

The Yang–Mills vacuum wave functional thirty-five years later

Štefan Olejník

Institute of Physics, Slovak Academy of Sciences, SK–845 11 Bratislava, Slovakia

E-mail: stefan.olejnik@savba.sk

Abstract. Beside anniversaries of the important discoveries celebrated at the *DISCRETE 2014* Symposium, there is another worth to mention: The first paper attempting direct calculation of the Yang–Mills vacuum wave functional was published by Greensite in 1979. I review some recent results of the determination of the vacuum wave functional in Monte Carlo simulations of SU(2) lattice gauge theory.

1. Introduction

The *DISCRETE 2014* Symposium commemorated a number of important events that had shaped modern physics. Maxwell presented his theory of electromagnetism to the Royal Society 150 years ago; non-abelian gauge theories were proposed by Yang and Mills 60 years ago; the Brout–Englert–Higgs mechanism, the quark model, and Bell inequalities are 50 years old; CP violation was experimentally discovered 50 years ago as well. In my talk I would like to draw attention to another anniversary: In February 1979, the first paper trying to calculate the ground-state wave functional of Yang–Mills (YM) theory was submitted to *Nuclear Physics* by Jeff Greensite [1]. Thirty-five years have passed since then, but the problem still defies satisfactory solution.

Formulation of the problem The vacuum wave functional (VWF) Ψ_0 of quantum chromodynamics in the Schrödinger representation depends on quark fields of six flavours with three colours, each represented by a Dirac four-component bispinor, and on eight four-vector gluon fields – this is altogether 104 fields at each point in space (not taking constraints from gauge invariance into account). This is a formidable object from both mathematical and practical point of view. To simplify the problem, one can reduce the number of colours from three to two, omit quarks, discretize space (*i.e.* formulate the theory on a lattice), and eventually go to lower-dimensional spacetime. One can hope [2] that the resulting model captures at least gross features of the full theory, in particular information on the mechanism of colour confinement.

Omitting quarks, the SU(2) YM Schrödinger equation in $(d + 1)$ dimensions in temporal gauge looks very simple:

$$\hat{H}\Psi[A] = \int d^d x \left[-\frac{1}{2} \frac{\delta^2}{\delta A_k^a(x)^2} + \frac{1}{4} F_{ij}^a(x)^2 \right] \Psi[A] = E\Psi[A]. \quad (1)$$



Physical states are simultaneously required to satisfy Gauß' law:

$$\left(\delta^{ac}\partial_k + g\epsilon^{abc}A_k^b\right)\frac{\delta}{\delta A_k^c}\Psi[A] = 0. \quad (2)$$

A few well-known facts If we set the gauge coupling g to 0, the Schrödinger equation (1) reduces to that of (three copies of) electrodynamics and its ground-state solution is known to be [3]:

$$\Psi_0[A] \stackrel{g=0}{=} \mathcal{N} \exp \left[-\frac{1}{4} \int d^d x d^d y F_{ij}^a(x) \left(\frac{\delta^{ab}}{\sqrt{-\Delta}} \right)_{xy} F_{ij}^b(y) \right]. \quad (3)$$

Due to (2), the ground state must be gauge-invariant. The simplest form consistent with (3) is

$$\Psi_0[A] = \mathcal{N} \exp \left[-\frac{1}{4} \int d^d x d^d y F_{ij}^a(x) \mathfrak{K}^{ab}(x, y) F_{ij}^b(y) \right], \quad (4)$$

where \mathfrak{K} is some adjoint-representation kernel that reduces, in the limit $g \rightarrow 0$, to $(-\Delta)^{-1/2}$.

At long-distance scales, one expects the VWF to be the state of *magnetic disorder* [1, 4, 5]:

$$\Psi_0[A] \approx \mathcal{N} \exp \left[-\frac{1}{4} \mu \int d^d x F_{ij}^a(x) F_{ij}^a(x) \right]. \quad (5)$$

This is also called the *dimensional-reduction* (DR) form. With such a VWF, the computation of a spacelike loop in $(d + 1)$ dimensions reduces to the calculation of a Wilson loop in YM theory in d (euclidean) dimensions. If the vacuum were of the DR form for YM theories in both $(3 + 1)$ and $(2 + 1)$ dimensions, then these would be confining, since the theory in 2 euclidean dimensions exhibits the area law. However, this cannot be the whole truth, for various reasons. Via DR, one gets *e.g.* the area law for colour charges from *all* representations r of the gauge group, and string tensions σ_r of the corresponding potentials are proportional to eigenvalues of the r -th quadratic Casimir operator. Approximate *Casimir scaling* is observed at short and intermediate distances, but at large distances, due to *colour screening*, string tensions depend on the N -ality of the representation.

Approaches to the problem A number of different strategies were adopted in attempts to determine the YM vacuum wave functional (see [6] for a more extensive set of references):

- (i) Strong-coupling expansion of the VWF [7, 8].
- (ii) Weak-coupling expansion of the VWF [9–12].
- (iii) Formulation of the theory in cleverly selected variables and expansion of the VWF in terms of these new variables [13–19].
- (iv) Variational Ansatz for the VWF in a certain gauge; determination of its parameters by minimizing the expectation value of the YM hamiltonian (see *e.g.* [20, 21]).
- (v) Guess of an approximate form of the VWF and tests of its consequences (see [22], [23–25]).

2. Flatland: A romance of two dimensions¹

I will start with the problem in the simplest setting: with SU(2) Yang–Mills theory in “*Flatland*”, *i.e.* in three spacetime dimensions. That model deserves attention not only because it is more tractable than the realistic case, but also due to its relevance to the high-temperature phase of chromodynamics in four dimensions.

¹ This section's heading paraphrases the title of a novella [26] by English schoolmaster and theologian Edwin Abbott Abbott, writing pseudonymously as *A Square*, which describes a two-dimensional world inhabited by geometric figures. The book was published in 1884 by a publishing house at that time located in Essex Street, less than half a kilometre from King's College.

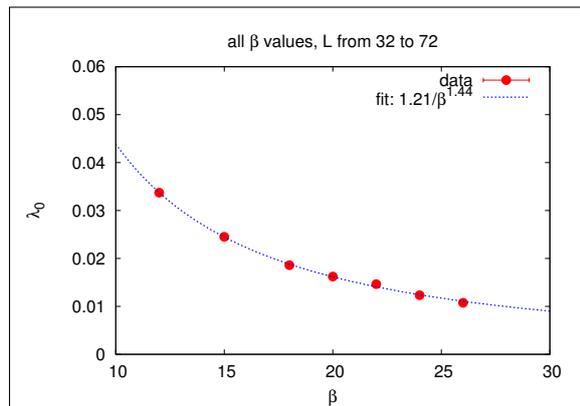


Figure 1. λ_0 vs. β from simulations of 3D euclidean SU(2) lattice gauge theory at various couplings β and lattice volumes L^3 . The best fit to data is $\lambda_0 \propto \beta^{-1.44}$, which differs from the expected β^{-2} dependence and indicates that λ_0 diverges in the continuum limit.

Hints from strong-coupling expansion In the lattice formulation, a systematic strong-coupling expansion of the YM VWF is of the form $\Psi_0 = \mathcal{N} \exp(-R[U])$, where the function R in the exponent is an expansion in terms of closed loops, products of link matrices U along closed contours on the lattice [7]. Guo, Chen and Li [8] computed the first few terms of this expansion and showed that for slowly varying fields they organize themselves into the following series²:

$$R[U] \propto \mu_0 \text{Tr} [\mathbf{B}^2] - \mu_1 \text{Tr} [\mathbf{B}(-\mathcal{D}^2)\mathbf{B}] + \dots \quad (6)$$

Here μ_0 and μ_1 are functions of the lattice spacing a and the coupling constant g , $\mathbf{B} = \mathbf{F}_{12}$ is the colour magnetic field strength, and $\mathcal{D}^2 = \mathcal{D}_k \cdot \mathcal{D}_k$ is the adjoint covariant laplacian, where $\mathcal{D}_k[\mathbf{A}]$ denotes the covariant derivative in the adjoint representation. The first term of (6) corresponds to the dimensional-reduction vacuum wave functional (5). One can imagine that an expansion of the form (6) might come from the wave functional

$$\Psi_0[A] = \mathcal{N} \exp \left\{ -\frac{1}{2} \int d^2x d^2y B^a(x) \mathfrak{K}_{xy}^{ab} [-\mathcal{D}^2] B^b(y) \right\}, \quad (7)$$

with the kernel \mathfrak{K} , introduced in (4), being a functional of the adjoint covariant laplacian.

The proposal of Samuel Almost 20 years ago, Samuel [22] put forward a simple vacuum wave functional of the form (7), interpolating between weak-coupling (3) and DR (5) limits:

$$\Psi_0[A] = \mathcal{N} \exp \left[-\frac{1}{2} \int d^2x d^2y B^a(x) \left(\frac{1}{\sqrt{-\mathcal{D}^2 + m_0^2}} \right)_{xy}^{ab} B^b(y) \right]. \quad (8)$$

He estimated with its use the 0^{++} glueball mass to be about 1.5 GeV. However, this particular form may be flawed if taken at face value: there are hints that the adjoint covariant laplacian needs to be regularized. We have computed its eigenvalues in numerical simulations of the three-dimensional euclidean SU(2) YM theory on a lattice. $(-\mathcal{D}^2)$ has a positive definite spectrum, finite with a lattice regulator. If its lowest eigenvalue λ_0 were finite in the continuum limit, it should scale, as a function of $\beta = 4/g^2$, as β^{-2} for large β . Our data (see figure 1) indicate that $\lim_{\beta \rightarrow \infty} \beta^2 \lambda_0(\beta) \rightarrow \infty$, *i.e.* λ_0 diverges for typical configurations in the continuum limit.

² The trace in this symbolic expression includes sums over colour indices and lattice sites.

The GO proposal We proposed [23] another simple form with a seemingly small, but crucial difference from that of Samuel:

$$\Psi_0[A] = \mathcal{N} \exp \left[-\frac{1}{2} \int d^2x d^2y B^a(x) \left(\frac{1}{\sqrt{(-\mathcal{D}^2 - \lambda_0) + m^2}} \right)_{xy}^{ab} B^b(y) \right]. \quad (9)$$

As a remedy to the problem mentioned above, it is suggested here to subtract from the covariant laplacian its lowest eigenvalue. The proposed VWF contains a single free parameter, a mass m , that should vanish in the free-field limit (for $g \rightarrow 0$). The expression is assumed to be regularized on a lattice, and we use the simplest discretized form of the adjoint covariant laplacian:

$$(-\mathcal{D}^2)_{xy}^{ab} = 4 \delta^{ab} \delta_{xy} - \sum_{k=1}^2 \left[\mathcal{U}_k^{ab}(x) \delta_{y, x+\hat{k}} + \mathcal{U}_k^{\dagger ba}(x - \hat{k}) \delta_{y, x-\hat{k}} \right], \quad (10)$$

where

$$\mathcal{U}_k^{ab}(x) = \frac{1}{2} \text{Tr} \left[\sigma^a U_k(x) \sigma^b U_k^\dagger(x) \right] \quad (11)$$

and $U_k(x)$ are the link matrices in the fundamental representation.

We have provided a number of (semi)analytic arguments in favour of the proposed VWF (9):

- (i) Ψ_0 reproduces the VWF of electrodynamics (3) in the free-field limit (for $g \rightarrow 0$).
- (ii) The proposed form is a good approximation to the true vacuum also for strong fields constant in space and varying only in time [23].
- (iii) If we split the colour magnetic field strength $\mathbf{B}(x)$ into “fast” and “slow” components, the part of the VWF that depends on \mathbf{B}_{slow} reduces to the magnetic-disorder (DR) form (5). The fundamental string tension is then easily computed as $\sigma_F = 3mg^2/16 = 3m/4\beta$. Non-zero value of the parameter m then implies non-zero σ_F , *i.e.* confinement of fundamental-representation colour charges.
- (iv) One can take the mass m in the wave functional as a free variational parameter and compute (approximately) the expectation value of the YM hamiltonian (see section VI of [23] for details). In the abelian free-field case, the optimal value of m equals λ_0 and λ_0 goes to 0 in the continuum limit, so the theory is non-confining. In the non-abelian case one can evaluate the energy density $\langle \hat{\mathcal{H}} \rangle / L^2$ numerically in Monte Carlo simulations, and finds that a non-zero (finite) value of m is energetically preferred.

Some numerical evidence All above arguments are encouraging, but quantitative tests are needed to gain more confidence in the proposed form of the VWF. Such tests are provided by numerical lattice simulations.

We have compared a set of physical quantities computed in two ensembles of lattice gauge-field configurations:

- I. *Monte Carlo lattices*: Ensemble of two-dimensional slices of configurations generated by Monte Carlo simulations of three-dimensional euclidean SU(2) lattice gauge theory with standard Wilson action at a coupling $\beta = 4/g^2$; from each configuration, only one (random) slice at fixed euclidean time was taken. These configurations are distributed with the weight proportional to the square of the true VWF of the theory, $|\Psi_{\text{true}}[U]|^2$.
- II. *“Recursion” lattices*: Ensemble of independent two-dimensional lattice configurations generated with the probability distribution given by the (square of the) VWF (9), with m and g^2 fixed to get the correct value of the fundamental string tension. These configurations can be generated efficiently by the recursion method proposed (and described in detail) in [23].

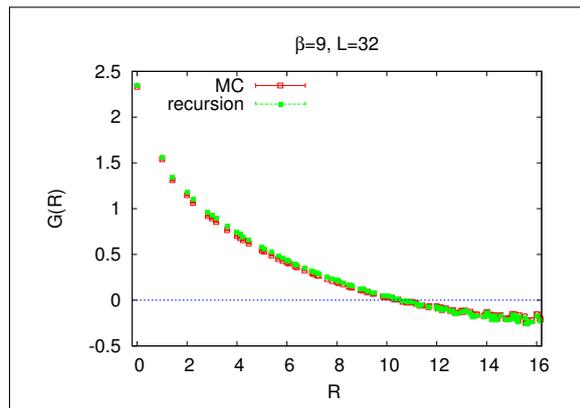


Figure 2. The Coulomb-gauge ghost propagator at $\beta = 9$ on 32^2 lattice.

We computed in both ensembles the mass gap [23], the Coulomb-gauge ghost propagator, and the colour Coulomb potential [24]. The latter two quantities are of particular interest because of their role in the so-called Gribov–Zwanziger mechanism of confinement [27, 28]. An example result is shown in figure 2. The agreement between quantities measured in MC and recursion ensembles was found very reasonable in all three cases.

One can also measure (*i.e.* compute in numerical simulations) amplitudes of various sets of test configurations in the true YM vacuum, and compare them with predictions based on the proposed VWF (9). The method for computing relative weights of configurations was proposed by Greensite and Iwasaki long ago [29] and will be described in section 3. The technique was applied in $(2 + 1)$ dimensions to sets of abelian plane wave configurations of varying amplitude and wavelength, and sets of non-abelian constant configurations [6]. The obtained data agree with expectations based on (9), but similar agreement was obtained also for some other forms of wave functionals which simplify to a DR form at large scales (see [6]).

Summarizing this section, we found analytic and numerical evidence that in $D = 2 + 1$ dimensions our Ansatz for the VWF seems a fairly good approximation to the true ground state of the theory. However, we do not live in *Flatland*, our world is *Spaceland*, so I will switch for the rest of this contribution to pure Yang–Mills theory in four spacetime dimensions.

3. Version in 3D or Spaceland³

The extension of the proposed vacuum wave functional (9) to $(3 + 1)$ dimensions is straightforward: one replaces the product $B^a(x) B^b(y)$ by $\frac{1}{2} F_{ij}^a(x) F_{ij}^b(y)$, and two-dimensional integrals by three-dimensional ones:

$$\Psi_0[A] = \mathcal{N} \exp \left[-\frac{1}{4} \int d^3x d^3y F_{ij}^a(x) \left(\frac{1}{\sqrt{(-\mathcal{D}^2 - \lambda_0) + m^2}} \right)_{xy}^{ab} F_{ij}^b(y) \right]. \quad (12)$$

Of course, the adjoint covariant laplacian now involves k -summation over three space directions:

$$(-\mathcal{D}^2)_{xy}^{ab} = 6 \delta^{ab} \delta_{xy} - \sum_{k=1}^3 \left[\mathcal{U}_k^{ab}(x) \delta_{y, x+\hat{k}} + \mathcal{U}_k^{\dagger ba}(x - \hat{k}) \delta_{y, x-\hat{k}} \right]. \quad (13)$$

Positive news, but... The wave functional (12) is also in $(3 + 1)$ dimensions exact in the free-field limit. It also approximately solves the YM Schrödinger equation in the zero-mode,

³ Not surprisingly, one can find also a book with *Spaceland* in the title [30]. It is a science-fiction novel written by American mathematician and computer scientist Rudy Rucker as a tribute to Edwin Abbott’s *Flatland*.

strong-field limit ($|gA|^2 \gg m^2, \lambda_0$). If we put such a physical system into a finite volume V , its lagrangian and hamiltonian are:

$$\mathcal{L} = \frac{1}{2}V \left(\sum_{k=1}^3 \partial_t \vec{A}_k \cdot \partial_t \vec{A}_k - g^2 \mathfrak{E}^2 \right), \quad \hat{\mathcal{H}} = -\frac{1}{2V} \sum_{k=1}^3 \frac{\partial^2}{\partial \vec{A}_k \cdot \partial \vec{A}_k} + \frac{1}{2}g^2 V \mathfrak{E}^2, \quad (14)$$

where

$$\mathfrak{E} = \sqrt{(\vec{A}_1 \times \vec{A}_2)^2 + (\vec{A}_2 \times \vec{A}_3)^2 + (\vec{A}_3 \times \vec{A}_1)^2}. \quad (15)$$

Other useful quantities are:

$$\mathfrak{L} = \sqrt{\vec{A}_1 \cdot \vec{A}_1 + \vec{A}_2 \cdot \vec{A}_2 + \vec{A}_3 \cdot \vec{A}_3}, \quad (16)$$

$$\mathfrak{V} = \left| \vec{A}_1 \cdot (\vec{A}_2 \times \vec{A}_3) \right|. \quad (17)$$

It is natural to look for the ground-state solution of the Schrödinger equation $\hat{\mathcal{H}}\Psi = E\Psi$ in the form of $1/V$ expansion:

$$\Psi_0 = \exp[-VR_0 - R_1 - V^{-1}R_2 - \dots]. \quad (18)$$

The leading term R_0 has to satisfy

$$\mathcal{T}_0 \equiv V \left[-\sum_{k=1}^3 \frac{\partial R_0}{\partial \vec{A}_k} \cdot \frac{\partial R_0}{\partial \vec{A}_k} + g^2 \mathfrak{E}^2 \right] = 0, \quad (19)$$

and is given by

$$R_0 = \frac{1}{2}g \frac{\mathfrak{E}^2}{\mathfrak{L}}, \quad (20)$$

since

$$\mathcal{T}_0 = 0 + g^2 V \left(\frac{7\mathfrak{E}^4}{4\mathfrak{L}^4} - \frac{3\mathfrak{V}^2}{\mathfrak{L}^2} \right) = 0 + \mathcal{O}\left(\frac{1}{V}\right) \quad (21)$$

for strong fields from the “abelian valley” where the components $\vec{A}_1, \vec{A}_2, \vec{A}_3$ are nearly aligned, or antialigned, in colour space.

In this same limit, the proposed VWF (12) reduces to $\Psi_0 = \mathcal{N} \exp(-Q)$ with

$$Q \approx \frac{1}{4}gV (\vec{A}_i \times \vec{A}_j)^a \left(\frac{\delta^{ab}}{\mathfrak{L}} - \frac{\delta^{a3}\delta^{b3}}{\mathfrak{L}} + \frac{\delta^{a3}\delta^{b3}}{m} \right) (\vec{A}_i \times \vec{A}_j)^b. \quad (22)$$

The first term dominates and gives $VR_0 \sim \mathcal{O}(1)$ as above, the other two are of order $\mathcal{O}(1/V)$ (see Appendix A of [23]).

However, the transition to three space dimensions causes complications associated with the Bianchi constraint that colour magnetic fields F_{ij}^a have to satisfy. Because of that constraint, direct numerical generation of gauge-field configurations with the probability distribution given by the square of the vacuum wave functional (12) is much more challenging. I have not yet been able to find a way of generating such configurations, similar to the recursion method used in two space dimensions (see section 2). A different approach to testing our proposal is required.

The relative-weight method The method, invented by Greensite and Iwasaki [29], is based on a formula that expresses the squared VWF of the pure YM theory through the path integral⁴:

$$\Psi_0^2[U'] = \frac{1}{Z} \int [DU] \prod_{\mathbf{x}, i} \delta[U_i(\mathbf{x}, 0) - U'(\mathbf{x})] \exp(-S[U]), \quad (23)$$

It enables one to compute ratios $\Psi_0^2[U^{(n)}]/\Psi_0^2[U^{(m)}]$ for configurations belonging to a finite set $\mathcal{U} = \{U_i^{(j)}(\mathbf{x}), j = 1, 2, \dots, M\}$ using a simple procedure: One performs Monte Carlo simulations with the usual update algorithm (*e.g.* heat-bath) for all spacelike links at $t \neq 0$ and for timelike links. Once in a while one updates the spacelike links at $t = 0$ all at once selecting one configuration from the set \mathcal{U} at random, and accepts/rejects it via the Metropolis prescription. Then, for a large number of updates N_{tot} ,

$$\frac{\Psi_0^2[U^{(n)}]}{\Psi_0^2[U^{(m)}]} = \lim_{N_{\text{tot}} \rightarrow \infty} \frac{N_n}{N_m}, \quad (24)$$

where N_m (N_n) denotes the number of times the m -th (n -th) configuration is accepted. To ensure a non-negligible acceptance rate of Metropolis updates for all configurations in the set \mathcal{U} , they must lie close in configuration space. This limits somewhat the applicability of the method.

If the VWF is assumed to be of the form $\Psi_0[U] = \mathcal{N} \exp(-R[U])$, then the measured values of $[-\log(N_n/N_{\text{tot}})]$ should fall on a straight line with unit slope as function of $R_n \equiv R[U^{(n)}]$. An example is shown in figure 3 for a set of non-abelian constant configurations (to be specified below).

Direct measurement of the vacuum wave functional We used the relative-weight method to calculate the squared WVF for the following two classes of lattice gauge-field configurations:

I. *Non-abelian constant (NAC) configurations:*

$$\mathcal{U}_{\text{NAC}} = \left\{ U_k^{(n)}(x) = \sqrt{1 - (u^{(n)})^2} \mathbf{1} + iu^{(n)} \boldsymbol{\sigma}_k \right\}, \quad (25)$$

where

$$u^{(n)} = \left(\frac{\kappa}{6L^3} n \right)^{1/4}, \quad n \in \{1, 2, \dots, 10\}. \quad (26)$$

The constant κ , regulating amplitudes of NAC configurations, is selected so that the ratio of the smallest to the largest weight within the set is not too small, at most $\mathcal{O}(10^{-4} \div 10^{-3})$. The expected dependence of relative weights on κ and n is linear:

$$-\log \left(\frac{N_n}{N_{\text{tot}}} \right) = R_n + \text{const.} = \kappa n \times \mu + \text{const.} \quad (27)$$

The constant μ coincides with the parameter that appears in the dimensional-reduction Ansatz for the VWF (5).

Predictions for NAC configurations resulting from the DR and our proposed vacuum wave functional are identical (up to parameter-naming conventions). Moreover, the dependence of μ on β was already computed in the pioneering work of Greensite and Iwasaki [29] more than 25 years ago, albeit at rather small-size lattices, 6^4 and 8^4 . Our new results from

⁴ One could insert into the path integral a factor imposing fixing to lattice temporal gauge, which sets all timelike links to $\mathbf{1}$ except on one time slice at $t \neq 0$. However, this gauge fixing is in fact not necessary.

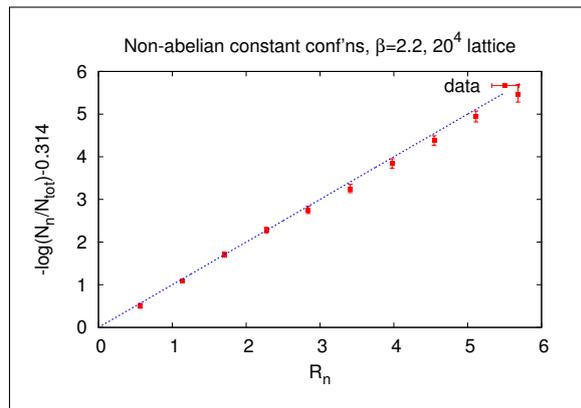


Figure 3. $[-\log(N_n/N_{\text{tot}})]$ vs. $R_n = \mu\kappa n$ for NAC configurations with $\kappa = 0.14$; μ at $\beta = 2.2$ on 20^4 lattice was $4.06(4)$.

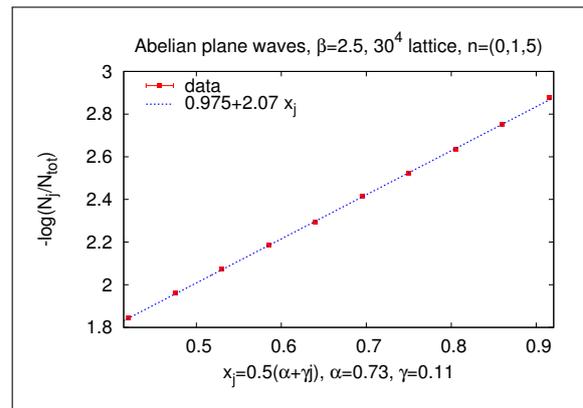


Figure 4. An example plot of $[-\log(N_{\mathbf{n}}^{(j)}/N_{\text{tot}})]$ vs. $\frac{1}{2}(\alpha_{\mathbf{n}} + \gamma_{\mathbf{n}}j)$ for APW configurations.

simulations on 20^4 and 24^4 lattices confirm their findings. In the weak-coupling region $\mu(\beta)$ behaves as a physical quantity with the dimension of inverse mass:

$$\mu(\beta)f(\beta) = \mu_{\text{phys}} \approx 0.0269(3), \quad (28)$$

where

$$f(\beta) = \left(\frac{6\pi^2\beta}{11}\right)^{\frac{51}{121}} \exp\left(-\frac{3\pi^2\beta}{11}\right). \quad (29)$$

II. Abelian plane-wave (APW) configurations:

$$\mathcal{U}_{\text{APW}} = \left\{ U_1^{(j)}(x) = \sqrt{1 - (w_{\mathbf{n}}^{(j)}(x))^2} \mathbf{1} + iw_{\mathbf{n}}^{(j)}(x)\sigma_3, \quad U_2^{(j)}(x) = U_3^{(j)}(x) = \mathbf{1} \right\}, \quad (30)$$

where

$$w_{\mathbf{n}}^{(j)} = \sqrt{\frac{\alpha_{\mathbf{n}} + \gamma_{\mathbf{n}}j}{L^3}} \cos\left(\frac{2\pi}{L} \mathbf{n} \cdot \mathbf{x}\right), \quad \mathbf{n} = (n_1, n_2, n_3), \quad j \in \{1, 2, \dots, 10\}. \quad (31)$$

Amplitudes in a particular set of plane waves with wave number \mathbf{n} are parametrized by a pair $(\alpha_{\mathbf{n}}, \gamma_{\mathbf{n}})$ and depend on integer j . For all sets, pairs of parameters were again carefully chosen so that the actions of configurations with different j in the set were not much different.

For APW configurations one expects:

$$-\log\left(\frac{N_{\mathbf{n}}^{(j)}}{N_{\text{tot}}}\right) = R_{\mathbf{n}}^{(j)} + \text{const.} = \frac{1}{2}(\alpha_{\mathbf{n}} + \gamma_{\mathbf{n}}j) \times \omega(\mathbf{n}) + \text{const.} \quad (32)$$

For a particular wave number \mathbf{n} , one can plot $[-\log(N_{\mathbf{n}}^{(j)}/N_{\text{tot}})]$ vs. $\frac{1}{2}(\alpha_{\mathbf{n}} + \gamma_{\mathbf{n}}j)$, and determine the slope $\omega(\mathbf{n})$ from a fit of the form (32). The expected linear dependence was seen in all our data sets at all couplings, wave numbers, and parameter choices; an example is displayed in figure 4.

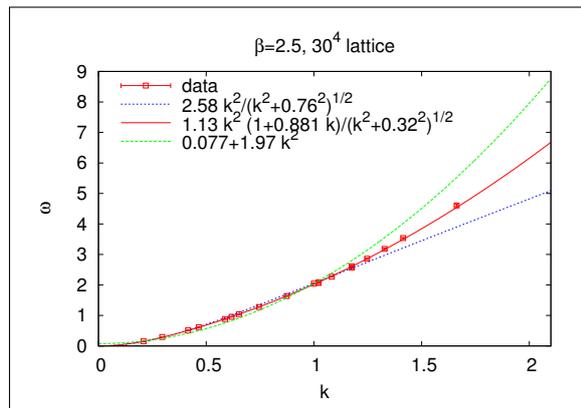


Figure 5. $\omega(\mathbf{n})$ vs. $k(\mathbf{n})$ with fits of the forms (36) and (37) for APW configurations.

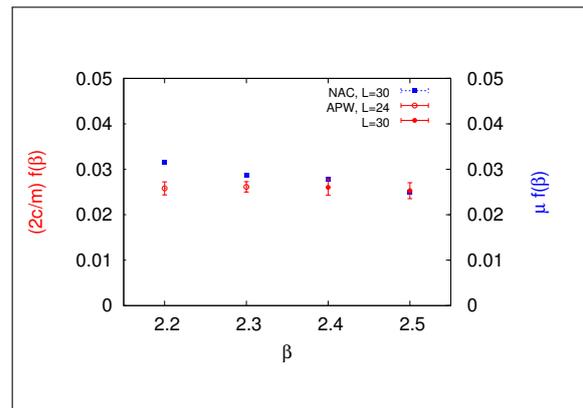


Figure 6. The combination $(2c/m)f(\beta)$ of the best fit (37) to APW data. Also displayed are values of $\mu f(\beta)$ extracted from NAC data.

Our main goal is to compare computed relative weights of test configurations with predictions of the DR (5) and GO (12) wave functionals. As already mentioned, NAC configurations are not suitable for that purpose, they only served us as test bed of our computer code. However, for APW the DR prediction for the dependence of the extracted function $\omega(\mathbf{n})$ on the wave number \mathbf{n} :

$$\omega(\mathbf{n}) \sim \mu k^2(\mathbf{n}) \quad \dots \quad \text{dim. reduction} \quad (33)$$

differs from our form:

$$\omega(\mathbf{n}) \sim \frac{k^2(\mathbf{n})}{\sqrt{k^2(\mathbf{n}) + m^2}} \quad \dots \quad \text{GO proposal}, \quad (34)$$

where the wave momentum k above fulfils

$$k^2(\mathbf{n}) = 2 \sum_i \left(1 - \cos \frac{2\pi n_i}{L} \right). \quad (35)$$

We therefore fitted our data for $\omega(\mathbf{n})$ at each coupling β by the following two-parameter forms:

$$\omega(\mathbf{n}) = \begin{cases} a + bk^2(\mathbf{n}) & \dots \quad \text{dim. reduction,} \\ \frac{ck^2(\mathbf{n})}{\sqrt{k^2(\mathbf{n}) + m^2}} & \dots \quad \text{GO proposal.} \end{cases} \quad (36)$$

The result at $\beta = 2.5$ (30^4 lattice) is displayed in figure 5 (green dashed line for DR, blue dotted one for our proposal). Both forms fit the data quite well at low plane-wave momenta, none of them is satisfactory for larger momenta. The situation at other gauge couplings is similar.

Considerable improvement at all couplings is achieved by adding another parameter d to our form:

$$\omega(\mathbf{n}) = \frac{ck^2(\mathbf{n})}{\sqrt{k^2(\mathbf{n}) + m^2}} [1 + dk(\mathbf{n})], \quad (37)$$

see the red solid line in figure 5. This would correspond, in the continuum limit, to adding a term

$$d \left(\frac{-\mathcal{D}^2 - \lambda_0}{(-\mathcal{D}^2 - \lambda_0) + m^2} \right)^{1/2} \quad (38)$$

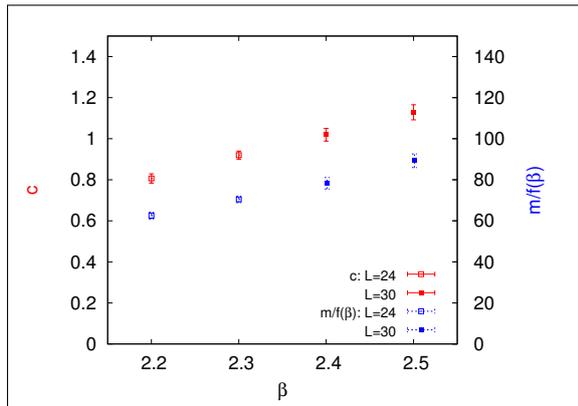


Figure 7. Parameter c (red) and rescaled mass $m/f(\beta)$ (blue) of the best fit (37) vs. β .

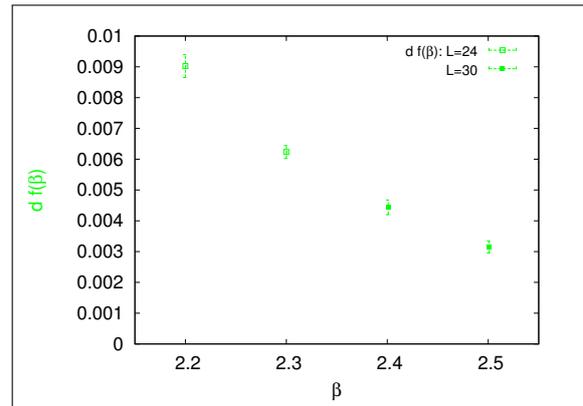


Figure 8. Rescaled parameter $df(\beta)$ (green points) of the best fit (37) vs. β .

to the adjoint kernel \mathfrak{K} that appears in the VWF (12).

For constant configurations with small amplitude the DR and GO forms coincide. For consistency between our data for NAC and APW configurations, the value of μ_{NAC} determined from sets of NAC configurations should agree with the appropriate combination ($2c_{\text{APW}}/m_{\text{APW}}$) of parameters obtained for abelian plane waves. Our results clearly pass this check quite successfully, both values converge to each other at large β , as exemplified in figure 6.

Finally, the parameters of the best fit (37), c , m and d , if they correspond to some physical quantities in the continuum limit, should scale correctly when multiplied by the appropriate power of the asymptotic-freedom function $f(\beta)$ in (29). While the scaling of the ratio ($2c/m$) multiplied by $f(\beta)$ has already been seen almost perfect in figure 6, it is not so convincing for individual parameters c and $m/f(\beta)$, though their growth in the range of $\beta = 2.2 \div 2.5$ is not large (see figure 7) and one may optimistically hope that it will level off at still higher couplings. On the other hand, the parameter d multiplied by $f(\beta)$ falls down quite rapidly in the same region (figure 8). The data thus suggest that the physical value of d might vanish in the continuum limit. This signals a possibility that the form (12) of the VWF might be recovered in the continuum limit.

4. Open end of the romance; roads to take

Let me summarize what has been achieved until now, both positive (\blacktriangle) and negative (\blacktriangledown) points:

- \blacktriangle We have proposed an approximate form of the SU(2) YM vacuum wave functional that looks good in $D = 2 + 1$, somewhat worse in $(3 + 1)$ dimensions.
- \blacktriangledown In $(3 + 1)$ dimensions, a method of generating configurations distributed according to the proposed vacuum wave functional is not (yet?) available.
- \blacktriangle The method of Greensite and Iwasaki allows one to compute numerically (on a lattice) relative probabilities of various gauge-field configurations in the YM vacuum.
- \blacktriangledown This relative-weight method is only applicable to compute weights of configurations rather close in configuration space.

- ▲ For non-abelian constant configurations and for long-wavelength abelian plane waves the measured probabilities are consistent with the dimensional-reduction form, and the coefficients μ for these sets agree.

▲ Numerical data for test configurations are nicely described by a natural modification of our proposal, and the correction term seems to vanish in the continuum limit.
- ▼ Neither the dimensional-reduction form, nor our proposal for the vacuum wave functional describe data satisfactorily for larger plane-wave momenta.

▼ No configurations tested so far, neither non-abelian constant nor abelian plane waves, can be considered typical. They are not in any sense true representatives of fields inhabiting the YM vacuum.

The investigation reported in this talk could be extended in various ways:

– One should compute, by the relative-weight method, weights of more realistic, “typical” configurations. One can *e.g.* generate ensembles of configurations of the full YM theory, take link matrices from a random time slice, make their Fourier decomposition, switch on/off or modify individual momentum modes, and compare the obtained momentum dependence of relative weights of configurations with that following from our, or some other, Ansatz for the VWF.

– It is most desirable to find a way of generating field configurations distributed according to (the square of) the VWF. What was possible in $D = 2 + 1$ dimensions, is made much more complicated by the Bianchi constraint in $(3 + 1)$.

– If one achieved progress in the above points and gained more evidence for the proposed form of the vacuum wave functional in $(3 + 1)$ dimensions, a number of other questions would call for an answer, *e.g.*: What are the dominant field configurations in the YM vacuum? Where do colour screening and N -ality dependence arise from in the Schrödinger picture? ...

One can just hope – on the crooked road towards understanding the QCD vacuum wave functional – not to run into a “Dead End” sign.

Acknowledgments

I am most grateful to Jeff Greensite for collaboration on many topics, including those covered in the present talk. I would also like to thank organizers of *DISCRETE 2014*, in particular Joannis Papavassiliou, the convener of its session on strongly coupled gauge theories, for inviting me to this interesting conference in solemn edifices of King’s College London. My research is supported by the Slovak Research and Development Agency under Contract No. APVV–0050–11, and by the Slovak Grant Agency for Science, Project VEGA No. 2/0072/13.

References

- [1] Greensite J P 1979 *Nucl. Phys. B* **158** 469
- [2] Feynman R P 1981 *Nucl. Phys. B* **188** 479
- [3] Wheeler J A 1962 *Geometrodynamics* (New York – London: Academic Press)
- [4] Halpern M 1979 *Phys. Rev. D* **19** 517
- [5] Kawamura M, Maeda K and Sakamoto M 1997 *Prog. Theor. Phys.* **97** 939 (*Preprint hep-th/9607176*)
- [6] Greensite J, Matevosyan H, Olejník Š, Quandt M, Reinhardt H and Szczepaniak A P 2011 *Phys. Rev. D* **83** 114509 (*Preprint arXiv:1102.3941*)
- [7] Greensite J P 1980 *Nucl. Phys. B* **166** 113

- [8] Guo S H, Chen Q Z and Li L 1994 *Phys. Rev. D* **49** 507
- [9] Hatfield B F 1984 *Phys. Lett. B* **147** 435
- [10] Krug S and Pineda A 2013 *Phys. Rev. D* **88** 125001 (*Preprint arXiv:1301.6922*)
- [11] Krug S and Pineda A 2014 *Nucl. Phys. B* **878** 82 (*Preprint arXiv:1308.2663*)
- [12] Krug S 2014 *The Yang-Mills Vacuum Wave Functional in 2+1 Dimensions* Ph.D. thesis Univ. Autònoma de Barcelona (*Preprint arXiv:1404.7005*)
- [13] Karabali D, Kim C j and Nair V P 1998 *Phys. Lett. B* **434** 103 (*Preprint arXiv:hep-th/9804132*)
- [14] Agarwal A, Karabali D and Nair V P 2008 *Nucl. Phys. B* **790** 216 (*Preprint arXiv:0705.0394*)
- [15] Leigh R G, Minic D and Yelnikov A 2006 *Phys. Rev. Lett.* **96** 222001 (*Preprint arXiv:hep-th/0512111*)
- [16] Leigh R G, Minic D and Yelnikov A 2007 *Phys. Rev. D* **76** 065018 (*Preprint arXiv:hep-th/0604060*)
- [17] Freidel L, Leigh R G and Minic D 2006 *Phys. Lett. B* **641** 105 (*Preprint arXiv:hep-th/0604184*)
- [18] Freidel L 2006 *On pure Yang-Mills theory in 3+1 dimensions: Hamiltonian, vacuum and gauge invariant variables* (*Preprint arXiv:hep-th/0604185*)
- [19] Schneider R 2011 *Non-perturbative approach to pure Yang-Mills theory in 2+1 dimensions* Master's thesis Ludwig-Maximilians-Univ. München
- [20] Szczepaniak A P and Swanson E S 2002 *Phys. Rev. D* **65** 025012 (*Preprint arXiv:hep-ph/0107078*)
- [21] Feuchter C and Reinhardt H 2004 *Phys. Rev. D* **70** 105021 (*Preprint arXiv:hep-th/0408236*)
- [22] Samuel S 1997 *Phys. Rev. D* **55** 4189 (*Preprint arXiv:hep-ph/9604405*)
- [23] Greensite J and Olejník Š 2008 *Phys. Rev. D* **77** 065003 (*Preprint arXiv:0707.2860*)
- [24] Greensite J and Olejník Š 2010 *Phys. Rev. D* **81** 074504 (*Preprint arXiv:1002.1189*)
- [25] Greensite J and Olejník Š 2014 *Phys. Rev. D* **89** 034504 (*Preprint arXiv:1310.6706*)
- [26] Abbott E A 1884 *Flatland: A Romance of Many Dimensions* (London: Seeley & Co)
- [27] Gribov V N 1978 *Nucl. Phys. B* **139** 1
- [28] Zwanziger D 1998 *Nucl. Phys. B* **518** 237
- [29] Greensite J and Iwasaki J 1989 *Phys. Lett. B* **223** 207
- [30] Rucker R 2002 *Spaceland: A Novel of the Fourth Dimension* (New York City: Tor Books)