Recent results in large-N lattice gauge theories

Marco Panero

Department of Physics and Helsinki Institute of Physics
University of Helsinki

Lattice 2012, The XXX International Symposium on Lattice Field Theory
Cairns, Australia, 26 June 2012

UNIVERSITY OF HELSINKI

Outline

Introductory reviews on large-N QCD:

- E. Brézin and S. R. Wadia, *The Large N Expansion in Quantum Field Theory and Statistical Physics: From Spin Systems to 2-Dimensional Gravity*, World Scientific, Singapore, 1993
- Y. Makeenko, hep-th/0001047
- M. Teper, 0912.3339
- B. Lucini and M. P., in preparation

At this conference, parallel talks relevant for this topic are presented by M. García Pérez, A. González-Arroyo, M. Hanada, M. Honda, D. Kadoh, L. Keegan, M. Koreń, J.-W. Lee, R. Lohmayer, F. Negro, M. Okawa and P. Orland.

Outline

QCD in the 't Hooft limit

Consider a generalization of QCD with $SU(N \to \infty)$ gauge group

- Take $g \to 0$, with $\lambda = g^2 N$ fixed, to have a perturbatively smooth limit
- Keep track of the number of independent color indices in Feynman diagrams through *double-line notation* for propagators
- Dominance of *planar* diagrams *without dynamical quark loops*
- Terms proportional to different powers of $1/N$ can be arranged in a *topological series*

$$\mathcal{A} = \sum_{h,b=0}^{\infty} N^{2-2h-b} \sum_{n=0}^{\infty} c_{(h,b),n} \lambda^n$$

  Analogous to a loop expansion in Riemann surfaces for string theory, upon replacing $1/N \to g_s$

- This also holds according to the conjectured holographic correspondence: In the large-N limit, loop effects on the string side become negligible (see also plenary talk by Hanada)

UNIVERSITY OF HELSINKI

QCD in the 't Hooft limit

Consider a generalization of QCD with $SU(N \to \infty)$ gauge group

- Take $g \to 0$, with $\lambda = g^2 N$ fixed, to have a perturbatively smooth limit
- Keep track of the number of independent color indices in Feynman diagrams through *double-line notation* for propagators
  - Quark: fundamental rep. $\Rightarrow$ single line
  - Gluon: adjoint rep. $\Rightarrow$ double line
- Dominance of *planar* diagrams *without dynamical quark loops*
- Terms proportional to different powers of $1/N$ can be arranged in a *topological series*

$$\mathcal{A} = \sum_{h,b=0}^{\infty} N^{2-2h-b} \sum_{n=0}^{\infty} c_{(h,b),n} \lambda^n$$

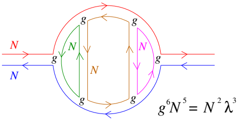
  Analogous to a loop expansion in Riemann surfaces for string theory, upon replacing $1/N \to g_s$
- This also holds according to the conjectured holographic correspondence: In the large-N limit, loop effects on the string side become negligible (see also plenary talk by Hanada)

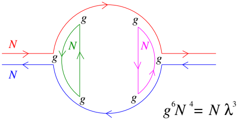
UNIVERSITY OF HELSINKI

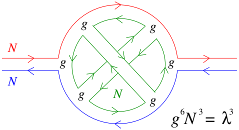
QCD in the 't Hooft limit

Consider a generalization of QCD with $\mathrm{SU}(N \to \infty)$ gauge group

- Take $g \to 0$, with $\lambda = g^2 N$ fixed, to have a perturbatively smooth limit
- Keep track of the number of independent color indices in Feynman diagrams through *double-line notation* for propagators
- Dominance of *planar* diagrams *without dynamical quark loops*







- Terms proportional to different powers of $1/N$ can be arranged in a *topological series*

$$\mathcal{A} = \sum_{h,b=0}^{\infty} N^{2-2h-b} \sum_{n=0}^{\infty} c_{(h,b),n} \lambda^n$$

Analogous to a loop expansion in Riemann surfaces for string theory, upon replacing $1/N \to g_s$

- This also holds according to the conjectured holographic correspondence: In the large-N limit, loop effects on the string side become negligible (see also plenary talk by Hanada)

QCD in the 't Hooft limit

Consider a generalization of QCD with SU($N \to \infty$) gauge group

- Take $g \to 0$, with $\lambda = g^2 N$ fixed, to have a perturbatively smooth limit
- Keep track of the number of independent color indices in Feynman diagrams through *double-line notation* for propagators
- Dominance of *planar* diagrams *without dynamical quark loops*
- Terms proportional to different powers of $1/N$ can be arranged in a *topological series*

$$\mathcal{A} = \sum_{h,b=0}^{\infty} N^{2-2h-b} \sum_{n=0}^{\infty} c_{(h,b),n} \lambda^n$$

  Analogous to a loop expansion in Riemann surfaces for string theory, upon replacing $1/N \to g_s$
- This also holds according to the conjectured holographic correspondence: In the large-N limit, loop effects on the string side become negligible (see also plenary talk by Hanada)

QCD in the 't Hooft limit

Consider a generalization of QCD with $\mathrm{SU}(N \to \infty)$ gauge group

- Take $g \to 0$, with $\lambda = g^2 N$ fixed, to have a perturbatively smooth limit
- Keep track of the number of independent color indices in Feynman diagrams through *double-line notation* for propagators
- Dominance of *planar* diagrams *without dynamical quark loops*
- Terms proportional to different powers of $1/N$ can be arranged in a *topological series*

$$\mathcal{A} = \sum_{h,b=0}^{\infty} N^{2-2h-b} \sum_{n=0}^{\infty} c_{(h,b),n} \lambda^n$$

  Analogous to a loop expansion in Riemann surfaces for string theory, upon replacing $1/N \to g_s$
- This also holds according to the conjectured holographic correspondence: In the large-N limit, loop effects on the string side become negligible (see also plenary talk by Hanada)

A wealth of phenomenological implications from large-N counting rules

Assuming that the large-N limit of QCD is confining:

- The spectrum consists of infinitely many stable glueballs and mesons, with masses $\mathcal{O}(1)$ and interactions suppressed by powers of $1/\sqrt{N}$: large-N QCD is a theory of *weakly coupled* hadrons
- Exotica (e.g. tetraquarks, molecules, et c.) are absent
- The OZI rule is *exact*
- Loop effects in the chiral Lagrangian are suppressed by $1/N$
- The axial anomaly is suppressed by $1/N$, and the square of the η' mass is $\mathcal{O}(1/N)$
- Baryons can be interpreted as *solitons* of the theory, with masses $\mathcal{O}(N)$
- Quantitative predictions for baryon-meson couplings, baryon masses, magnetic moments, et c. from consistency conditions based on unitarity
- Implications for the QCD phase diagram—quarkyonic matter (McLerran and Pisarski, 2007)?
- Further implications for high-energy QCD (evolution equations, hadronic cross-sections, parton distributions and structure functions, large-N Standard Model, ...)

A wealth of phenomenological implications from large-N counting rules

Assuming that the large-N limit of QCD is confining:

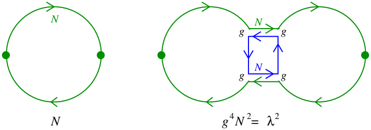
- The spectrum consists of infinitely many stable glueballs and mesons, with masses $\mathcal{O}(1)$ and interactions suppressed by powers of $1/\sqrt{N}$: large-N QCD is a theory of *weakly coupled* hadrons
- Exotica (e.g. tetraquarks, molecules, et c.) are absent
- The OZI rule is *exact*
- Loop effects in the chiral Lagrangian are suppressed by $1/N$
- The axial anomaly is suppressed by $1/N$, and the square of the η' mass is $\mathcal{O}(1/N)$
- Baryons can be interpreted as *solitons* of the theory, with masses $\mathcal{O}(N)$
- Quantitative predictions for baryon-meson couplings, baryon masses, magnetic moments, et c. from consistency conditions based on unitarity
- Implications for the QCD phase diagram—quarkyonic matter (McLerran and Pisarski, 2007)?
- Further implications for high-energy QCD (evolution equations, hadronic cross-sections, parton distributions and structure functions, large-N Standard Model, ...)

UNIVERSITY OF HELSINKI

A wealth of phenomenological implications from large-N counting rules

Assuming that the large-N limit of QCD is confining:

- The spectrum consists of infinitely many stable glueballs and mesons, with masses $\mathcal{O}(1)$ and interactions suppressed by powers of $1/\sqrt{N}$: large-N QCD is a theory of *weakly coupled* hadrons
- Exotica (e.g. tetraquarks, molecules, et c.) are absent
- The OZI rule is *exact*



- Loop effects in the chiral Lagrangian are suppressed by $1/N$
- The axial anomaly is suppressed by $1/N$, and the square of the η' mass is $\mathcal{O}(1/N)$
- Baryons can be interpreted as *solitons* of the theory, with masses $\mathcal{O}(N)$
- Quantitative predictions for baryon-meson couplings, baryon masses, magnetic moments, et c. from consistency conditions based on unitarity
- Implications for the QCD phase diagram—quarkyonic matter (McLerran and Pisarski, 2007)?
- Further implications for high-energy QCD (evolution equations, hadronic

A wealth of phenomenological implications from large-N counting rules

Assuming that the large-N limit of QCD is confining:

- The spectrum consists of infinitely many stable glueballs and mesons, with masses $\mathcal{O}(1)$ and interactions suppressed by powers of $1/\sqrt{N}$: large-N QCD is a theory of *weakly coupled* hadrons
- Exotica (e.g. tetraquarks, molecules, et c.) are absent
- The OZI rule is *exact*
- Loop effects in the chiral Lagrangian are suppressed by $1/N$
- The axial anomaly is suppressed by $1/N$, and the square of the η' mass is $\mathcal{O}(1/N)$
- Baryons can be interpreted as *solitons* of the theory, with masses $\mathcal{O}(N)$
- Quantitative predictions for baryon-meson couplings, baryon masses, magnetic moments, et c. from consistency conditions based on unitarity
- Implications for the QCD phase diagram—quarkyonic matter (McLerran and Pisarski, 2007)?
- Further implications for high-energy QCD (evolution equations, hadronic cross-sections, parton distributions and structure functions, large-N Standard Model, ...)

UNIVERSITY OF HELSINKI

A wealth of phenomenological implications from large-N counting rules

Assuming that the large-N limit of QCD is confining:

- The spectrum consists of infinitely many stable glueballs and mesons, with masses $\mathcal{O}(1)$ and interactions suppressed by powers of $1/\sqrt{N}$: large-N QCD is a theory of *weakly coupled* hadrons
- Exotica (e.g. tetraquarks, molecules, et c.) are absent
- The OZI rule is *exact*
- Loop effects in the chiral Lagrangian are suppressed by $1/N$
- The axial anomaly is suppressed by $1/N$, and the square of the η' mass is $\mathcal{O}(1/N)$
- Baryons can be interpreted as *solitons* of the theory, with masses $\mathcal{O}(N)$
- Quantitative predictions for baryon-meson couplings, baryon masses, magnetic moments, et c. from consistency conditions based on unitarity
- Implications for the QCD phase diagram—quarkyonic matter (McLerran and Pisarski, 2007)?
- Further implications for high-energy QCD (evolution equations, hadronic cross-sections, parton distributions and structure functions, large-N Standard Model, ...)

A wealth of phenomenological implications from large-N counting rules

Assuming that the large-N limit of QCD is confining:

- The spectrum consists of infinitely many stable glueballs and mesons, with masses $\mathcal{O}(1)$ and interactions suppressed by powers of $1/\sqrt{N}$: large-N QCD is a theory of *weakly coupled* hadrons
- Exotica (e.g. tetraquarks, molecules, et c.) are absent
- The OZI rule is *exact*
- Loop effects in the chiral Lagrangian are suppressed by $1/N$
- The axial anomaly is suppressed by $1/N$, and the square of the η' mass is $\mathcal{O}(1/N)$
- Baryons can be interpreted as *solitons* of the theory, with masses $\mathcal{O}(N)$
- Quantitative predictions for baryon-meson couplings, baryon masses, magnetic moments, et c. from consistency conditions based on unitarity
- Implications for the QCD phase diagram—quarkyonic matter (McLerran and Pisarski, 2007)?
- Further implications for high-energy QCD (evolution equations, hadronic cross-sections, parton distributions and structure functions, large-N Standard Model, . . .)

A wealth of phenomenological implications from large-N counting rules

Assuming that the large-N limit of QCD is confining:

- The spectrum consists of infinitely many stable glueballs and mesons, with masses $\mathcal{O}(1)$ and interactions suppressed by powers of $1/\sqrt{N}$: large-N QCD is a theory of *weakly coupled* hadrons
- Exotica (e.g. tetraquarks, molecules, et c.) are absent
- The OZI rule is *exact*
- Loop effects in the chiral Lagrangian are suppressed by $1/N$
- The axial anomaly is suppressed by $1/N$, and the square of the η' mass is $\mathcal{O}(1/N)$
- Baryons can be interpreted as *solitons* of the theory, with masses $\mathcal{O}(N)$
- Quantitative predictions for baryon-meson couplings, baryon masses, magnetic moments, et c. from consistency conditions based on unitarity
- Implications for the QCD phase diagram—quarkyonic matter (McLerran and Pisarski, 2007)?
- Further implications for high-energy QCD (evolution equations, hadronic cross-sections, parton distributions and structure functions, large-N Standard Model, . . .)

A wealth of phenomenological implications from large-N counting rules

Assuming that the large-N limit of QCD is confining:

- The spectrum consists of infinitely many stable glueballs and mesons, with masses $\mathcal{O}(1)$ and interactions suppressed by powers of $1/\sqrt{N}$: large-N QCD is a theory of *weakly coupled* hadrons
- Exotica (e.g. tetraquarks, molecules, et c.) are absent
- The OZI rule is *exact*
- Loop effects in the chiral Lagrangian are suppressed by $1/N$
- The axial anomaly is suppressed by $1/N$, and the square of the η' mass is $\mathcal{O}(1/N)$
- Baryons can be interpreted as *solitons* of the theory, with masses $\mathcal{O}(N)$
- Quantitative predictions for baryon-meson couplings, baryon masses, magnetic moments, et c. from consistency conditions based on unitarity
- Implications for the QCD phase diagram—quarkyonic matter (McLerran and Pisarski, 2007)?
- Further implications for high-energy QCD (evolution equations, hadronic cross-sections, parton distributions and structure functions, large-N Standard Model, . . .)

UNIVERSITY OF HELSINKI

A wealth of phenomenological implications from large-N counting rules

Assuming that the large-N limit of QCD is confining:

- The spectrum consists of infinitely many stable glueballs and mesons, with masses $\mathcal{O}(1)$ and interactions suppressed by powers of $1/\sqrt{N}$: large-N QCD is a theory of *weakly coupled* hadrons
- Exotica (e.g. tetraquarks, molecules, et c.) are absent
- The OZI rule is *exact*
- Loop effects in the chiral Lagrangian are suppressed by $1/N$
- The axial anomaly is suppressed by $1/N$, and the square of the η' mass is $\mathcal{O}(1/N)$
- Baryons can be interpreted as *solitons* of the theory, with masses $\mathcal{O}(N)$
- Quantitative predictions for baryon-meson couplings, baryon masses, magnetic moments, et c. from consistency conditions based on unitarity
- Implications for the QCD phase diagram—quarkyonic matter (McLerran and Pisarski, 2007)?
- Further implications for high-energy QCD (evolution equations, hadronic cross-sections, parton distributions and structure functions, large-N Standard Model, ...)

Factorization, volume reduction and large-N equivalences

"You can hide a lot in a large-N matrix"
—Stephen Shenker

- Large-N counting rules imply that vev's of products of gauge-invariant operators are dominated by *disconnected contributions* $\Rightarrow$ Factorization of vev's of physical operators

$$\langle O_1 O_2 \rangle = \langle O_1 \rangle \langle O_2 \rangle + \mathcal{O}(1/N)$$

  The analogy with a *classical limit* can be made explicit by constructing appropriate *coherent states* (Yaffe, 1982)
- Factorization leads to volume independence
- Volume reduction can be interpreted as a large-N "orbifold" equivalence: Projection using a discrete subgroup of the global symmetries of the theory (Kovtun, Ünsal and Yaffe)
- Orbifold equivalences at large N also relate theories with different field content—e.g., orientifold planar equivalence (Armoni, Shifman and Veneziano—see also numerical studies by Lucini et al.)
- Finally, orbifold projections are also relevant for lattice supersymmetry (Catterall, Kaplan and Ünsal; see also Tsuchiya et al., Nishimura et al.)

UNIVERSITY OF HELSINKI

Factorization, volume reduction and large-N equivalences

"You can hide a lot in a large-N matrix"
—Stephen Shenker

- Large-N counting rules imply that vev's of products of gauge-invariant operators are dominated by *disconnected contributions* $\Rightarrow$ Factorization of vev's of physical operators
- Factorization leads to Eguchi-Kawai volume independence: the lattice theory can be formulated in an arbitrary small volume *provided center symmetry is unbroken*
- Volume reduction can be interpreted as a large-N "orbifold" equivalence: Projection using a discrete subgroup of the global symmetries of the theory (Kovtun, Ünsal and Yaffe)
- Orbifold equivalences at large N also relate theories with different field content—e.g., orientifold planar equivalence (Armoni, Shifman and Veneziano—see also numerical studies by Lucini et al.)
- Finally, orbifold projections are also relevant for lattice supersymmetry (Catterall, Kaplan and Ünsal; see also Tsuchiya et al., Nishimura et al.)

Factorization, volume reduction and large-N equivalences

"You can hide a lot in a large-N matrix"
—Stephen Shenker

- Large-N counting rules imply that vev's of products of gauge-invariant operators are dominated by *disconnected contributions* $\Rightarrow$ Factorization of vev's of physical operators
- Factorization leads to Eguchi-Kawai volume independence: the lattice theory can be formulated in an arbitrary small volume *provided center symmetry is unbroken*
- But center symmetry *does* get broken in a small volume in the continuum limit
- Volume reduction can be interpreted as a large-N "orbifold" equivalence: Projection using a discrete subgroup of the global symmetries of the theory (Kovtun, Ünsal and Yaffe)
- Orbifold equivalences at large N also relate theories with different field content—e.g., orientifold planar equivalence (Armoni, Shifman and Veneziano—see also numerical studies by Lucini et al.)
- Finally, orbifold projections are also relevant for lattice supersymmetry (Catterall, Kaplan and Ünsal; see also Tsuchiya et al., Nishimura et al.)

Factorization, volume reduction and large-N equivalences

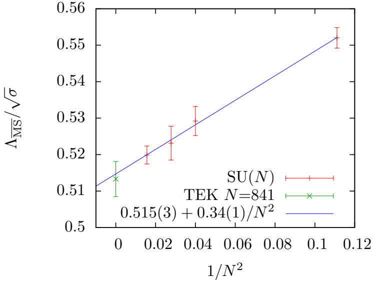
"You can hide a lot in a large-N matrix"
—Stephen Shenker

- Large-N counting rules imply that vev's of products of gauge-invariant operators are dominated by *disconnected contributions* $\Rightarrow$ Factorization of vev's of physical operators
- Factorization leads to Eguchi-Kawai volume independence: the lattice theory can be formulated in an arbitrary small volume *provided center symmetry is unbroken*
- But center symmetry *does* get broken in a small volume in the continuum limit; fixes:
  - Quenched EK (Bhanot, Heller and Neuberger)—but see (Bringoltz and Sharpe)
  - Twisted EK
  - Add dynamical adjoint fermions
  - Double-trace deformations
  - Partial reduction
- Volume reduction can be interpreted as a large-N "orbifold" equivalence: Projection using a discrete subgroup of the global symmetries of the theory (Kovtun, Ünsal and Yaffe)
- Orbifold equivalences at large N also relate theories with different field content—e.g., orientifold planar equivalence (Armoni, Shifman and Veneziano—see also numerical studies by Lucini et al.)
- Finally, orbifold projections are also relevant for lattice supersymmetry (Catterall, Kaplan and Ünsal; see also Tsuchiya et al., Nishimura et al.)

Factorization, volume reduction and large-N equivalences

"You can hide a lot in a large-N matrix"
—Stephen Shenker

- Large-N counting rules lead to factorization of vev's
- Factorization leads to EK volume independence if center symmetry is unbroken
- But center symmetry *does* get broken in a small volume in the continuum limit; fixes:
  - Quenched EK
  - Twisted EK (González-Arroyo and Okawa; Teper and Vairinhos, Azeyanagi et al., Bietenholz et al., García Pérez et al.)



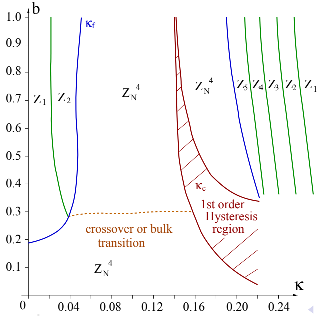
  - Add dynamical adjoint fermions
  - Double-trace deformations
  - Partial reduction
- Volume reduction can be interpreted as a large-N "orbifold" equivalence:

UNIVERSITY OF HELSINKI

Factorization, volume reduction and large-N equivalences

"You can hide a lot in a large-N matrix"
—Stephen Shenker

- Large-N counting rules lead to factorization of vev's
- Factorization leads to EK volume independence if center symmetry is unbroken
- But center symmetry *does* get broken in a small volume in the continuum limit; fixes:
  - Quenched EK
  - Twisted EK
  - Add dynamical adjoint fermions (Kovtun, Ünsal and Yaffe)—see also (Hollowood and Myers; Azeyanagi et al.; Catterall, Galvez and Ünsal; Bringoltz, Koreń and Sharpe; Cossu and D'Elia; Hietanen and Narayanan; Lee, Hanada and Yamada; Okawa et al.)



- Double-trace deformations

UNIVERSITY OF HELSINKI

Factorization, volume reduction and large-N equivalences

"You can hide a lot in a large-N matrix"
—Stephen Shenker

- Large-N counting rules lead to factorization of vev's
- Factorization leads to EK volume independence if center symmetry is unbroken
- But center symmetry *does* get broken in a small volume in the continuum limit; fixes:
    - Quenched EK
    - Twisted EK
    - Add dynamical adjoint fermions
    - Double-trace deformations (Ünsal and Yaffe; Ogilvie et al.; Vairinhos; Hanada et al.)

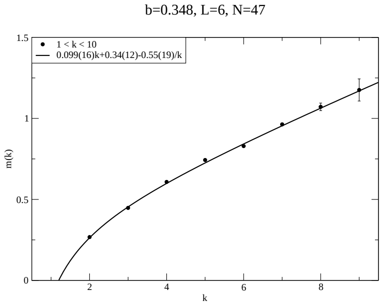
$$S_{\mathrm{YM}} \longrightarrow S_{\mathrm{YM}} + \frac{1}{N_t^3} \sum_{\vec{x}} \sum_{n=1}^{\lfloor N/2 \rfloor} a_n \left|\mathrm{tr}(L^n(\vec{x}))\right|^2$$

    - Partial reduction
- Volume reduction can be interpreted as a large-N "orbifold" equivalence: Projection using a discrete subgroup of the global symmetries of the theory (Kovtun, Ünsal and Yaffe)
- Orbifold equivalences at large N also relate theories with different field content—e.g., orientifold planar equivalence (Armoni, Shifman and Veneziano—see also numerical studies by Lucini et al.)
- Finally, orbifold projections are also relevant for lattice supersymmetry (Catterall, Kaplan and Ünsal; see also Tsuchiya et al., Nishimura et al.)

Factorization, volume reduction and large-N equivalences

"You can hide a lot in a large-N matrix"
—Stephen Shenker

- Large-N counting rules lead to factorization of vev's
- Factorization leads to EK volume independence if center symmetry is unbroken
- But center symmetry *does* get broken in a small volume in the continuum limit; fixes:
  - Quenched EK
  - Twisted EK
  - Add dynamical adjoint fermions
  - Double-trace deformations
  - Partial reduction (Kiskis, Narayanan and Neuberger)



Factorization, volume reduction and large-N equivalences

"You can hide a lot in a large-N matrix"
—Stephen Shenker

- Large-N counting rules lead to factorization of vev's
- Factorization leads to EK volume independence if center symmetry is unbroken
- Volume reduction can be interpreted as a large-N "orbifold" equivalence: Projection using a discrete subgroup of the global symmetries of the theory (Kovtun, Ünsal and Yaffe)
- Orbifold equivalences at large N also relate theories with different field content—e.g., orientifold planar equivalence (Armoni, Shifman and Veneziano—see also numerical studies by Lucini et al.)
- Finally, orbifold projections are also relevant for lattice supersymmetry (Catterall, Kaplan and Ünsal; see also Tsuchiya et al., Nishimura et al.)

Factorization, volume reduction and large-N equivalences

"You can hide a lot in a large-N matrix"
—Stephen Shenker

- Large-N counting rules lead to factorization of vev's
- Factorization leads to EK volume independence if center symmetry is unbroken
- Volume reduction can be interpreted as a large-N "orbifold" equivalence: Projection using a discrete subgroup of the global symmetries of the theory (Kovtun, Ünsal and Yaffe)
- Orbifold equivalences at large N also relate theories with different field content—e.g., orientifold planar equivalence (Armoni, Shifman and Veneziano—see also numerical studies by Lucini et al.)
- Finally, orbifold projections are also relevant for lattice supersymmetry (Catterall, Kaplan and Ünsal; see also Tsuchiya et al., Nishimura et al.)

Factorization, volume reduction and large-N equivalences

"You can hide a lot in a large-N matrix"
—Stephen Shenker

- Large-N counting rules lead to factorization of vev's
- Factorization leads to EK volume independence if center symmetry is unbroken
- Volume reduction can be interpreted as a large-N "orbifold" equivalence: Projection using a discrete subgroup of the global symmetries of the theory (Kovtun, Ünsal and Yaffe)
- Orbifold equivalences at large N also relate theories with different field content—e.g., orientifold planar equivalence (Armoni, Shifman and Veneziano—see also numerical studies by Lucini et al.)
- Finally, orbifold projections are also relevant for lattice supersymmetry (Catterall, Kaplan and Ünsal; see also Tsuchiya et al., Nishimura et al.)

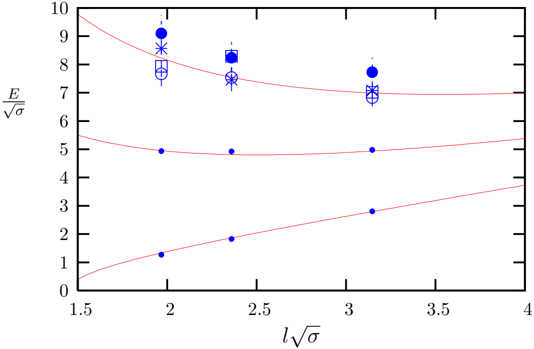
Outline

Results in 4D

- SU(N) is a confining theory in the large-N limit (see, e.g., Meyer and Teper hep-lat/0411039)
- Confining flux tubes behave like Nambu-Goto strings
- Glueball masses have a smooth dependence on N
- Well-behaved scale-dependence of the coupling
- The deconfinement temperature has a smooth dependence on N
- The equation of state appears to have only a *trivial* dependence on N
- Topological susceptibility and θ-dependence
- Quenched mesonic spectrum
- Quenched baryonic spectrum

Results in 4D

- SU(N) is a confining theory in the large-N limit
- Confining flux tubes behave like Nambu-Goto strings



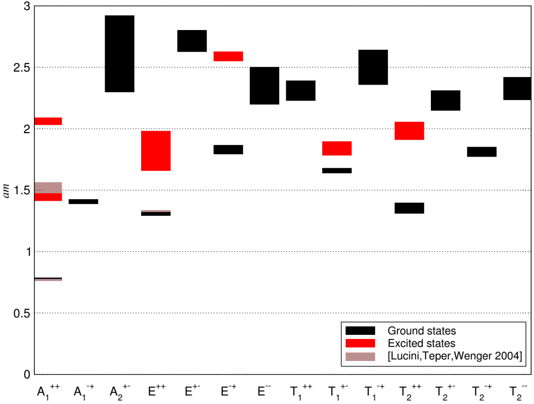
Torelon spectrum in SU(5) (Athenodorou et al., 1007.4720)

See also: Lucini and Teper, hep-lat/0107007; Lohmayer and Neuberger, 1206.4015; Mykkänen, in progress

- Glueball masses have a smooth dependence on N
- Well-behaved scale-dependence of the coupling
- The deconfinement temperature has a smooth dependence on N
- The equation of state appears to have only a *trivial* dependence on N

Results in 4D

- SU(N) is a confining theory in the large-N limit
- Confining flux tubes behave like Nambu-Goto strings
- Glueball masses have a smooth dependence on N

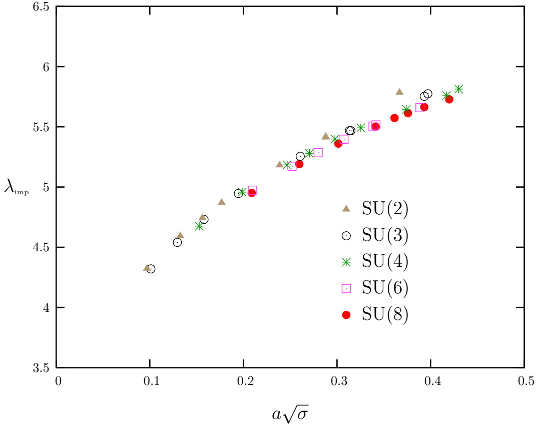


YM spectrum (Lucini, Rago and Rinaldi, 1007.3879)

- Well-behaved scale-dependence of the coupling
- The deconfinement temperature has a smooth dependence on N
- The equation of state appears to have only a *trivial* dependence on N
- Topological susceptibility and θ-dependence

Results in 4D

- SU(N) is a confining theory in the large-N limit
- Confining flux tubes behave like Nambu-Goto strings
- Glueball masses have a smooth dependence on N
- Well-behaved scale-dependence of the coupling



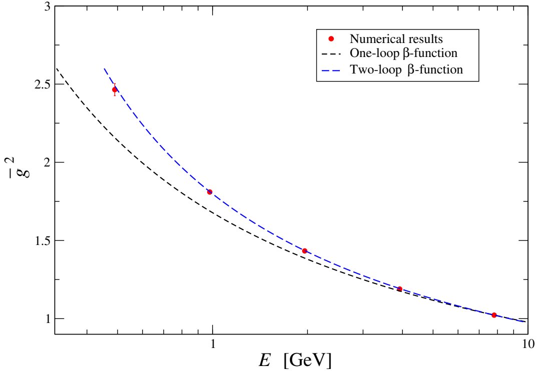
Bare coupling in pure YM (Allton et al., 0803.1092)

UNIVERSITY OF HELSINKI

- The deconfinement temperature has a smooth dependence on N

Results in 4D

- SU(N) is a confining theory in the large-N limit
- Confining flux tubes behave like Nambu-Goto strings
- Glueball masses have a smooth dependence on N
- Well-behaved scale-dependence of the coupling

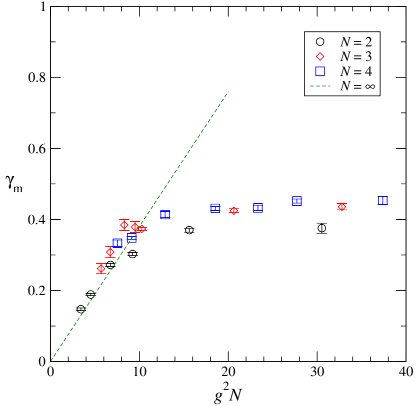


SU(4) YM, SF scheme (Lucini and Moraitis, 0805.2913)

- The deconfinement temperature has a smooth dependence on N
- The equation of state appears to have only a *trivial* dependence on N
- Topological susceptibility and θ-dependence
- Quenched mesonic spectrum
- Quenched baryonic spectrum

Results in 4D

- SU(N) is a confining theory in the large-N limit
- Confining flux tubes behave like Nambu-Goto strings
- Glueball masses have a smooth dependence on N
- Well-behaved scale-dependence of the coupling

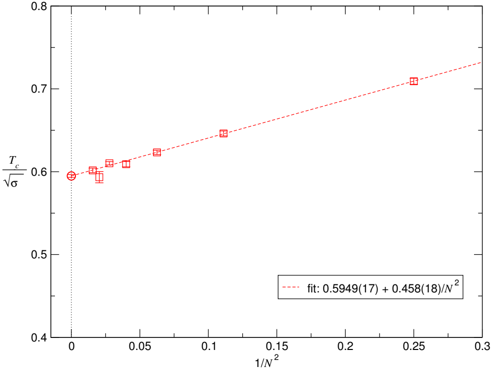


Mass anomalous dimension in QCD$_N$ with $n_f = 2$ 2S fermions
(DeGrand, Shamir and Svetitsky, 1202.2675)

- The deconfinement temperature has a smooth dependence on N
- The equation of state appears to have only a *trivial* dependence on N

Results in 4D

- SU(N) is a confining theory in the large-N limit
- Confining flux tubes behave like Nambu-Goto strings
- Glueball masses have a smooth dependence on N
- Well-behaved scale-dependence of the coupling
- The deconfinement temperature has a smooth dependence on N



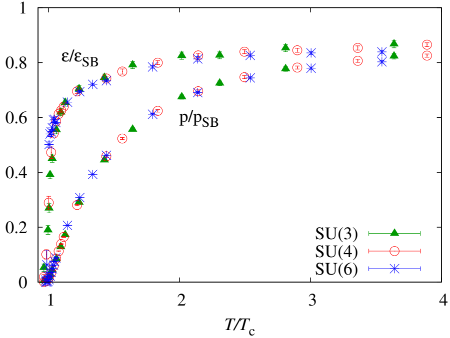
(Lucini, Rago and Rinaldi, 1202.6684)

See also: Lucini, Teper and Wenger, hep-lat/0307017 and hep-lat/0502003; Piemonte et al., in progress

- The equation of state appears to have only a *trivial* dependence on N

Results in 4D

- SU(N) is a confining theory in the large-N limit
- Confining flux tubes behave like Nambu-Goto strings
- Glueball masses have a smooth dependence on N
- Well-behaved scale-dependence of the coupling
- The deconfinement temperature has a smooth dependence on N
- The equation of state appears to have only a *trivial* dependence on N



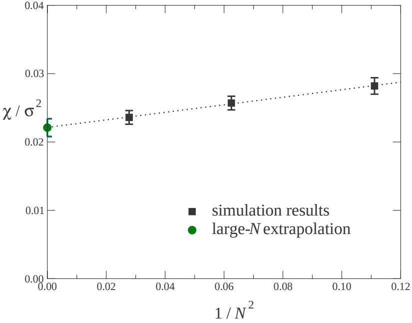
(Datta and Gupta, 1006.0938)

See also: Bringoltz and Teper, hep-lat/0506034, M.P., 0907.3719; Mykkänen et al., 1202.2762

- Topological susceptibility and θ-dependence
- Quenched mesonic spectrum

Results in 4D

- SU(N) is a confining theory in the large-N limit
- Confining flux tubes behave like Nambu-Goto strings
- Glueball masses have a smooth dependence on N
- Well-behaved scale-dependence of the coupling
- The deconfinement temperature has a smooth dependence on N
- The equation of state appears to have only a *trivial* dependence on N
- Topological susceptibility and θ-dependence



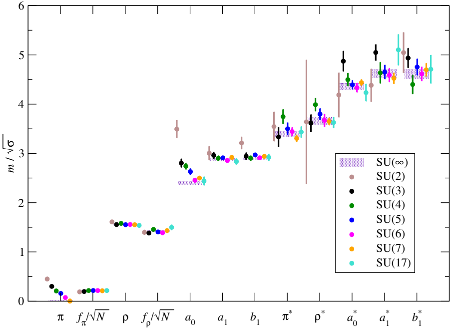
(Del Debbio et al., 2002)

See also: Lucini and Teper, hep-lat/0110004, hep-lat/0401028, Cundy et al., hep-lat/0203030, Panagopoulos et al., 1109.6815

- Quenched mesonic spectrum

Results in 4D

- SU(N) is a confining theory in the large-N limit
- Confining flux tubes behave like Nambu-Goto strings
- Glueball masses have a smooth dependence on N
- Well-behaved scale-dependence of the coupling
- The deconfinement temperature has a smooth dependence on N
- The equation of state appears to have only a *trivial* dependence on N
- Topological susceptibility and θ-dependence
- Quenched mesonic spectrum



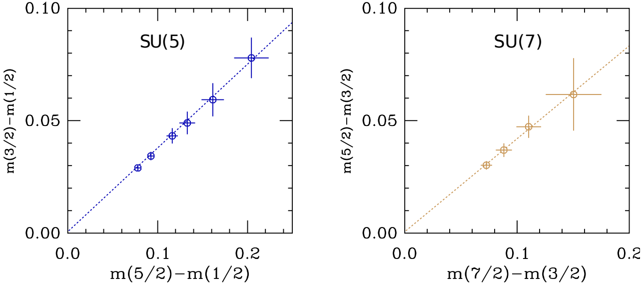
(Bali et al., in progress)

See also: Del Debbio et al., 0712.3036, Bali and Bursa, 0806.2278, Hietanen et al., 0901.3752

UNIVERSITY OF HELSINKI

Results in 4D

- SU(N) is a confining theory in the large-N limit
- Confining flux tubes behave like Nambu-Goto strings
- Glueball masses have a smooth dependence on N
- Well-behaved scale-dependence of the coupling
- The deconfinement temperature has a smooth dependence on N
- The equation of state appears to have only a *trivial* dependence on N
- Topological susceptibility and θ-dependence
- Quenched mesonic spectrum
- Quenched baryonic spectrum



(DeGrand, 1205.0235)

Results in 3D

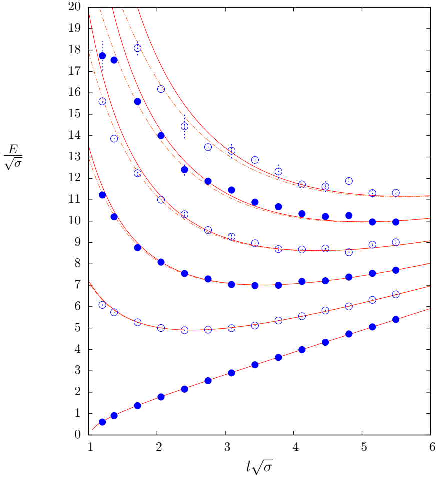
Much like in 4D:

- SU(N) is a confining theory in the large-N limit (Teper, hep-lat/9804008)
- Confining flux tubes behave as Nambu-Goto strings (Athenodorou et al., 1103.5854; Caselle et al., 1102.0723; Mykkänen, in progress)
- Glueball masses have a smooth dependence on N (Johnson and Teper, hep-ph/0012287; Meyer, hep-lat/0508002)
- The equation of state depends only trivially on N (Caselle et al., 1105.0359 and 1111.0580)

Results in 3D

Much like in 4D:

- SU(N) is a confining theory in the large-N limit (Teper, hep-lat/9804008)
- Confining flux tubes behave as Nambu-Goto strings (Athenodorou et al., 1103.5854; Caselle et al., 1102.0723; Mykkänen, in progress)



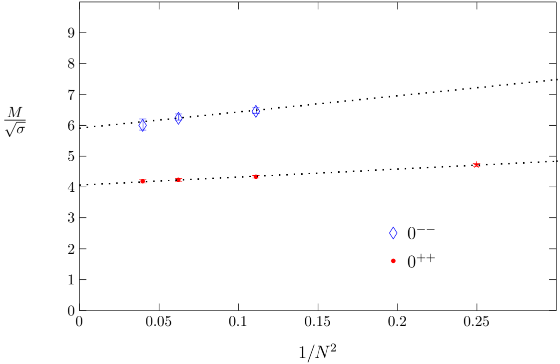
UNIVERSITY OF HELSINKI

- Glueball masses have a smooth dependence on N (Johnson and Teper,

Results in 3D

Much like in 4D:

- SU(N) is a confining theory in the large-N limit (Teper, hep-lat/9804008)
- Confining flux tubes behave as Nambu-Goto strings (Athenodorou et al., 1103.5854; Caselle et al., 1102.0723; Mykkänen, in progress)
- Glueball masses have a smooth dependence on N (Johnson and Teper, hep-ph/0012287; Meyer, hep-lat/0508002)

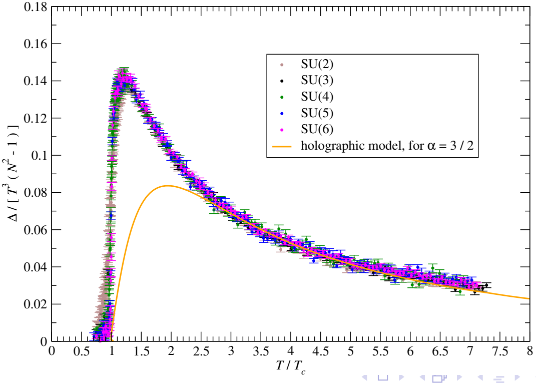


- The equation of state depends only trivially on N (Caselle et al., 1105.0359 and 1111.0580)

Results in 3D

Much like in 4D:

- SU(N) is a confining theory in the large-N limit (Teper, hep-lat/9804008)
- Confining flux tubes behave as Nambu-Goto strings (Athenodorou et al., 1103.5854; Caselle et al., 1102.0723; Mykkänen, in progress)
- Glueball masses have a smooth dependence on N (Johnson and Teper, hep-ph/0012287; Meyer, hep-lat/0508002)
- The equation of state depends only trivially on N (Caselle et al., 1105.0359 and 1111.0580)



Results in 2D

Several exact results are known; in particular:

- The continuum spectrum of large-N QCD in 2D was computed by 't Hooft in 1974
- In 1979, Gross and Witten found a third-order transition in the lattice theory
- The spectral density of Wilson loops was studied by Durhuus and Olesen in 1981

In general, a 2D world can be a useful laboratory for QCD toy models (see, e.g., works by Narayanan, Neuberger and Vicari; Orland et al., . . .)

Recently, the eigenvalue density of Wilson loops in 2D has been studied by Lohmayer, Neuberger and Wettig; similar studies have also been done in 4D (Lohmayer and Neuberger)

Various groups (e.g. Bringoltz; Galvez, Hietanen and Narayanan, et c.) have addressed the problem of 2D large-N theories at finite chemical potential

Outline

UNIVERSITY OF HELSINKI

Concluding remarks

Lattice studies of gauge theories in the large-N limit are theoretically very appealing, numerically tractable, and interesting for a *very broad* community.

Concluding remarks

Lattice studies of gauge theories in the large-N limit are theoretically very appealing, numerically tractable, and interesting for a *very broad* community (as you can see).

Concluding remarks

Lattice studies of gauge theories in the large-N limit are theoretically very appealing, numerically tractable, and interesting for a *very broad* community.

During the last fifteen years, numerical simulations in this field have given conclusive answers to various long-standing questions. However, many other issues are still open, and waiting for your involvement.

Concluding remarks

Lattice studies of gauge theories in the large-N limit are theoretically very appealing, numerically tractable, and interesting for a *very broad* community.

During the last fifteen years, numerical simulations in this field have given conclusive answers to various long-standing questions. However, many other issues are still open, and waiting for your involvement.

From my personal point of view, particularly promising research directions for further numerical studies at large N include:

- Simulations with dynamical fermions, in various representations
- Finite temperature/finite density; comparisons with perturbative computations, with holography, or with effective models
- Topological properties (see, e.g., Lucini et al., hep-lat/0401028, hep-lat/0502003; Panagopoulos and Vicari, 0803.1593, 1109.6815; D'Elia and Negro, 1205.0238)
- Large-N equivalences and volume reduction