D-term Dynamical SUSY Breaking

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Plan

- Introduction
- Basic Idea
- Gap equation
- Some Comments on Phenomenological Application
- Summary

Introduction

SUPERSYMMETRY

is one of the attractive scenarios
solving the hierarchy problem,
but it must be broken at low energy

Dynamical SUSY breaking(DSB)
is most desirable to solve
the hierarchy problem

F-term DSB is induced by non-perturbative effects
due to nonrenormalization theorem
and well studied so far

D-term SUSY breaking is NOT affected
by the nonrenormalization theorem

In principle, D-term DSB is possible,
but no known explicit model as far as we know

In this talk, we will accomplish

D-term DSB (DDSB)

in a self-consistent

Hartree-Fock approximation

Basic Idea

N=1 SUSY U(N) gauge theory with an adjoint chiral multiplet

$$\mathcal{L} = \int d^4\theta K\left(\Phi^a, \bar{\Phi}^a, V\right) + \int d^2\theta \, \mathrm{Im} \frac{1}{2} \tau_{ab}\left(\Phi^a\right) \mathcal{W}^{a\alpha} \mathcal{W}^b_\alpha + \left[\int d^2\theta W\left(\Phi^a\right) + h.c. \right]$$

$$\mathcal{W}^a_\alpha = -i\lambda^a_\alpha(y) + \left[\delta^\beta_\alpha D^a(y) - \frac{i}{2}\left(\sigma^\mu \bar{\sigma}^\nu\right)_\alpha^\beta F^a_{\mu\nu}(y) \right] \theta_\beta$$

$$\Phi^a = \phi^a(y) + \sqrt{2}\theta\psi^a(y) + \theta\theta F^a(y) \quad y^\mu = x^\mu + i\theta\sigma^\mu\bar{\theta}$$

$\partial W(\Phi^a)/\partial\Phi^a = 0$ @tree level assumed

Fermion masses

Important dim 5 operator

$$\int d^2\theta \tau_{ab}(\Phi) \mathcal{W}^{a\alpha} \mathcal{W}^b_\alpha \supset \tau_{abc}(\Phi)\psi^c \lambda^a D^b + \tau_{abc}(\Phi) F^c \lambda^a \lambda^b$$

Dirac mass term

$$\int d^2\theta W(\Phi) \supset -\frac{1}{2}\partial_a \partial_b W(\Phi)\psi^a \psi^b$$

$$\tau_{abc} \equiv \partial\tau_{ab}(\Phi)/\partial\phi^c$$

Fermion mass terms

Mixed Majorana-Dirac type masses (<F>=0 assumed)

$$-\frac{1}{2}\begin{pmatrix}\lambda^a & \psi^a\end{pmatrix}\begin{pmatrix} 0 & -\frac{\sqrt{2}}{4}\tau_{abc}D^b \\ -\frac{\sqrt{2}}{4}\tau_{abc}D^b & \partial_a\partial_c W \end{pmatrix}\begin{pmatrix}\lambda^c \\ \psi^c\end{pmatrix} + h.c.$$

Mass matrix

$$M_F \equiv \begin{pmatrix} 0 & -\frac{\sqrt{2}}{4}\left\langle \tau_{0aa}D^0 \right\rangle \\ -\frac{\sqrt{2}}{4}\left\langle \tau_{0aa}D^0 \right\rangle & \left\langle \partial_a\partial_a W \right\rangle \end{pmatrix}$$

Only U(1) part of D-term VEV is assumed

if $\langle D \rangle \neq 0 \,\&\, \langle \partial_a \partial_a W \rangle \neq 0$

$$m_{\pm} = \frac{1}{2}\langle \partial_a \partial_a W \rangle \left[1 \pm \sqrt{1 + \left(\frac{2\langle D \rangle}{\langle \partial_a \partial_a W \rangle} \right)^2} \right]$$

$$D \equiv -\frac{\sqrt{2}}{4} \tau_{0aa} D^0$$

Gaugino becomes massive
by nonzero <D>

$\Rightarrow$ SUSY is broken

D-term equation of motion:

$$\left\langle D^0 \right\rangle = -\frac{1}{2\sqrt{2}} \left\langle g^{00} \left(\tau_{0cd} \psi^d \lambda^c + \bar{\tau}_{0cd} \bar{\psi}^d \bar{\lambda}^c \right) \right\rangle$$

Dirac bilinear condensation

The value of <D> will be determined by the gap equation

Gap equation

1-loop effective potential for D-term

Tree level D-term pot. + 1-loop CW pot.
+ counter term (-Im Λ/2 ∫d²Θ WᵅW_α)

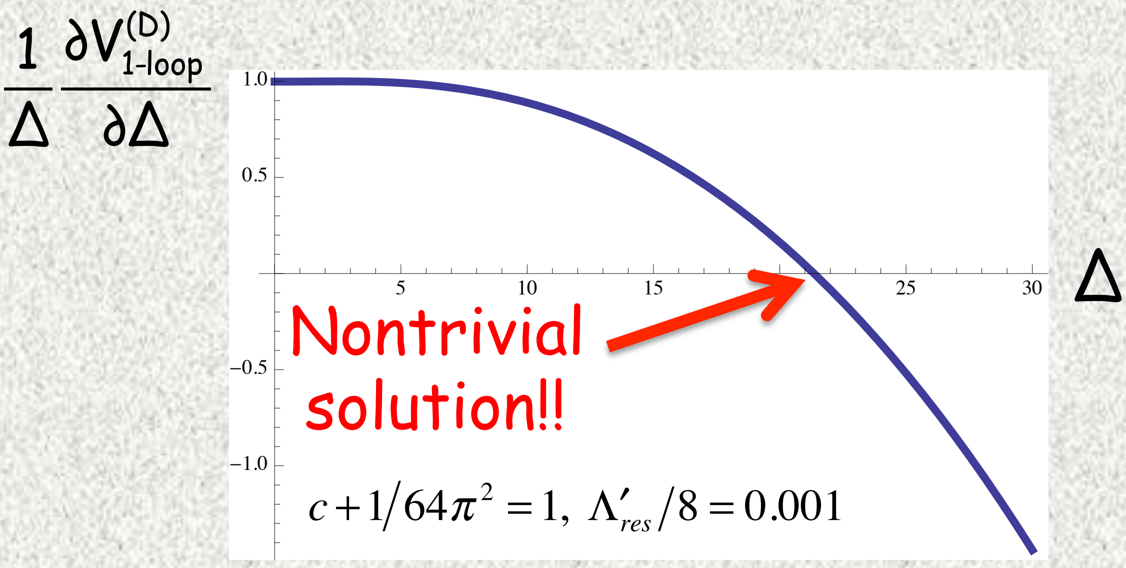
$$V_{1-loop}^{(D)} = \sum_a |m_a|^4 \left\{ \left(c + \frac{1}{64\pi^2} \right) \Delta^2 + \Lambda'_{res} \frac{\Delta^4}{8} - \frac{1}{32\pi^2} \left[\lambda^{(+)4} \log \lambda^{(+)2} + \lambda^{(-)4} \log \lambda^{(-)2} \right] \right\}$$

$$m_a \equiv \langle \partial_a \partial_a W \rangle, \lambda^{(\pm)} \equiv \frac{1}{2}\left[1 \pm \sqrt{1+\Delta^2} \right], \Delta \equiv \frac{\langle \tau_{0aa} D^0 \rangle}{\sqrt{2} m_a}, \Lambda'_{res} \equiv c + \beta + \Lambda_{res} + \frac{1}{64\pi^2},$$

$$\frac{1}{\sum_a |m_a|^4} \frac{\partial^2 V}{(\partial\Delta)^2}\bigg|_{\Delta=0} = 2c, \beta \equiv \frac{\langle g_{00} \rangle |\langle \partial_a \partial_a W \rangle|^2}{\sum_a |m_a|^4 |\langle \tau_{0aa} \rangle|^2}, \quad \Lambda_{res} \equiv \frac{(\mathrm{Im}\,\Lambda) |\langle \partial_a \partial_a W \rangle|^2}{\sum_a |m_a|^4 |\langle \tau_{0aa} \rangle|^2}$$

Gap equation

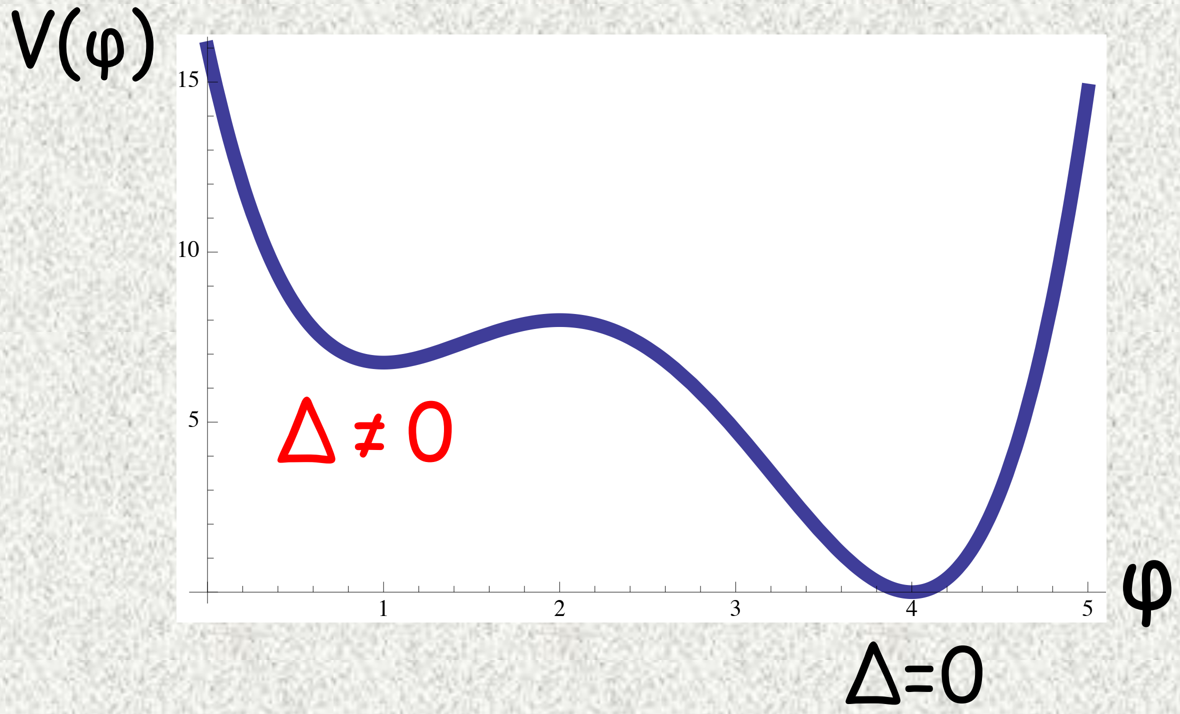
$$0 = \frac{\partial V^{(D)}_{1-loop}}{\partial \Delta} = \Delta \left[c + \frac{1}{64\pi^2} + \frac{\Lambda'_{res}}{4} \Delta^2 \right.$$
$$\left. - \frac{1}{64\pi^2 \sqrt{1+\Delta^2}} \left\{ \lambda^{(+)3} \left(2 \log \lambda^{(+)2} + 1 \right) - \lambda^{(-)3} \left(2 \log \lambda^{(-)2} + 1 \right) \right\} \right]$$



$E = D^2/2 \geqq 0$ in SUSY

⇒ Trivial solution $\Delta=0$ is NOT lifted

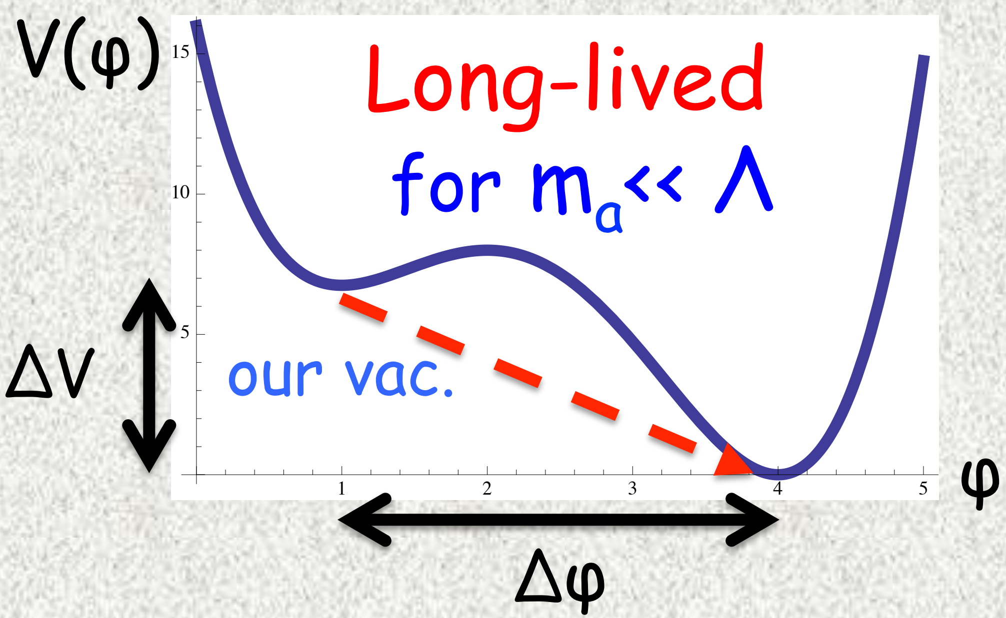
⇒ Our SUSY breaking vac. is a local min.



Metastability of our false vacuum

<D> = 0 tree vacuum is not lifted

⇒ check if our vacuum <D> ≠ 0 is sufficiently long-lived



Coleman & De Luccia(1980)

Decay rate of the false vacuum

$$\propto \exp\left[-\frac{\langle\Delta\phi\rangle^4}{\langle\Delta V\rangle}\right] \approx \exp\left[-\frac{\Lambda^2}{m_a^2}\right] \ll 1$$

m_a: mass of Φ, Λ: cutoff scale

Some Comments on Phenomenological Application

Following the model of Fox, Nelson & Weiner (2002),

consider a N=2 gauge sector & N=1 matter sector in MSSM

↑

Chirality, Asymptotic freedom of QCD

Take the gauge group $U(1)' \times G_{SM}$ (U(1)':hidden gauge group)

Dim 5 gauge kinetic term

provides Dirac gaugino mass term

$$\int d^2\theta \tau_{abc}(\Phi)\Phi^c_{SM}\mathcal{W}'^{\alpha a}\mathcal{W}^b_{\alpha SM} \Rightarrow \tau_{abc}(\langle\Phi\rangle)\langle D'^a\rangle \psi^c_{SM}\lambda^b_{SM}$$

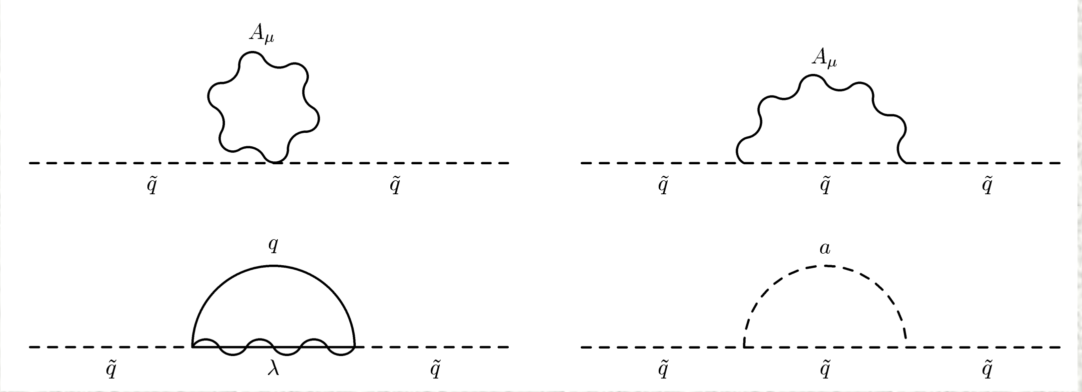
Gaugino masses are generated at tree level

Once gaugino masses are generated at tree level,
sfermion masses are generated by RGE effects

sfermion masses @1-loop

$$M_{sf}^2 \approx \frac{C_i(R)\alpha_i}{\pi} M_{\lambda_i}^2 \log\left[\frac{m_a^2}{M_{\lambda_i}^2}\right]$$

(i = SU(3)c, SU(2)L, U(1)Y)



Fox, Nelson & Weiner, JHEP08 (2002) 035

Flavor blind ⇒ No SUSY flavor & CP problems

Summary

- A new dynamical mechanism of DDSB proposed
- Shown a nontrivial solution of the gap eq. with nonzero <D> in a self-consistent Hartree-Fock approx.
- Our vacuum is metastable & can be made long-lived
- Phenomenological Application briefly discussed

Backup

$$\left\langle D^0 \right\rangle \neq 0 \Rightarrow \left\langle F^0 \right\rangle \neq 0$$

Effective potenital up to 1-loop

$$V = g^{ab}\,\partial_a W \overline{\partial_b W} - \frac{1}{2} g_{ab} D^a D^b + V_{1-loop} + V_{c.t.}$$

Stationary condition

$$\left\langle \delta V \right\rangle = 0$$

$$\Rightarrow \left| \left\langle F^0 \right\rangle \right|^2 + \frac{m_0}{\left\langle g^{00}\,\partial_0 g_{00} \right\rangle} \left\langle F^0 \right\rangle + \frac{1}{2} \left\langle D^0 \right\rangle^2 + 2 \left\langle g^{00} \right\rangle \left\langle V_{1-loop} \right\rangle = 0$$

This determines the value of nonvanishing <F>

Fermion masses

Fermion masses are modified as follows

SU(N) part:

$$\mathcal{L}_{mass}^{(holo)} = -\frac{1}{2}\langle g_{0a,a}\rangle\langle \bar{F}^0\rangle \psi^a\psi^a + \frac{i}{4}\langle \mathcal{F}_{0aa}\rangle\langle F^0\rangle \lambda^a\lambda^a - \frac{1}{2}\langle \partial_a\partial_a W\rangle \psi^a\psi^a + \frac{\sqrt{2}}{4}\langle \mathcal{F}_{0aa}\rangle\langle D^0\rangle \psi^a\lambda^a$$

U(1) part:

NG fermion: admixture of λ^0 and ψ^0

Once SUSY is broken,
the next issue we should consider is
how to mediate its breaking to our world

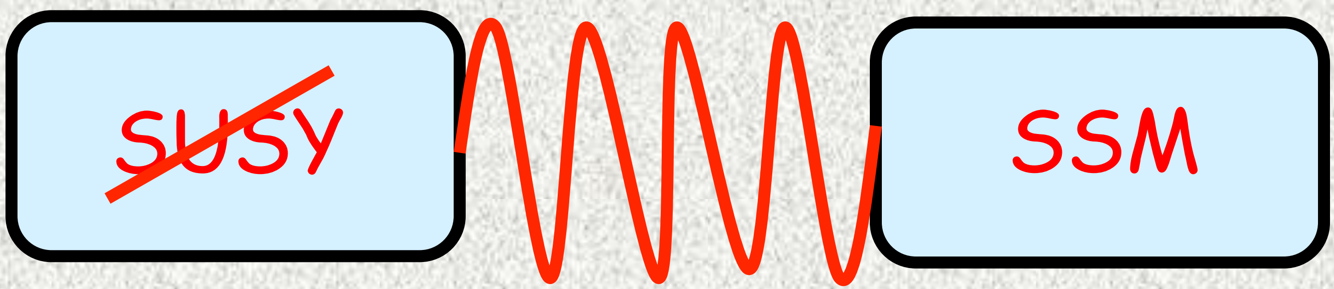
SUSY breaking mediation mechanism reflects
the pattern of sparticle spectrum,
which must satisfy severe constraints from experiments

$ex.\, K^0 - \bar{K}^0$ mixing

$$\left(\delta^d_{12}\right)_{LL} \equiv \frac{m^2_{Q,12}}{\tilde{m}^2} \leq 0.01\left(\frac{\tilde{m}}{100\ \text{GeV}}\right)$$

Gauge mediation is one of the attractive scenarios

SM gauge interaction loops



Super-Higgs mechanism

If we couple our theory to supergravity,
a super-Higgs mechanism works

Gravitino mass

$$e^{-1}\mathcal{L}_{gravitino\ mass} = -e^{K/2}W^{\dagger}\psi_{\mu}\sigma^{\mu\nu}\psi_{\nu} + \psi_{\mu}\sigma^{\mu}\left[-\frac{g}{2}D_a\bar{\lambda}^a + e^{K/2}\frac{i}{\sqrt{2}}D_aW^{\dagger}\bar{\psi}^a\right] + h.c.$$

can be diagonalized by the following redefinition
of the gravitino

$$\psi'_{\mu} = \psi_{\mu} + \frac{i}{2}\frac{e^{-K/2}}{W^{\dagger}}\sigma_{\mu}\left[-\frac{g}{2}D_a\bar{\lambda}^a + e^{K/2}\frac{i}{\sqrt{2}}D_aW^{\dagger}\bar{\psi}^a\right]$$

$$e^{-1}\mathcal{L}_{gravitino\ mass} = -e^{K/2}W^{\dagger}\psi'_{\mu}\sigma^{\mu\nu}\psi'_{\nu} + \frac{i}{2}\frac{e^{K/2}}{W^{\dagger}}\left[-\frac{g}{2}D_a\bar{\lambda}^a + e^{K/2}\frac{i}{\sqrt{2}}D_aW^{\dagger}\bar{\psi}^a\right]^2 + h.c.$$

Gravitino mass

$$m_{3/2} = e^{\langle K \rangle/2} \frac{\langle W \rangle}{M_P^2} \underbrace{\approx}_{0 \approx \langle V \rangle} e^{\langle K \rangle/2} \frac{\sqrt{\left|\langle D_a W \rangle\right|^2 + \frac{g^2}{2} \langle D^a \rangle^2}}{\sqrt{3} M_P^2}$$

$\mathcal{N} = 2 \to \mathcal{N} = 1$ Model

Fujiwara, Itoyama & Sakaguchi (2005, 2006)

Take the following N=2 SYM

$$\mathcal{L}_{U(N)} = \mathrm{Im}\left[\int d^4\theta\, Tr\bar{\Phi}e^V \frac{\partial \mathcal{F}(\Phi)}{\partial \Phi} + \int d^2\theta \frac{1}{2}\frac{\partial^2 \mathcal{F}(\Phi)}{\partial \Phi^a \partial \Phi^b}\mathcal{W}^{\alpha a}\mathcal{W}^b_\alpha\right]$$

$$+\left(\int d^2\theta\, Tr\left[2e\Phi + m\frac{\partial \mathcal{F}(\Phi)}{\partial \Phi}\right] + h.c.\right)$$

"Electric" & "Magnetic" FI terms

$\mathcal{F}(\Phi)$: "*prepotential*" holomorphic function of Φ

N=2 theory can be obtained from N=1 theory by imposing SU(2)R invariance

$$\left(\lambda^a\ \psi^a\right) \to \left(\psi^a\ -\lambda^a\right)$$

SUSY transformation

$$\left\langle \delta \begin{pmatrix} \lambda^a \\ \psi^a \end{pmatrix} \right\rangle = 2\sqrt{N} \left\langle g^{ab} \right\rangle \begin{pmatrix} 0 & \left\langle e\delta_b^0 + m\mathcal{F}_{0b} \right\rangle \\ -\left\langle \bar{e}\delta_b^0 + m\mathcal{F}_{0b} \right\rangle & 0 \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$

$$= 2\sqrt{N} \left\langle g^{ab} \right\rangle \begin{pmatrix} 0 \\ (e - \bar{e})\delta_b^0 \eta_1 \end{pmatrix}$$

Vacuum condition chosen as $\left\langle e\delta_b^0 + m\mathcal{F}_{0b} \right\rangle = 0$ (F=0) from

$$0 = \left\langle \frac{\partial V}{\partial \phi^a} \right\rangle = \left\langle g^{bd} \mathcal{F}_{ade} g^{ec} \right\rangle \left\langle e\delta_b^0 + m\bar{\mathcal{F}}_{0b} \right\rangle \underbrace{\left\langle \bar{e}\delta_c^0 + m\bar{\mathcal{F}}_{0c} \right\rangle}_{=0}$$

N=2 SUSY is partially broken to N=1

NG fermion: ψ

In the present model, the gaugino masses are

$$\Lambda_a^{(\pm)} = m_a \lambda^{(\pm)}, \quad \lambda^{(\pm)} \equiv \frac{1}{2}\left(1 \pm \sqrt{1+\Delta^2}\right)$$

$$m_a \equiv \sqrt{2N} m \left\langle g^{aa} \mathcal{F}_{0aa} \right\rangle, \quad \Delta^2 \equiv \frac{\left(D^0\right)^2}{4Nm^2}$$

↑ Adjoint scalar mass