Confinement Criterion for QCD with Dynamical Quarks

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Outlook

Confinement

colour charged particles cannot be isolated

OR

all finite-energy states are invariant under global gauge transformations

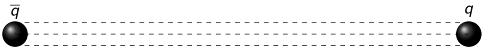
Interquark Potential

Pure Gauge Theory

- static quark-antiquark pair separated by distance R
- chromoelectric flux forms flux tube due to self-interaction of gluons
- potential between quarks increases linearly for asymptotic distances (linear confinement)
- static quark potential

$$V(R) \underset{R \to \infty}{\sim} \alpha \cdot R$$

where α denotes string tension

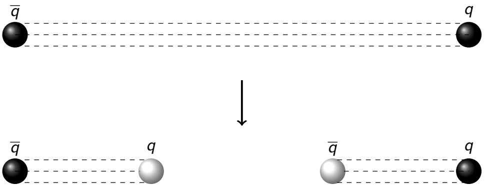


Interquark Potential

In Presence of Dynamical Matter Fields

- potential at large distances flattens due to production of light quark-antiquark pairs
- string breaking if energy of gauge string becomes as large as energy required to produce light $q\overline{q}$-pair

$$V\left(R_b \ll R \to \infty\right) = 2\mu$$



String Breaking in Pure Gauge Theory?

- quarks live in fundamental representation

$$\Psi(x) \to U(x)\,\Psi(x)$$

where $U(x) = \exp\{-ig\Lambda^a(x)\,T^a\}$

- gluons live in adjoint representation

$$A_\mu(x) \to U(x)\,A_\mu(x)\,U^\dagger(x) + \frac{i}{g}U(x)\,\partial_\mu U^\dagger(x)$$

- gluons cannot form an object in fundamental representation
$\Rightarrow$ string cannot break down

QFT on the Lattice

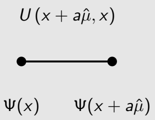
- hypercubic lattice (a: lattice constant)

$$\Lambda = a\mathbb{Z}^4 = \left\{ x \,\middle|\, \frac{x_\mu}{a} \in \mathbb{Z} \right\}$$

- matter fields $\Psi(x)$ are defined on points $x \in \Lambda$
- link variable: elementary parallel transporters are associated with link $b = \langle x + a\hat{\mu}, x \rangle$

$$U(b) = U(x + a\hat{\mu}, x)$$

- lattice gauge field = collection of all link variables $\{U(b)\}$

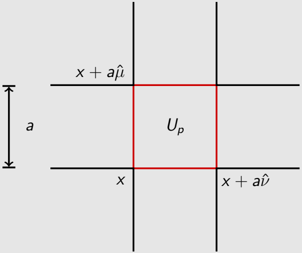


QFT on the Lattice

- plaquette p = smallest closed loop on the lattice
- plaquette variable U_p

$$= U\left(x, x + a\hat{\nu}\right) U\left(x + a\hat{\nu}, x + a\hat{\mu} + a\hat{\nu}\right) \cdot$$

$$\cdot U\left(x + a\hat{\mu} + a\hat{\nu}, x + a\hat{\mu}\right) U\left(x + a\hat{\mu}, x\right)$$



- Wilson action for pure lattice gauge theory

$$S\left[U\right] = \beta \sum_p \left[1 - \frac{1}{N} \mathrm{Re}\,\mathrm{Tr}\, U_p\right] \quad \text{for SU(N)}$$

- Wilson action $\xrightarrow{a \to 0}$ Yang-Mills action for $\beta = \frac{2N}{g^2}$

Wilson Loop

- consider closed contour $\mathcal{C}$

Wilson loop in continuum

$$W(\mathcal{C}) := \mathrm{Tr}\left[P \cdot \exp\left(\int_{\mathcal{C}} A_i \,\mathrm{d}x^i\right)\right]$$

Wilson loop on the lattice

$$W(\mathcal{C}) := \mathrm{Tr}\, U(\mathcal{C})$$

Vacuum Expectation Value of Wilson Loop

- carry test charge Ψ along the closed contour $\mathcal{C}$

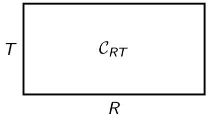
  $\Rightarrow$ corresponding quantum mechanical amplitude
  $=$ vacuum expectation value of Wilson loop

$$\langle 0 | W(\mathcal{C}) | 0 \rangle$$

- *now:* reactangular contour $\mathcal{C}_{RT}$

  T: length in timelike direction

  R: length in spacelike direktion



Vacuum Expectation Value of Wilson Loop

- VEV of Wilson loop

$$\langle 0| W\left(\mathcal{C}_{RT}\right)|0\rangle = \sum_{m,m'} \left\langle 0| U^{\dagger}_{mm'}\left(R,T\right) U_{m'm}\left(R,0\right)|0\right\rangle$$

- relate $U^{\dagger}\left(R,T\right)$ to $U\left(R,0\right)$ with time evolution operator

$$\langle 0| W\left(\mathcal{C}_{RT}\right)|0\rangle = \sum_{m,m'} \langle 0| U^{\dagger}_{mm'}\left(R,0\right) e^{iHT} U_{m'm}\left(R,0\right)|0\rangle$$

- insert complete set of energy eigenstates

$$\langle 0| W\left(\mathcal{C}_{RT}\right)|0\rangle = \sum_{m,m',n} \langle 0| U^{\dagger}_{mm'}\left(R,0\right) e^{iHT}|n\rangle \langle n| U_{m'm}\left(R,0\right)|0\rangle$$

- use $e^{iHT}|n\rangle = e^{iE_nT}|n\rangle$

$$\langle 0| W\left(\mathcal{C}_{RT}\right)|0\rangle = \sum_{m,m',n} \left|\langle n| U_{m'm}\left(R,0\right)|0\rangle\right|^2 e^{iE_n(R)T}$$

Vacuum Expectation Value of Wilson Loop

- VEV of Wilson loop

$$\langle 0| W(\mathcal{C}_{RT}) |0\rangle = \sum_{m,m'} \left\langle 0| U^{\dagger}_{mm'}(R,T)\, U_{m'm}(R,0) |0\right\rangle$$

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Vacuum Expectation Value of Wilson Loop

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$$\langle 0| W(\mathcal{C}_{RT}) |0\rangle = \sum_{m,m',n} |\langle n| U_{m'm}(R,0) |0\rangle|^2\, e^{iE_n(R)T}$$

Vacuum Expectation Value of Wilson Loop

- VEV of Wilson loop

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- insert complete set of energy eigenstates

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- use $e^{iHT}|n\rangle = e^{iE_nT}|n\rangle$

$$\langle 0|W(\mathcal{C}_{RT})|0\rangle = \sum_{m,m',n} |\langle n|U_{m'm}(R,0)\,|0\rangle|^2\, e^{iE_n(R)T}$$

Vacuum Expectation Value of Wilson Loop

- Euclidean version $T \to iT$

$$\langle 0| W\left(\mathcal{C}_{RT}\right)|0\rangle = \sum_{m,m',n} \left|\langle n| U_{m'm}\left(R,0\right)|0\rangle\right|^2 e^{-E_n(R)T}$$

- ground state is the only important contribution for long contours $(T \to \infty)$
- with $E_0 = V\left(R\right)$

$$\langle 0| W\left(\mathcal{C}_{RT}\right)|0\rangle \underset{T\to\infty}{=} \underbrace{\mathrm{Tr}\left|\langle n| U\left(R,0\right)|0\rangle\right|^2}_{\text{overlap}} \cdot e^{-V(R)T}$$

Wilson Loop Criterion

$$\langle 0|W\left(\mathcal{C}_{RT}\right)|0\rangle \underset{T\to\infty}{\sim} e^{-V(R)T}$$

confinement phase: $V\left(R\right) \underset{R\to\infty}{\sim} \alpha R$

area law

$$\langle 0|W\left(\mathcal{C}\right)|0\rangle \underset{R,T\to\infty}{\sim} \exp\left(-\alpha RT\right)$$

deconfinement phase: $V\left(R\right) \underset{R\to\infty}{=} 2\mu$

perimeter law

$$\langle 0|W\left(\mathcal{C}\right)|0\rangle \underset{R,T\to\infty}{\sim} \exp\left[-2\mu\cdot\left(T+R\right)\right]$$

Wilson Loop Criterion

- Wilson loop describes string state of gauge field
  $\Rightarrow$ good operator for linearly rising potential
- impossible to detect string breaking with Wilson loop due to insufficient overlap with two-meson states
- string breaking is mixing phenomenon involving string and two-meson states
  $\Rightarrow$ Wilson loop operator has to be supplemented by two-meson operators

Basic Idea

K. Fredenhagen, M. Marcu, *Confinement Criterion for QCD with Dynamical Quarks*, Phys. Rev. Lett. 56, 223 - 224 (1986)

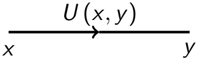
- in presence of dynamical matter fields:
  redefine "confinement" to mean string breaking, rather than a linearly increasing static potential
- investigate sequence of "dipole" states

$$\left|\Phi_{xy}\right\rangle = \sum_c \overline{\Psi}_c\left(\vec{x}\right) U\left(\mathcal{C}_{xy}\right) \Psi_c\left(\vec{y}\right) \left|0\right\rangle$$

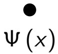
- energy of state $\left|\Phi_{xy}\right\rangle$ diverges as $R = |\vec{x} - \vec{y}| \to \infty$

Construction of new Criterion

- Wilson loop has large overlap with string-type states
- quark/Higgs field has dominant overlap with meson-type states
- $\Rightarrow$ combine them in correlation function to measure mixed state
- $U(x, y)$ denotes product of gauge links along the straight line connecting y with x



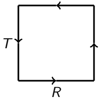
- $\Psi(x)$ denotes quark field at point x



Construction of new Criterion

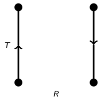
- short distance between the quarks/ pure gauge theory

$$\left\langle \mathrm{Tr}\left[U\left(x,y\right)U\left(y,y+T\hat{0}\right)U\left(y+T\hat{0},x+t\hat{0}\right)U\left(x+T\hat{0},x\right)\right]\right\rangle$$



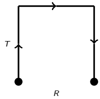
- large distance between the quarks

$$\left\langle \overline{\Psi}\left(x\right)U\left(x,x+T\hat{0}\right)\Psi\left(x+T\hat{0}\right)\overline{\Psi}\left(y+T\hat{0}\right)U\left(y+T\hat{0},y\right)\Psi\left(y\right)\right\rangle$$



- intermediate distance between the quarks

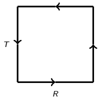
$$\left\langle \overline{\Psi}\left(x\right)U\left(x,x+T\hat{0}\right)U\left(x+T\hat{0},y+T\hat{0}\right)U\left(y+T\hat{0},y\right)\Psi\left(y\right)\right\rangle$$



Construction of new Criterion

- short distance between the quarks/ pure gauge threory

$$\left\langle \mathrm{Tr}\left[U(x,y)\,U\left(y,y+T\hat{0}\right)\,U\left(y+T\hat{0},x+t\hat{0}\right)\,U\left(x+T\hat{0},x\right)\right]\right\rangle$$



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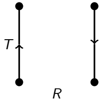

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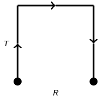

Construction of new Criterion

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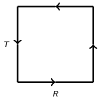

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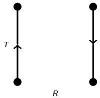

- intermediate distance between the quarks

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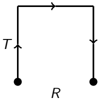


Construction of new Criterion

- result of translation of parallel transporter $U(\mathcal{C}_{xy})$ by n steps in Euclidean time

$$U^{(n)}(\mathcal{C}_{xy}) = T^n U(\mathcal{C}_{xy}) T^{-n}$$

with time evolution operator/ transfer matrix T

- energy of dipole states

$$|\Phi_{xy}^{(n)}\rangle = \sum_c \overline{\Psi}_c(\vec{x}) U^{(n)}(\mathcal{C}_{xy}) \Psi_c(\vec{y}) |0\rangle$$

stays bounded as $R = |\vec{x} - \vec{y}| \to \infty$ if $n \sim R$

- take $\vec{x} - \vec{y}$ along an axis and choose $n = \frac{1}{2}|\vec{x} - \vec{y}| = \frac{R}{2}$

New Confinement Criterion

if quark fragmentation occurs as $y \to \infty$: transition probability of $\Phi_{xy}^{(n)}$ in hadronic states (incl. $|0\rangle$) should go to 1
if all hadronic states are local excitations of vacuum

$$\lim_{R\to\infty} \frac{\left|\left\langle 0 \middle| \Phi_{xy}^{(n)} \right\rangle\right|^2}{\left|\Phi_{xy}^{(n)}\right|^2} = const. \neq 0$$

if limit is 0: sequence of dipole states becomes orthogonal to all hadronic states and approximates isolated quark

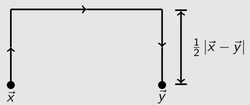
New Confinement Criterion

- to compute

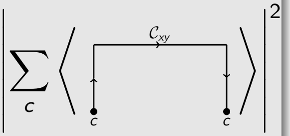
$$\frac{\left|\left\langle 0 \left| \Phi_{xy}^{(n)} \right\rangle\right|^2}{\left|\Phi_{xy}^{(n)}\right|^2} = \frac{\left|\sum_c \left\langle 0 \right| \overline{\Psi}_c \left(\vec{x}\right) U^{(n)} \left(\mathcal{C}_{xy}\right) \Psi_c \left(\vec{y}\right) \left|0\right\rangle\right|^2}{\left|\Phi_{xy}^{(n)}\right|^2}$$

express matrix elements in terms of expectation values of gauge invariant strings and loops

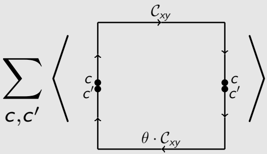
$\mathcal{C}_{xy}$



numerator



denominator

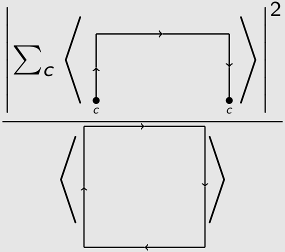


New Confinement Criterion

- regularise denominator by replacing it by expectation value of Wilson loop $W(\mathcal{C}) = \mathcal{C}_{xy} \cdot \theta\mathcal{C}_{xy}$

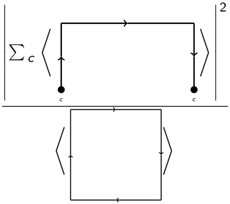
Fredenhagen-Marcu Confinement Criterion

$$\rho = \lim_{|x-y|\to\infty} \frac{\left|\sum_c \left\langle 0 \middle| \overline{\Psi}_c(\vec{x})\, U^{(n)}(\mathcal{C}_{xy})\, \Psi_c(\vec{y}) \middle| 0 \right\rangle\right|^2}{\left\langle \mathcal{C}_{xy} \cdot \theta\mathcal{C}_{xy} \right\rangle}$$

$\rho = \lim_{|x-y|\to\infty}$ 

New Confinement Criterion

$$\rho = \lim_{|x-y|\to\infty}$$



- ρ tests origin of perimeter behaviour of Wilson loop in presence of dynamical quarks

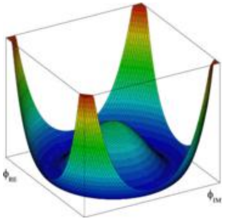
behaviour is dominated by charge screening due to matter fields
$\Rightarrow$ numerator and denominator decrease exp. at same rate
$\Rightarrow \rho \neq 0$ confinement

behaviour is independent of charge screening
$\Rightarrow$ decay of denominator is slower
$\Rightarrow \rho = 0$ deconfinement

Higgs Mechanism

- based on electroweak symmetry breaking, suggested to explain observed masses of W and Z bosons in Standard Model
- gauge bosons are massless in gauge theory
- Higgs mechanism ⇒ gauge bosons acquire mass by requiring Higgs field, which interacts with gauge fields

- Higgs field has non-trivial self-interaction: Mexican hat potential ⇒ symmetry breaking



- Higgs field in SM is SU(2)×U(1) doublet = four real components with phase from U(1)
- after symmetry breaking: three degrees of freedom mix with W and Z bosons, the one remaining degree of freedom becomes Higgs boson

SU(2) Higgs Model as First Approximation

- phase structure of Higgs model contains confinement phase and Higgs phase;
  confinement phase has properties which are similar to QCD $\rightarrow$ string breaking
- Higgs model describes self-interaction of Higgs field and coupling to SU(2) and U(1) gauge fields
- ratio of gauge coupling constants is related to Weinberg angle

$$\tan\theta_W = \frac{g'}{g}$$

  θ_W is small $\Rightarrow$ neglect U(1) gauge fields
- fermions are coupled to Higgs field through Yukawa couplings
  $\Rightarrow$ neglect fermions

Parametrisation I of SU(2) Doublet

- four degrees of freedom of SU(2) doublet
- choose parametrisation of Higgs field

$$\Phi\left(x\right) = \sigma\left(x\right) + i\tau_r\pi_r\left(x\right)$$

σ: Higgs boson field
$\vec{\pi}$: Goldstone boson field
$\vec{\tau}$: Pauli matrices

- lattice action: pure gauge part $S_g\left[U\right]$ plus gauged scalar part $S_\Phi\left[U,\Phi\right]$

$$S\left[U,\Phi\right] = S_g\left[U\right] + S_\Phi\left[U,\Phi\right]$$

Lattice Action ($a = 1$)

$$S_g[U] = \beta \sum_p \left(1 - \frac{1}{2}\mathrm{Tr}\, U_p\right)$$

$$\begin{aligned} S_\Phi[U,\Phi] \;=\; & \sum_x \Bigg\{ \frac{1}{2}\mathrm{Tr}\left(\Phi^\dagger(x)\,\Phi(x)\right) + \lambda\left[\frac{1}{2}\mathrm{Tr}\left(\Phi^\dagger(x)\,\Phi(x)\right) - 1\right]^2 - \\ & - \kappa \sum_{\mu=1}^{4} \mathrm{Tr}\left(\Phi^\dagger(x+\hat\mu)\, U(x+\hat\mu, x)\,\Phi(x)\right) \Bigg\} \end{aligned}$$

β: lattice coupling

λ: scalar quartic coupling

κ: hopping parameter

$$\Phi^\dagger(x) = \tau_2 \Phi^{\mathrm{T}}(x)\,\tau_2$$

Parametrisation II of SU(2) Doublet

- split Higgs field

$$\Phi(x) = \rho(x) \cdot \alpha(x)$$

in its length $\rho(x) \in \mathbb{R}$

$$\rho^2(x) = \frac{1}{2}\mathrm{Tr}\left(\Phi^\dagger(x)\Phi(x)\right) \geq 0$$

and $\alpha(x) \in \mathrm{SU}(2)$ which contains all information about angular variables

$$\alpha(x) = \frac{1}{\rho(x)}\Phi(x)$$

Parameters of Higgs Model

- parameters: lattice coupling β, hopping parameter κ and scalar quartic coupling λ
- control physics of Higgs model

bare gauge coupling

$$g^2 = \frac{4}{\beta}$$

bare Higgs boson mass

$$m_0^2 = \frac{1 - 2\lambda}{\kappa} - 8$$

Continuum Action

- continuum action

$$S_C\left[A_\mu,\phi\right] = \int \mathrm{d}^4x \left\{ \frac{1}{4} F_{\mu\nu}F_{\mu\nu} + \left(D_\mu\phi\right)^\dagger\left(D_\mu\phi\right) + m_C^2\left(\phi^\dagger\phi\right) + \lambda_C\left(\phi^\dagger\phi\right)^2 \right\}$$

$$\phi = \frac{1}{2}\left(\sigma + i\vec{\pi}\vec{\tau}\right)$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$D_\mu\phi = \left(\partial_\mu - i\frac{g}{2}\vec{\tau}\vec{A}_\mu\right)\phi$$

σ: Higgs boson field
$\vec{\pi}$: Goldstone boson field
$\vec{A}_\mu$: vector boson field

- relation to lattice values: $\phi\left(x\right) = \frac{\sqrt{\kappa}}{a}\Phi_x$, $\lambda_C = \frac{\lambda}{\kappa^2}$ and $m_C^2 = \frac{m_0^2}{a^2}$

Continuum Action

- Higgs boson field is shifted by its vacuum expectation value v

$$\sigma(x) = v + \sigma'(x)$$

- full Lagrangian is obtained by fixing the gauge

$$\mathcal{L}_{\mathrm{gauge}} = \frac{1}{2\xi}\left(G^a\right)^2$$

and adjusting ghost terms

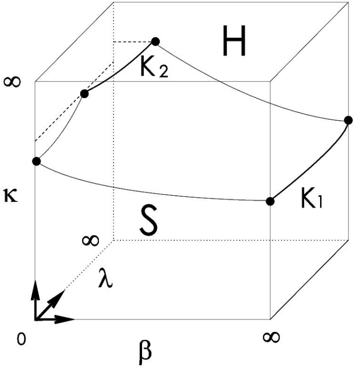
$$\mathcal{L}_{\mathrm{ghost}} = -c^{*a}\frac{\delta G^a}{\delta \Lambda^b}c^b$$

$$G^a = \partial_\mu A^a_\mu + \xi \frac{g}{2} v \pi^a$$

ξ: gauge parameter
c^a: ghost field

$\Lambda^a(x)$: transformation parameter

Phase Structure



phase transition between

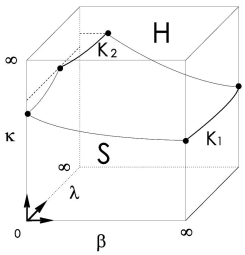
- confinement phase (small κ) and
- Higgs phase (larger κ)

phase transition surface is suggested to be of 1^{st} order, except at boundaries

- at $\beta \to \infty$ (K_1) and
- at large enough λ and small β (K_2)

Phase Structure

Confinement Phase

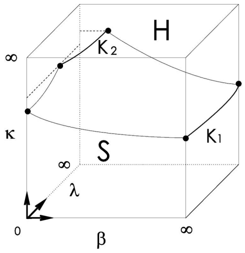


- at $\beta \to \infty$ ($g^2 = 0$): gauge field decouples from scalar field $\Rightarrow$ ϕ^4-model
- boundary K_1 is 2^{nd} order phase transition line separating
  - symmetric phase (small κ) from
  - phase with spontaneously broken symmetry (larger κ)

- at $g \neq 0$: symmetric phase of ϕ^4-model is continued by confinement phase (similar to QCD)
- at $\kappa = 0$: scalar field is decoupled due to infinite mass $\Rightarrow$ pure SU(2) gauge theory
- increasing κ: scalars become lighter, glueball states of pure gauge theory mix with bound states of scalar particles

Phase Structure

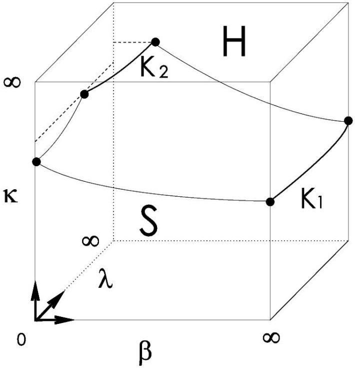
Higgs Phase



- at $\beta \to \infty$ ($g^2 = 0$): gauge field decouples from scalar field $\Rightarrow$ ϕ^4-model
- boundary K_1 is 2^{nd} order phase transition line separating
  - symmetric phase (small κ) from
  - phase with spontaneously broken symmetry (larger κ)

- at $g \neq 0$: spontaneously broken phase of ϕ^4-model is continued by Higgs phase
- 3 massless Goldstone bosons of ϕ^4-model become massive by mixing with degrees of freedom of gauge vector bosons $\Rightarrow$ massive isovector spin-1 W-Boson + isovector spin-0 Higgs boson

Phase Structure



- characteristic change in mass ratio

$$R_{HW} = \frac{m_H}{m_W}$$

  across phase transition surface;
  for large λ:
  - R_{HW} small in confinement phase
  - R_{HW} large in Higgs phase

- for small β (strong gauge coupling) and larger κ: analytic connection between two regions beyond K_2
- two different region within a single phase, but quantitative differences

Outlook

1

“advanced“ confinement criterion proposed by Fredenhagen and Marcu

+

2

SU(2) Higgs model containing Higgs phase and confinement phase

(similar to QCD
$\Rightarrow$ string breaking)

=

1 + **2**

use SU(2) Higgs model to test confinement criterion on the lattice

Outlook

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Thank You for Your Attention!