Improved results for the mass spectrum of $\mathcal{N} = 1$ SU(3) supersymmetric Yang-Mills theory

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1. Supersymmetry on the lattice
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in collaboration with P. Giudice, S. Kuberski, G. Münster, I. Montvay, S. Piemonte, S. Ali, H. Gerber, P. Scior

THE SCIENCES

Is Supersymmetry Dead?

[Scientific American,2012]

No!

- We don't even understand it: Supersymmetric particle physics requires breaking terms based on an unknown non-perturbative mechanism.
  $\Rightarrow$ need to understand non-perturbative SUSY
- Supersymmetry is a general beautiful theoretical concept: (Extended) SUSY simplifies theoretical analysis and leads to new non-perturbative approaches.
  $\Rightarrow$ need to bridge the gap between "beauty" and "reality"
- Lattice investigations: challenging task to realize SUSY

  [G.B., S. Catterall, arXiv:1603.04478]

$\mathcal{N}=1$ supersymmetric Yang-Mills theory

Supersymmetric Yang-Mills theory:

$$\mathcal{L} = \mathrm{Tr}\left[-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{i}{2}\bar{\lambda}\not{D}\lambda - \frac{m_g}{2}\bar{\lambda}\lambda\right]$$

- supersymmetric counterpart of Yang-Mills theory; but in several respects similar to QCD
- λ Majorana fermion in the adjoint representation

Supersymmetric Yang-Mills theory: Symmetries

SUSY

- gluino mass term $m_g \Rightarrow$ soft SUSY breaking

$U_R(1)$ symmetry, "chiral symmetry": $\lambda \to e^{-i\theta\gamma_5}\lambda$

- $U_R(1)$ anomaly: $\theta = \frac{k\pi}{N_c}$, $U_R(1) \to \mathbb{Z}_{2N_c}$
- $U_R(1)$ spontaneous breaking: $\mathbb{Z}_{2N_c} \overset{\langle\lambda\lambda\rangle\neq 0}{\to} \mathbb{Z}_2$

Supersymmetric Yang-Mills theory: effective actions

symmetries + confinement $\rightarrow$ low energy effective theory

- exact value of $\langle \bar{\lambda}\lambda \rangle$
- exact beta function
- low energy effective actions:
  1. multiplet[1]:
  mesons : $a - f_0$ and $a - \eta'$
  fermionic gluino-glue
- 2. multiplet[2]:
  glueballs: 0^{++} and 0^{-+}
  fermionic gluino-glue

Supersymmetry

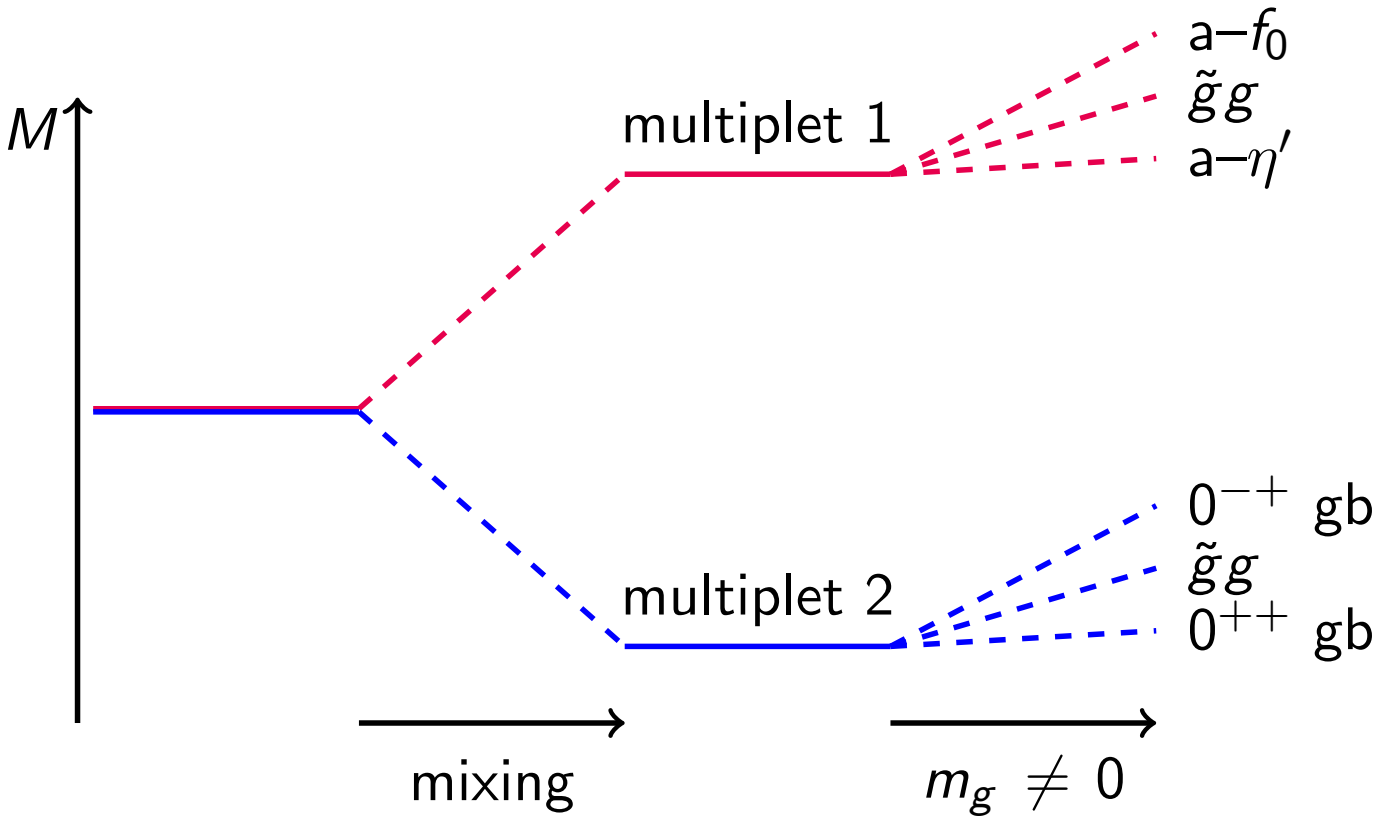
All particles of a multiplet must have the same mass.

[1] [Veneziano, Yankielowicz, Phys.Lett.B113 (1982)]

[2] [Farrar, Gabadadze, Schwetz, Phys.Rev. D58 (1998)]

Conjectured multiplet splitting

$$\frac{\Delta m_{\mathrm{a}-\eta'}}{m_0} \div \frac{\Delta m_{gg}}{m_0} \div \frac{\Delta m_{\mathrm{a}-f_0}}{m_0} \propto 5 \div 6 \div 7$$



On the lattice: Talk by H. Gerber

Why study $\mathcal{N}=1$ supersymmetric Yang-Mills theory on the lattice ?

1. extension of the standard model
   - gauge part of SUSY models
   - understand non-perturbative sector: check effective actions etc.
2. controlled confinement:
   - compactified SYM: continuity expected
   - small R regime: allows semiclassical treatment
3. connection to QCD
   - orientifold planar equivalence: SYM $\leftrightarrow$ QCD
   - Remnants of SYM in QCD ?
   - comparison with one flavor QCD

Supersymmetric Yang-Mills theory on the lattice

Lattice action:

$$\mathcal{S}_L = \beta \sum_P \left(1 - \frac{1}{N_c} \Re U_P\right) + \frac{1}{2} \sum_{xy} \bar{\lambda}_x \left(\mathrm{D}_w(m_g)\right)_{xy} \lambda_y$$

- Wilson fermions:

$$\mathrm{D}_w = 1 - \kappa \sum_{\mu=1}^{4} \left[(1-\gamma_\mu)_{\alpha,\beta} T_\mu + (1+\gamma_\mu)_{\alpha,\beta} T_\mu^\dagger\right]$$

gauge invariant transport: $T_\mu \lambda(x) = V_\mu \lambda(x+\hat{\mu})$;

$$\kappa = \frac{1}{2(m_g+4)}$$

- links in adjoint representation: $(V_\mu)_{ab} = 2\mathrm{Tr}[U_\mu^\dagger T^a U_\mu T^b]$ of $SU(2)$, $SU(3)$

Recovering symmetry

Fine-tuning (Veneziano, Curci)[1]:

chiral limit = SUSY limit $+O(a)$, obtained at critical $\kappa(m_g)$

Wilson fermions:

- explicit breaking of symmetries: ~~chiral Sym. ($U_R(1)$)~~, ~~SUSY~~
- restored in chiral continuum limit

practical determination of critical κ:

- limit of zero mass of adjoint pion $(a-\pi)$

$\Rightarrow$ definition of gluino mass: $\propto (m_{a-\pi})^2$

[1] [Veneziano, Curci, Nucl.Phys.B292 (1987)]

The status of the project

- verification of VC scenario: chiral symmetry breaking and supersymmetric Ward identities
  (SU(3) case: see talk by S. Ali)
- multiplet formation found in the continuum limit of SU(2) SYM [JHEP 1603, 080 (2016)]
- SYM thermodynamics: coincidence of chiral and deconfinement transition [JHEP **1411**, 049 (2014)]
- SYM compactification: Witten index and absence of deconfinement [JHEP **1412**, 133 (2014)]
- first indication of multiplet formation in the excited states (talk by H. Gerber)
- first SU(3) results: P. Giudice [PoS LATTICE 2016]
  $\Rightarrow$ now clover improved results

Supersymmetric Yang-Mills theory: Scale and mass determination

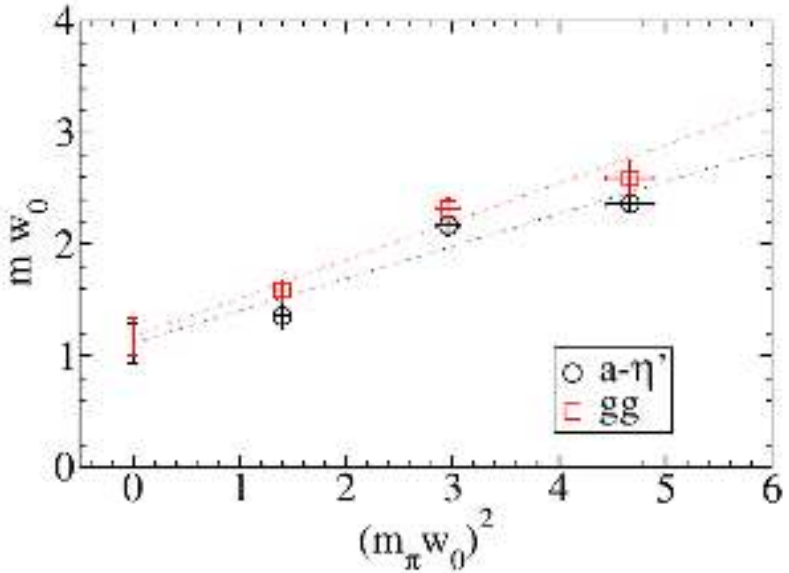
- scale setting:
  - parameters: r_0, w_0
  - can be used for comparison to Yang-Mills theory, QCD
- meson states (singlet)
  - a–f_0 $(\bar{\lambda}\lambda)$, a–η' $(\bar{\lambda}\gamma_5\lambda)$
  - methods for disconnected contributions [PoS LATTICE 2011]
- glueballs
- spin-1/2 state (gluino-glue)

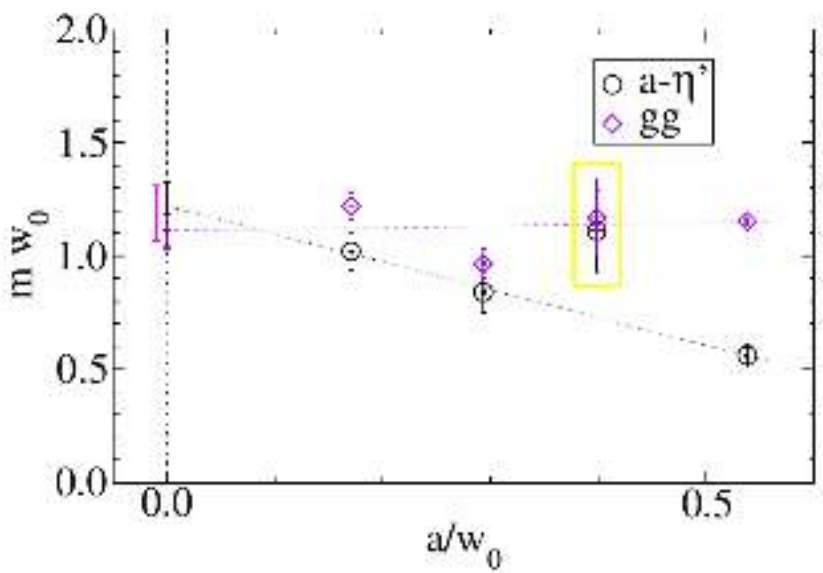
$$\sum_{\mu,\nu} \sigma_{\mu\nu} \mathrm{tr}\,[F^{\mu\nu}\lambda]$$

Simulations of SU(3) supersymmetric Yang-Mills theory

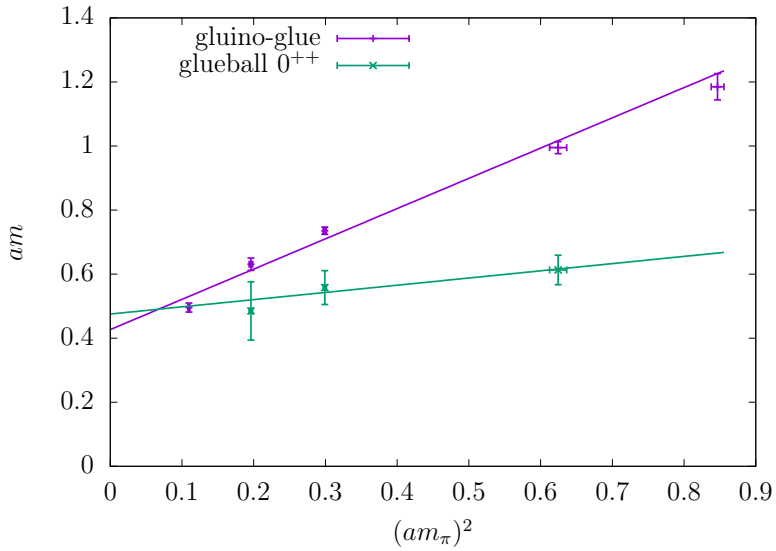
- simulations algorithm: (TS)PHMC, (W)RHMC
- compared to QCD scale setting: $a \sim 0.08$fm, $L \sim 1.3$fm ($a \sim 0.04$fm)
- Why clover?
  Tests of tadpole improved clover in SU(2) SYM ($a \sim 0.08$fm)

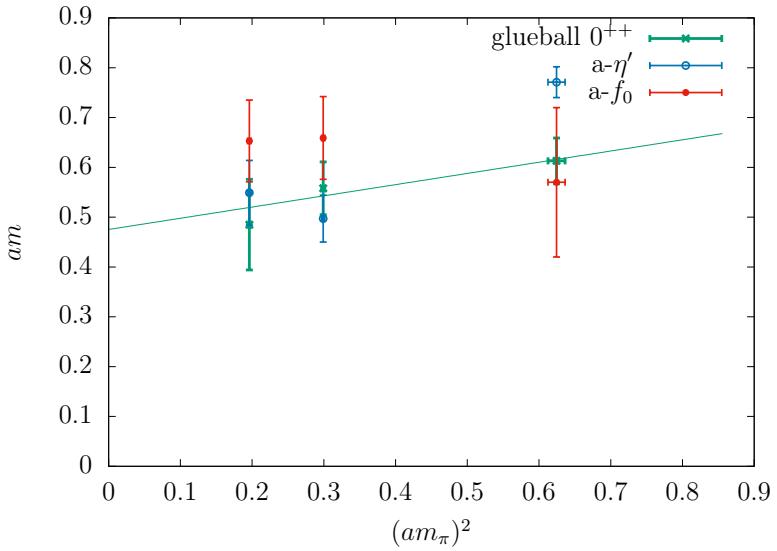
  [JHEP 1603, 080 (2016)]





The mass states of supersymmetric Yang-Mills theory





- situation similar to the SU(2) case with comparable lattice spacing
- indication for a multiplet formation and *restored SUSY* in chiral limit

Conclusions and outlook

- Similar to the SU(2) case: regime of SUSY multiplet formation can be reached in $\mathcal{N} = 1$ SU(3) supersymmetric Yang-Mills theory
- VC scenario valid and practical for lattice simulation of SYM
- Additional data will help to substantiate these observations
- Simulations working: investigations of theoretical predictions for SYM possible
- Extensions to further theories? SQCD and extended SUSY