\mu}\overline{\chi}_{n+\mu} U_{\mu,n+\mu}\chi_{n+2\mu} \rangle_{n_\mu \text{ even}}$$





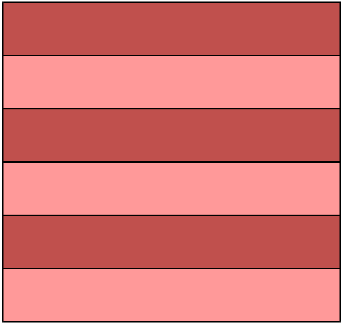


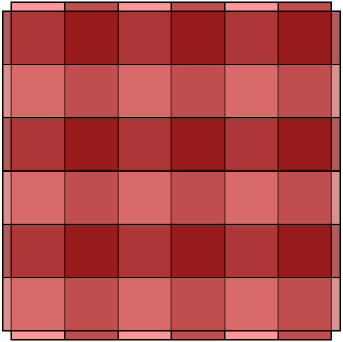
Single-site shift symmetry of staggered action spontaneously broken in intermediate phase (“$\not{S}^4$”)

Consequences of shift symmetry breaking

Observables alternate between slices

Breaking can develop in one or more directions
Breaking can change direction(s) during HMC evolution





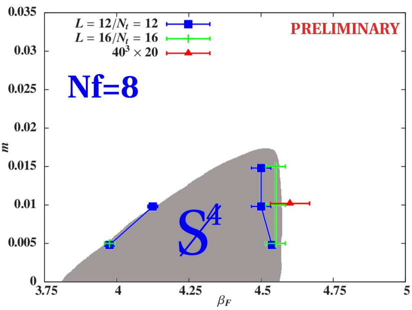
Present in plaquette $\Longrightarrow$ feature of gauge configurations themselves

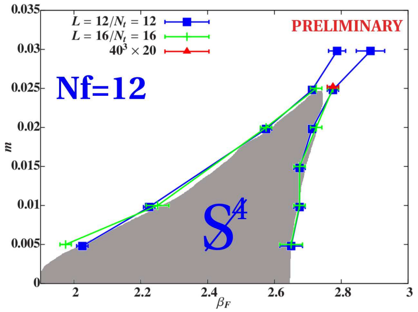
Implications of $\not{S}^4$ lattice phase

$\not{S}^4$ phase seems to have no continuum limit

- Confining but chirally symmetric (forbidden by anomaly matching)
- Bounded by first-order bulk transitions (merge as *m* increases)
- Observed for both $N_F = 8$ and 12

(Potential Aoki-like phase? Relation to staggered taste breaking?)





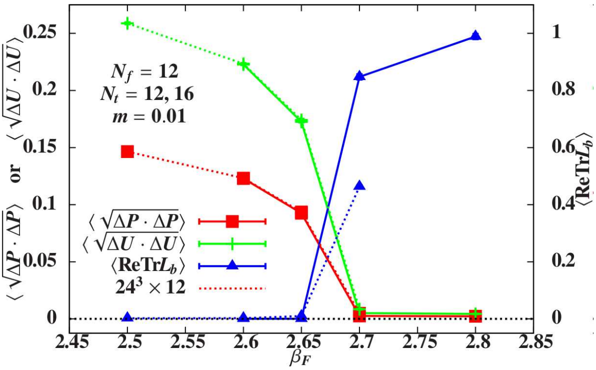
How do finite-temperature transitions behave around bulk transitions?

Finite-temperature transitions around the $\not{S}^4$ phase

$\mathbf{N_F = 12}$, $m = 0.01$, $24^3 \times 12$ and $32^3 \times 16$

$\not{S}^4$ order parameters fall to zero at the same time as
the RG-blocked Polyakov loop becomes large
(compared to $N_F = 2+1$ deconfinement transition)

$\Longrightarrow$ At $m = 0.01$, move from $\not{S}^4$ phase into deconfined phase



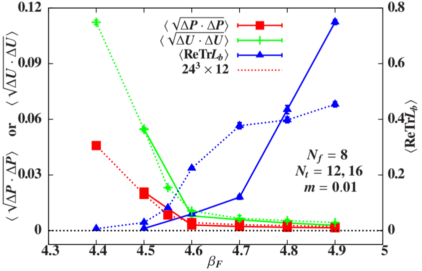
Finite-temperature transitions around the $\not S^4$ phase

$\mathbf{N_F = 8}$, $m = 0.01$, $24^3 \times 12$ and $32^3 \times 16$

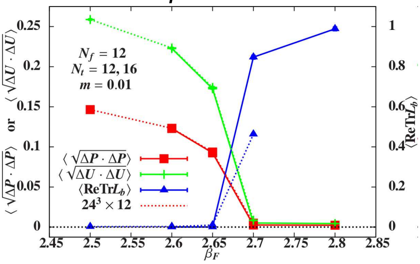
Rise in RG-blocked Polyakov loop depends on N_T,
not simultaneous with fall in $\not S^4$ order parameters

$\Longrightarrow$ At $m = 0.01$, move from $\not S^4$ phase into confined phase;
Deconfinement transition moves with N_T

$N_F = 8$



$N_F = 12$

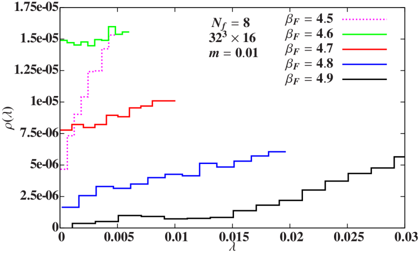


Eigenvalue density $\rho(\lambda)$ around the $\not{S}^4$ phase

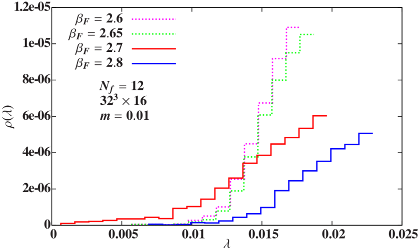
$N_F = 8$ and 12, $m = 0.01$, $32^3 \times 16$

- Soft edge appears both in $\not{S}^4$ phase and at high temperature
- For $N_F = 12$, we move straight from $\not{S}^4$ phase to chiral symmetry
- For $N_F = 8$, we observe a chirally broken phase in between the $\not{S}^4$ phase and chiral symmetry restoration

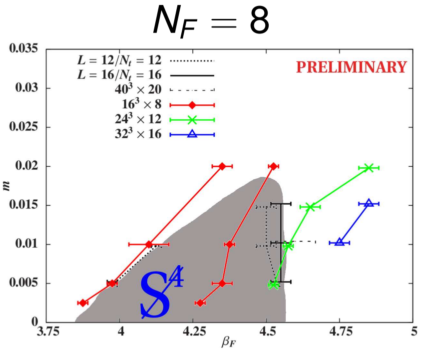
$N_F = 8$

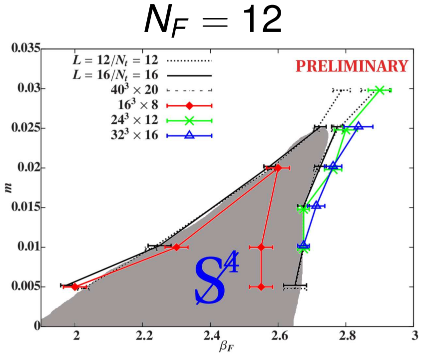


$N_F = 12$



Resulting $N_F = 8$ and 12 phase diagrams





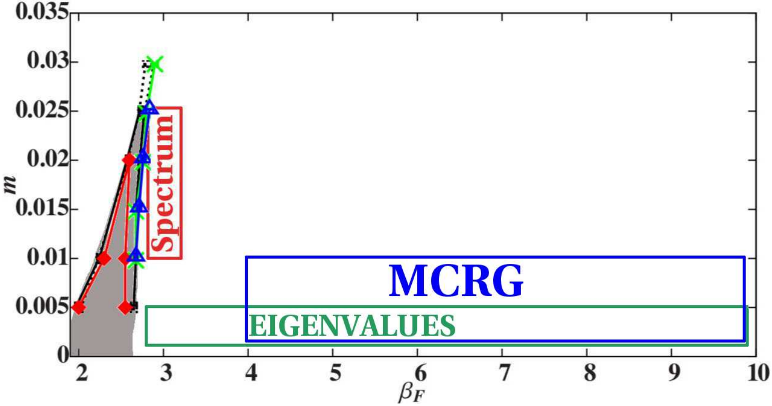
$T > 0$ transitions
pass through $\cancel{S}^4$ bulk transition
$N_T = 12, 16$ move to weaker β

$T > 0$ transitions
congregate at $\cancel{S}^4$ bulk transition
$N_T = 12, 16$ indistinguishable

Finite-temperature analysis appears feasible despite novel $\cancel{S}^4$ phase

Outlook

Complementing finite-temperature studies with MCRG,
Dirac eigenvalues and meson spectrum analyses



Eigenvalues: Anna Hasenfratz, Tuesday 14:50
MCRG: Greg Petropoulos, Thursday 14:30

Thank you!

Thank you!

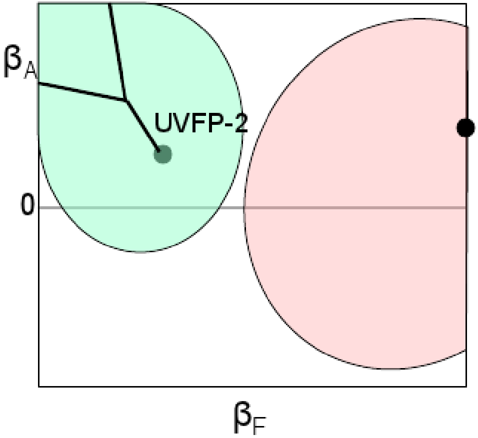
Collaborators

Anqi Cheng, Anna Hasenfratz, Greg Petropolous

Funding and computing resources

Backup: spurious UV fixed point from lattice artifacts

We add a negative adjoint plaquette term to the gauge action ($\beta_A = -0.25\beta_F$) to avoid a well-known spurious UV fixed point



(A. Hasenfratz)

Gaussian FP

Between the basins of attraction is a no-man's land

Backup: Blocked Polyakov loop

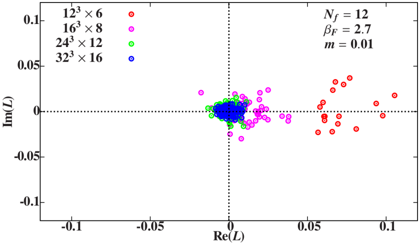
RG-blocked observables enhance signals over noise

Simply the usual observables measured on RG-blocked configurations

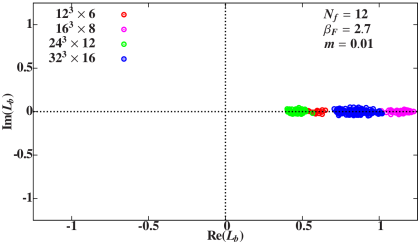
Can be thought of as extended observables on original lattices, improved to remove UV fluctuations

Example below: Polyakov loop for $N_F = 12$, $\beta_F = 2.7$, $m = 0.01$

Unblocked



Blocked



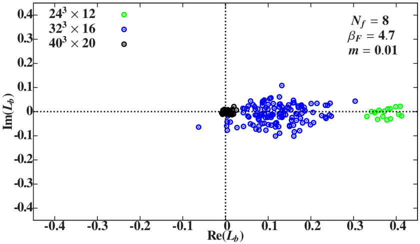
Note different volumes permit different numbers of blocking steps

Backup: Blocked Polyakov loop

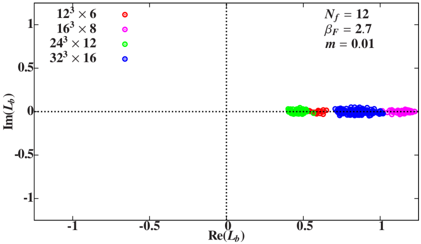
RG-blocked observables preserve existing signals

Simply the usual observables measured on RG-blocked configurations
Can be thought of as extended observables on original lattices, improved to remove UV fluctuations
RG-blocked Polyakov loop can still indicate transition

$N_F = 8$



$N_F = 12$



As for other observables, qualitative difference between $N_F = 8$ and 12

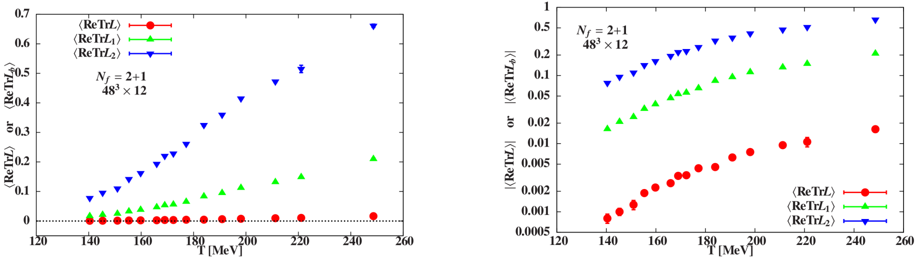
Backup: Blocked Polyakov loop

RG-blocked observables checked for $N_F = 2+1$

Simply the usual observables measured on RG-blocked configurations

Can be thought of as extended observables on original lattices, improved to remove UV fluctuations

Behave as expected for finite-temperature lattice QCD



Thanks!

Tested on $48^3 \times 12$ configurations provided by HotQCD Collaboration

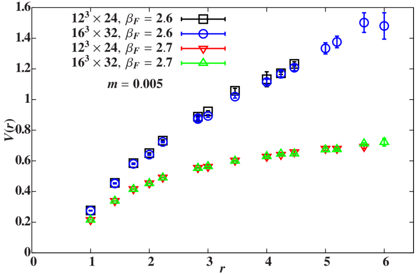
Backup: $\not{S}^4$ phase is confining but chirally symmetric

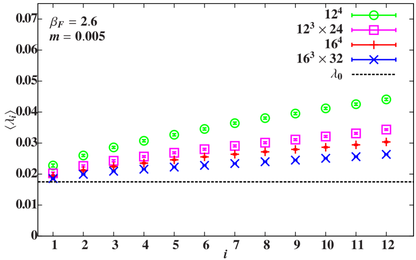
Confinement:

- RG-blocked Polyakov loop is small
- Potential has clear linear term, small Sommer parameter $r_0 \approx 3$

Chiral symmetry:

- Meson spectrum is parity-doubled and volume-independent
- Dirac eigenvalue distribution has "soft edge" $\lambda_0 = 0.0175(5)$





Backup: parity doubling in the $\not{S}^4$ meson spectrum

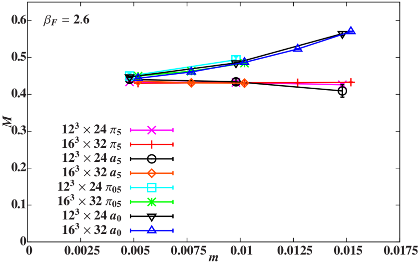
In the $\not{S}^4$ phase,

meson spectrum is parity-doubled and volume-independent

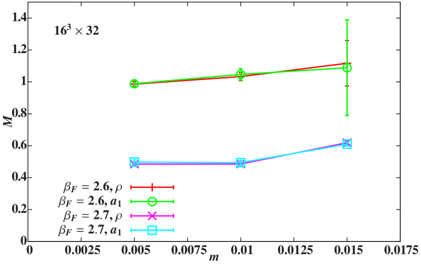
Goldstone pion possesses a scalar parity partner "a_5"

(forbidden in QCD-like systems)

Scalars and pseudoscalars



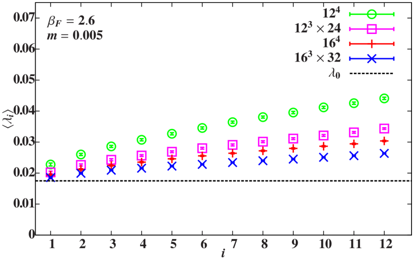
Vector and axial

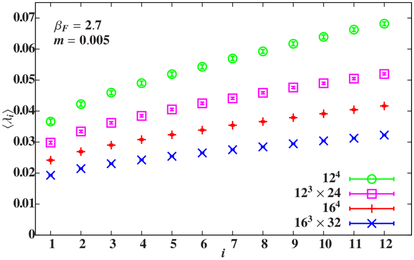


Backup: Volume scaling of Dirac eigenvalues

$\not{S}^4$ phase soft edge visible in eigenvalues themselves (left)

Contrast with weak-coupling phase (right)

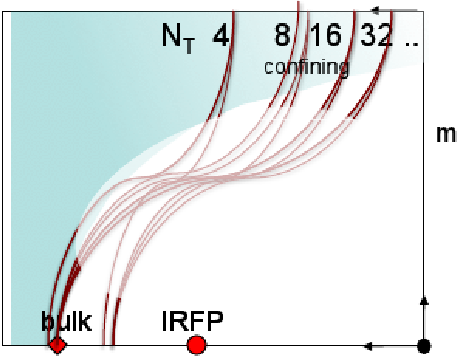




$\lim_{V \to \infty} \rho(\lambda) \propto (\lambda - \lambda_0)^\alpha$

$\lambda_0 = 0.0175(5) > 0$ is **soft edge**

Backup: Cartoon of phase diagram including $\not{S}^4$ phase



$\beta_c \rightarrow \beta_{bulk}$ as $N_T \rightarrow \infty$

Staggered single-site shift symmetry:

$$\chi(n) \rightarrow \xi_\mu(n)\chi(n+\mu) \qquad \xi_\mu(n) \equiv (-1)^{\sum_{\nu>\mu} n_\nu}$$

$$\overline{\chi}(n) \rightarrow \xi_\mu(n)\overline{\chi}(n+\mu) \qquad U_\mu(n) \rightarrow U_\mu(n+\mu)$$