Higgs Mass in D-term Triggered Dynamical SUSY Breaking

Nobuhito Maru
(Osaka City University)

with H. Itoyama
(Osaka City University)

3/5/2015 SCGT15@Nagoya University

References

"126 GeV Higgs Boson Associated with D-Term Triggered Dynamical Supersymmetry Breaking"
H. Itoyama and NM, Symmetry 2015 7 193

"D-Term Triggered Dynamical Supersymmetry Breaking"
H. Itoyama and NM, PRD88 (2013) 025012

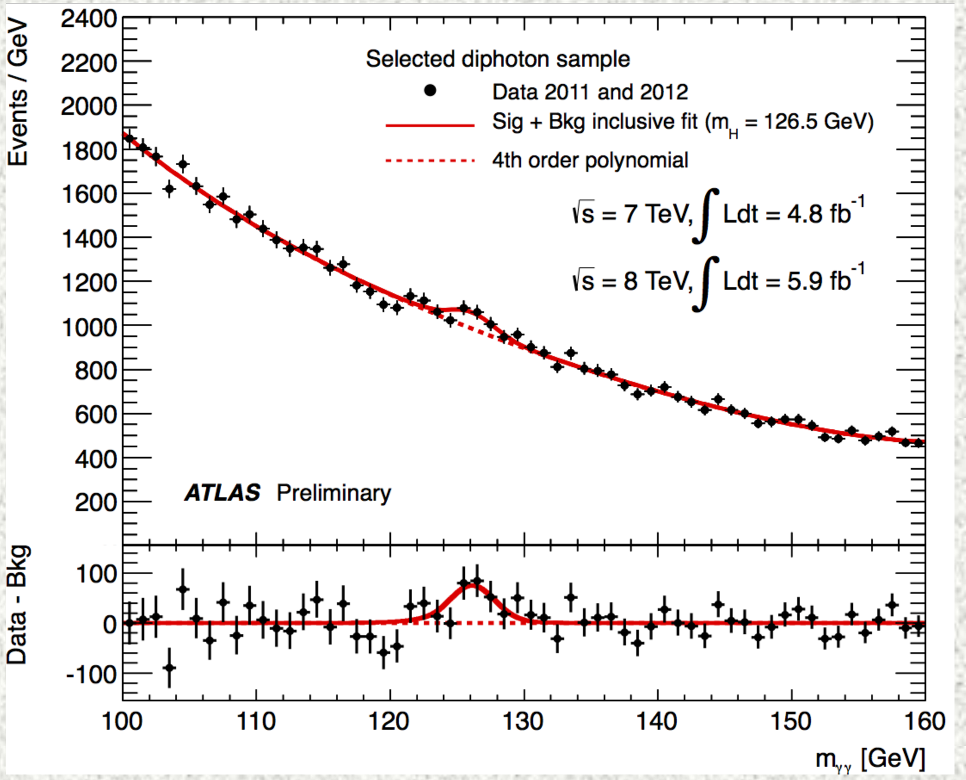
"D-Term Dynamical Supersymmetry Breaking Generating Split N=2 Gaugino Masses of Majorana-Dirac Type"
H. Itoyama and NM, IJMPA27 (2012) 1250159

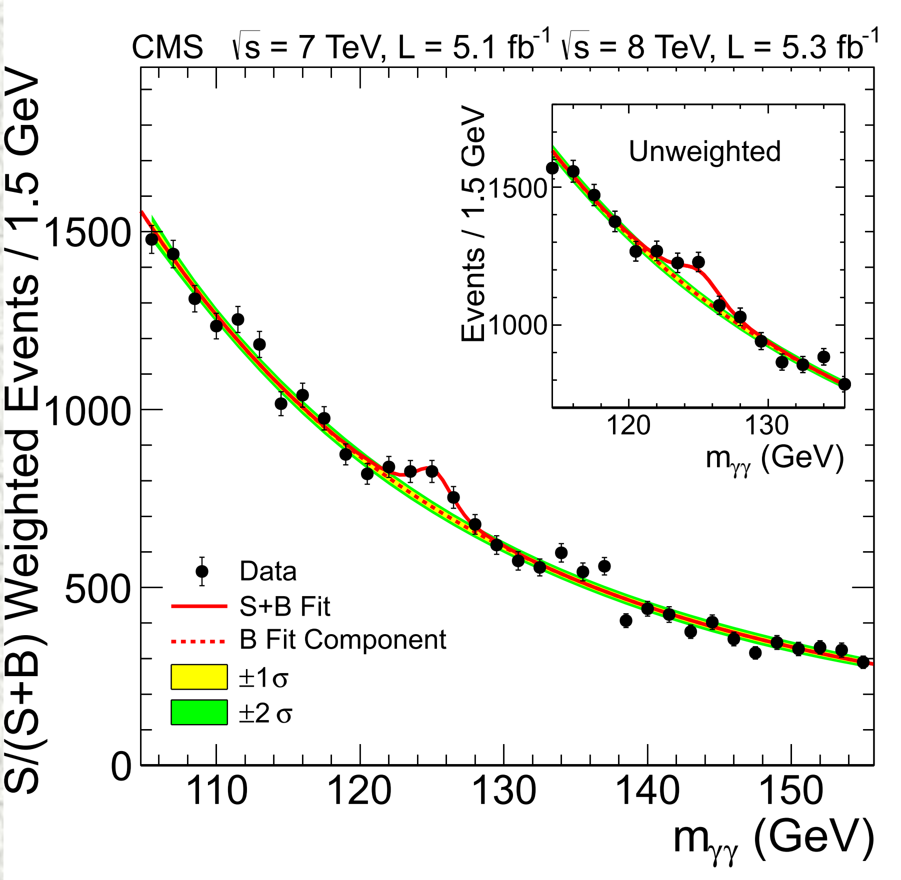
Plan

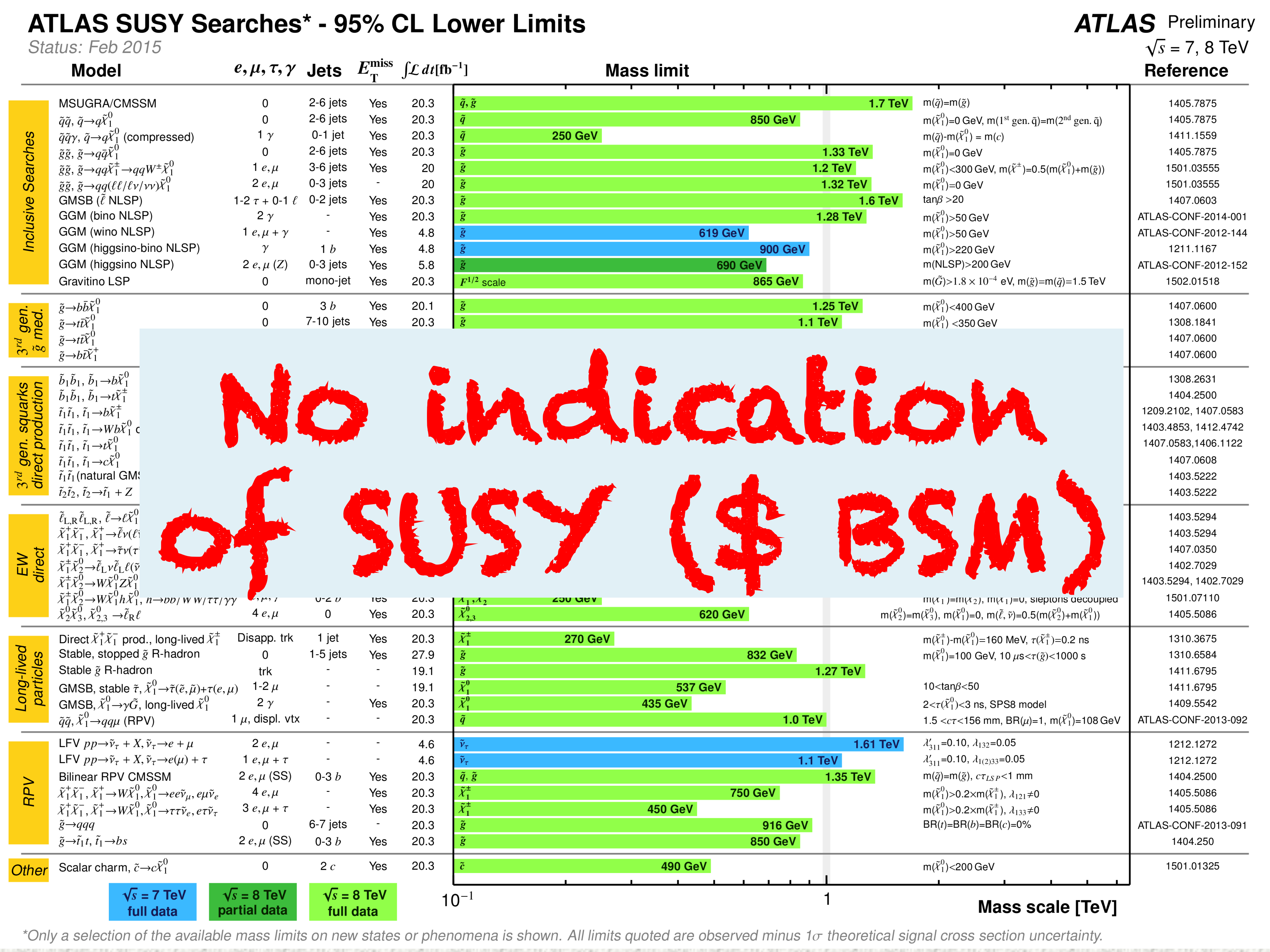
- Introduction
- A New Mechanism of D-term Dynamical SUSY Breaking
- Higgs Mass via D-term effects
- Summary

Introduction

A Higgs boson was discovored, but…







ATLAS SUSY Searches* - 95% CL Lower Limits
Status: Feb 2015
ATLAS Preliminary
√s = 7, 8 TeV
Model
e, μ, τ, γ
Jets
E_T^miss
∫L dt[fb^-1]
Mass limit
Reference
Inclusive Searches
MSUGRA/CMSSM 0 2-6 jets Yes 20.3 q̃, g̃ 1.7 TeV m(q̃)=m(g̃) 1405.7875
q̃q̃, q̃→qχ̃⁰₁ 0 2-6 jets Yes 20.3 q̃ 850 GeV 1405.7875
q̃q̃γ, q̃→qχ̃⁰₁ (compressed) 1 γ 0-1 jet Yes 20.3 q̃ 250 GeV 1411.1559
g̃g̃, g̃→qq̄χ̃⁰₁ 0 2-6 jets Yes 20.3 g̃ 1.33 TeV m(χ̃⁰₁)=0 GeV 1405.7875
g̃g̃, g̃→qqχ̃±₁→qqW±χ̃⁰₁ 1 e,μ 3-6 jets Yes 20 g̃ 1.2 TeV 1501.03555
g̃g̃, g̃→qq(ℓℓ/ℓν/νν)χ̃⁰₁ 2 e,μ 0-3 jets - 20 g̃ 1.32 TeV m(χ̃⁰₁)=0 GeV 1501.03555
GMSB (ℓ̃ NLSP) 1-2 τ + 0-1 ℓ 0-2 jets Yes 20.3 g̃ 1.6 TeV tanβ >20 1407.0603
GGM (bino NLSP) 2 γ - Yes 20.3 g̃ 1.28 TeV m(χ̃⁰₁)>50 GeV ATLAS-CONF-2014-001
GGM (wino NLSP) 1 e,μ + γ - Yes 4.8 g̃ 619 GeV m(χ̃⁰₁)>50 GeV ATLAS-CONF-2012-144
GGM (higgsino-bino NLSP) γ 1 b Yes 4.8 g̃ 900 GeV m(χ̃⁰₁)>220 GeV 1211.1167
GGM (higgsino NLSP) 2 e,μ (Z) 0-3 jets Yes 5.8 g̃ 690 GeV m(NLSP)>200 GeV ATLAS-CONF-2012-152
Gravitino LSP 0 mono-jet Yes 20.3 F^1/2 scale 865 GeV 1502.01518
3rd gen. g̃ med.
g̃→bb̄χ̃⁰₁ 0 3 b Yes 20.1 g̃ 1.25 TeV m(χ̃⁰₁)<400 GeV 1407.0600
g̃→tt̄χ̃⁰₁ 0 7-10 jets Yes 20.3 g̃ 1.1 TeV m(χ̃⁰₁) <350 GeV 1308.1841
1407.0600
1407.0600
3rd gen. squarks direct production
1308.2631
1404.2500
1209.2102, 1407.0583
1403.4853, 1412.4742
1407.0583,1406.1122
1407.0608
1403.5222
1403.5222
EW direct
1403.5294
1403.5294
1407.0350
1402.7029
1403.5294, 1402.7029
1501.07110
χ̃⁰₂χ̃⁰₃, χ̃⁰₂,₃ →ℓ̃_Rℓ 4 e,μ 0 Yes 20.3 χ̃⁰₂,₃ 620 GeV 1405.5086
Long-lived particles
Direct χ̃⁺₁χ̃⁻₁ prod., long-lived χ̃±₁ Disapp. trk 1 jet Yes 20.3 χ̃±₁ 270 GeV m(χ̃±₁)-m(χ̃⁰₁)=160 MeV, τ(χ̃±₁)=0.2 ns 1310.3675
Stable, stopped g̃ R-hadron 0 1-5 jets Yes 27.9 g̃ 832 GeV m(χ̃⁰₁)=100 GeV, 10 μs<τ(g̃)<1000 s 1310.6584
Stable g̃ R-hadron trk - - 19.1 g̃ 1.27 TeV 1411.6795
GMSB, stable τ̃, χ̃⁰₁→τ̃(ẽ,μ̃)+τ(e,μ) 1-2 μ - - 19.1 χ̃⁰₁ 537 GeV 10<tanβ<50 1411.6795
GMSB, χ̃⁰₁→γG̃, long-lived χ̃⁰₁ 2 γ - Yes 20.3 χ̃⁰₁ 435 GeV 2<τ(χ̃⁰₁)<3 ns, SPS8 model 1409.5542
q̃q̃, χ̃⁰₁→qqμ (RPV) 1 μ, displ. vtx - - 20.3 q̃ 1.0 TeV 1.5 <cτ<156 mm, BR(μ)=1, m(χ̃⁰₁)=108 GeV ATLAS-CONF-2013-092
RPV
LFV pp→ν̃_τ + X, ν̃_τ→e + μ 2 e,μ - - 4.6 ν̃_τ 1.61 TeV λ′₃₁₁=0.10, λ₁₃₂=0.05 1212.1272
LFV pp→ν̃_τ + X, ν̃_τ→e(μ) + τ 1 e,μ + τ - - 4.6 ν̃_τ 1.1 TeV λ′₃₁₁=0.10, λ₁(₂)₃₃=0.05 1212.1272
Bilinear RPV CMSSM 2 e,μ (SS) 0-3 b Yes 20.3 q̃, g̃ 1.35 TeV m(q̃)=m(g̃), cτ_LSP<1 mm 1404.2500
χ̃⁺₁χ̃⁻₁, χ̃⁺₁→Wχ̃⁰₁, χ̃⁰₁→eeν̃_μ, eμν̃_e 4 e,μ - Yes 20.3 χ̃±₁ 750 GeV m(χ̃⁰₁)>0.2×m(χ̃±₁), λ₁₂₁≠0 1405.5086
χ̃⁺₁χ̃⁻₁, χ̃⁺₁→Wχ̃⁰₁, χ̃⁰₁→ττν̃_e, eτν̃_τ 3 e,μ + τ - Yes 20.3 χ̃±₁ 450 GeV m(χ̃⁰₁)>0.2×m(χ̃±₁), λ₁₃₃≠0 1405.5086
g̃→qqq 0 6-7 jets - 20.3 g̃ 916 GeV BR(t)=BR(b)=BR(c)=0% ATLAS-CONF-2013-091
g̃→t̃₁t, t̃₁→bs 2 e,μ (SS) 0-3 b Yes 20.3 g̃ 850 GeV 1404.250
Other
Scalar charm, c̃→cχ̃⁰₁ 0 2 c Yes 20.3 c̃ 490 GeV m(χ̃⁰₁)<200 GeV 1501.01325
√s = 7 TeV full data
√s = 8 TeV partial data
√s = 8 TeV full data
10^-1
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.
No indication of SUSY ($ BSM)

Observed Higgs Mass 126 GeV

⇒ Severe constraints on MSSM parameter space (MSSM + light sparticles)

MSSM
+
heavy sparticles

Extension
of
MSSM

Observed Higgs Mass 126 GeV

Severe constraints on MSSM parameter space (MSSM + light sparticles)

MSSM + heavy sparticles

Dirac Gaugino scenario

Dirac Gaugino Scenario

Fox, Nelson & Weiner (2012)

Gauge sector: N=2 extension

→ adj. chiral superfields added

$$\Phi_{a=SU(3),SU(2),U(1)} = (\varphi_a, \psi_a, F_a)$$

Matter sector: N=1

Dirac gaugino masses from

$$\mathcal{L} = \int d^2\theta \sqrt{2}\, \frac{\mathcal{W}_\alpha^0 \mathcal{W}_a^\alpha \Phi_a}{\Lambda} = \frac{\langle D^0 \rangle}{\Lambda} \lambda_a \psi_a + \ldots$$

if $\langle D^0 \rangle \neq 0 \subset \mathcal{W}_\alpha^0 = \theta_\alpha D^0$ in hidden U(1)

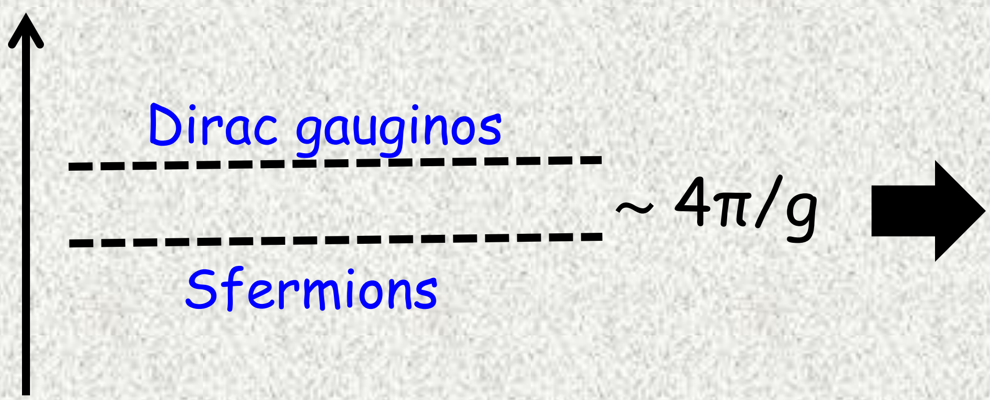
Once gaugino masses are generated at tree level, sfermion masses are generated by RGE effects

Sfermion masses @1-loop

$$M_{\tilde{f}}^2 \approx \frac{C_a(f)\alpha_a}{\pi} M_{\lambda_a}^2 \log\left[\frac{m_{\varphi_a}^2}{M_{\lambda_a}^2}\right]$$

(a = $SU(3)_C$, $SU(2)_L$, $U(1)_Y$)

Flavor blind ⇒ No SUSY flavor & CP problems



LHC bounds relaxed

(gluino/squark production suppressed)

Kribs & Martin (2012)

A New Mechanism of D-term Dynamical SUSY Breaking

Itoyama & NM (2012,2013)

SUSY U(N) gauge theory

with adjoint chiral supermultiplets

$$\mathcal{L} = \int d^4\theta K\left(\Phi^a, \bar{\Phi}^a, V\right) \quad \text{Kahler potential}$$

$$+ \int d^2\theta \, \mathrm{Im} \frac{1}{2} \mathcal{F}_{ab}\left(\Phi^a\right) \mathcal{W}^{a\alpha} \mathcal{W}_\alpha^b + \left[\int d^2\theta W\left(\Phi^a\right) + h.c. \right]$$

Gauge kinetic function　　Superpotential

SUSY U(N) gauge theory with adjoint chiral supermultiplets

$$\mathcal{L} = \int d^4\theta K\left(\Phi^a, \bar{\Phi}^a, V\right) \quad \text{Kahler potential}$$

$$+\int d^2\theta \, \mathrm{Im} \frac{1}{2} \mathcal{F}_{ab}\left(\Phi^a\right) \mathcal{W}^{a\alpha} \mathcal{W}^b_\alpha + \left[\int d^2\theta W\left(\Phi^a\right) + h.c.\right]$$

Gauge kinetic function

Superpotential

Fermion mass terms

$$\int d^2\theta \mathcal{F}_{ab}(\Phi) \mathcal{W}^{a\alpha} \mathcal{W}^b_\alpha \supset \mathcal{F}_{a0c}(\Phi) \psi^c \lambda^a D^0 + \mathcal{F}_{ab0}(\Phi) F^0 \lambda^a \lambda^b$$

Dirac gaugino mass

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

Fermion mass terms

Mixed Majorana-Dirac type masses

$$\int d^2\theta \mathcal{F}_{ab}(\Phi)\mathcal{W}^{a\alpha}\mathcal{W}^b_\alpha \supset \mathcal{F}_{a0c}(\Phi)\psi^c\lambda^a D^0 + \mathcal{F}_{ab0}(\Phi)F^0\lambda^a\lambda^b$$

Dirac mass

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

<F>=0 assumed

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

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

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

$$D \equiv -\frac{\sqrt{2}}{4} \mathcal{F}_{0aa} D^0$$

Gaugino(m_) becomes massive by nonzero <D>

⇒ SUSY is broken

D-term equation of motion:

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

Dirac bilinears condensation

The value of $\langle D^0 \rangle$ will be determined by **the gap equation**

Potential analysis

3 constant background fields:

$$\varphi \equiv \varphi^0 , D \equiv D^0 , F \equiv F^0$$

Work in the region where $\langle F^0 \rangle \ll \langle D^0 \rangle$ and perturbative

$$\frac{\partial V\left(D,\varphi,\bar{\varphi},F=\bar{F}=0\right)}{\partial D}=0$$

$$\frac{\partial V\left(D,\varphi,\bar{\varphi},F=\bar{F}=0\right)}{\partial \varphi}=0$$

$\Rightarrow$ gap equation

Stationary values $\left(D_*,\varphi_*,\bar{\varphi}_*\right)$

$$\left.\frac{\partial V\left(D=D_*\left(F,\bar{F}\right),\varphi=\varphi_*\left(F,\bar{F}\right),\bar{\varphi}=\bar{\varphi}_*\left(F,\bar{F}\right),F,\bar{F}\right)}{\partial F}\right|_{D,\varphi,\bar{\varphi},\bar{F}\ \text{fixed}}=0$$

$\Rightarrow \left(F_*,\bar{F}_*\right)$

D-term effective potential@1-loop

$$V = N^2 \left| m_\varphi \right|^4 \Big[c_1(\varphi,\bar{\varphi}) \Delta_0^2 \longleftarrow \text{Tree}$$

$$+ \frac{1}{32\pi^2} \left(c_2 \Delta_0^4 - \left|\lambda^{(+)}\right|^4 \log\left|\lambda^{(+)}\right|^2 - \left|\lambda^{(-)}\right|^4 \log\left|\lambda^{(-)}\right|^2 \right) \Big]$$

$$\lambda^{(\pm)} = \frac{1}{2}\left(1 \pm \sqrt{1+\Delta_0^2}\right),\ \Delta_0 \approx \frac{\mathcal{F}'''}{W''} \left\langle D^0 \right\rangle$$

C_2: constants

1-loop part = CW potential

gauge + adjoint chiral superfield contributions

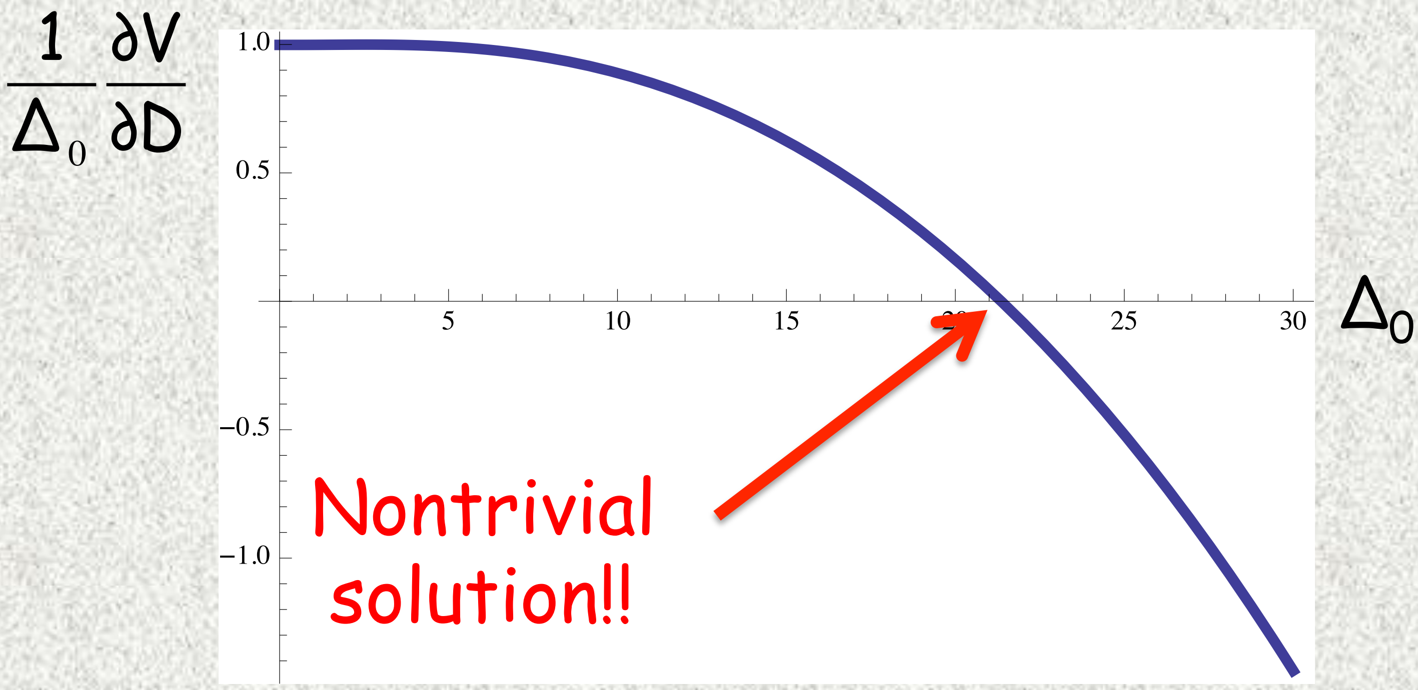
Gap equation

$$0 = \left.\frac{\partial V}{\partial D}\right|_{\varphi,\bar{\varphi}}$$

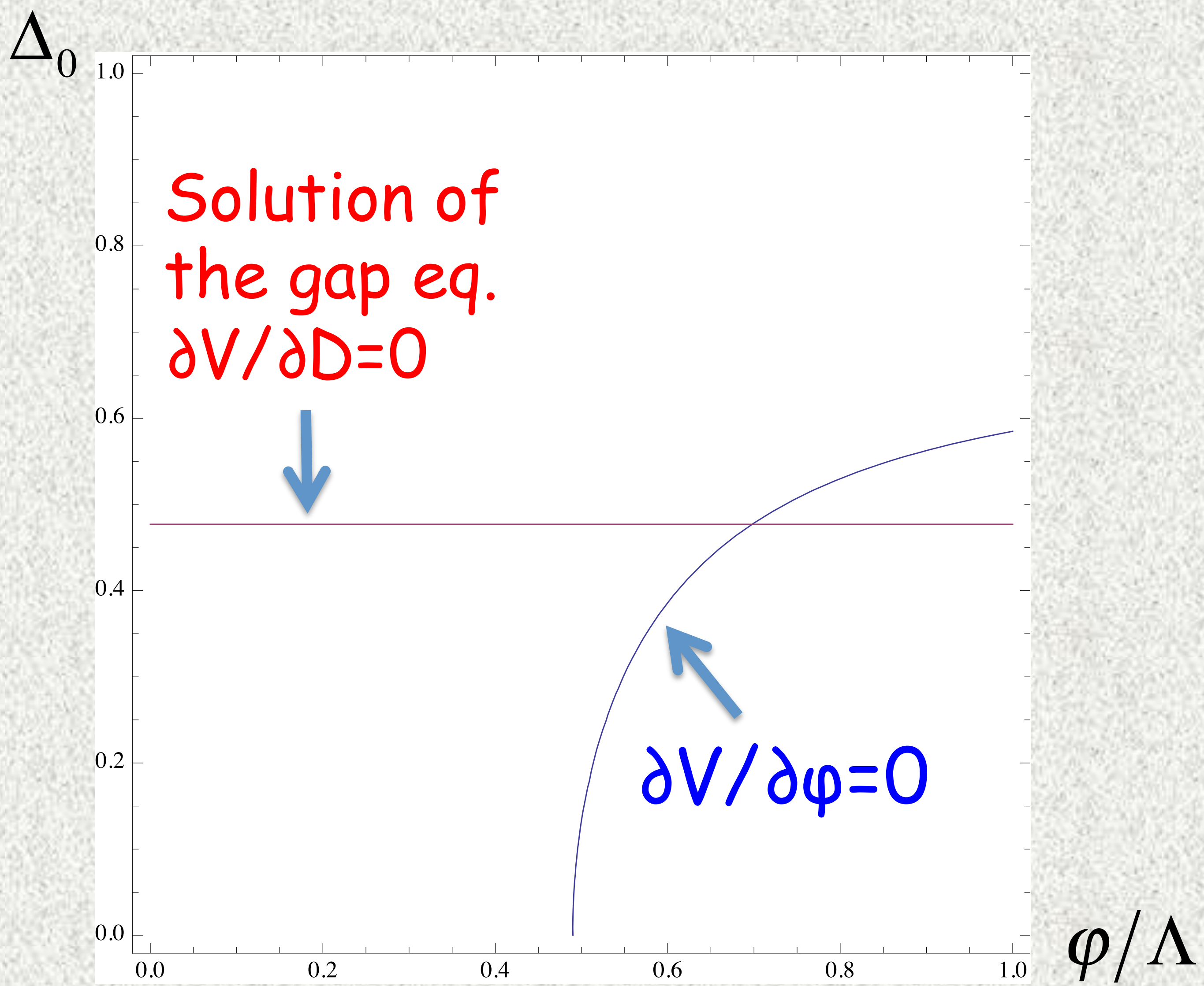
Trivial solution Δ_0=0 is NOT lifted

$$= \Delta_0 \left[c_1 + \frac{1}{64\pi^2} \left\{ 4c_2\Delta_0^2 - \frac{1}{\sqrt{1+\Delta_0^2}} \left\{ \lambda^{(+)3} \left(2\log\lambda^{(+)2} + 1 \right) - \lambda^{(-)3} \left(2\log\lambda^{(-)2} + 1 \right) \right\} \right\} \right]$$

Itoyama & NM (2012)



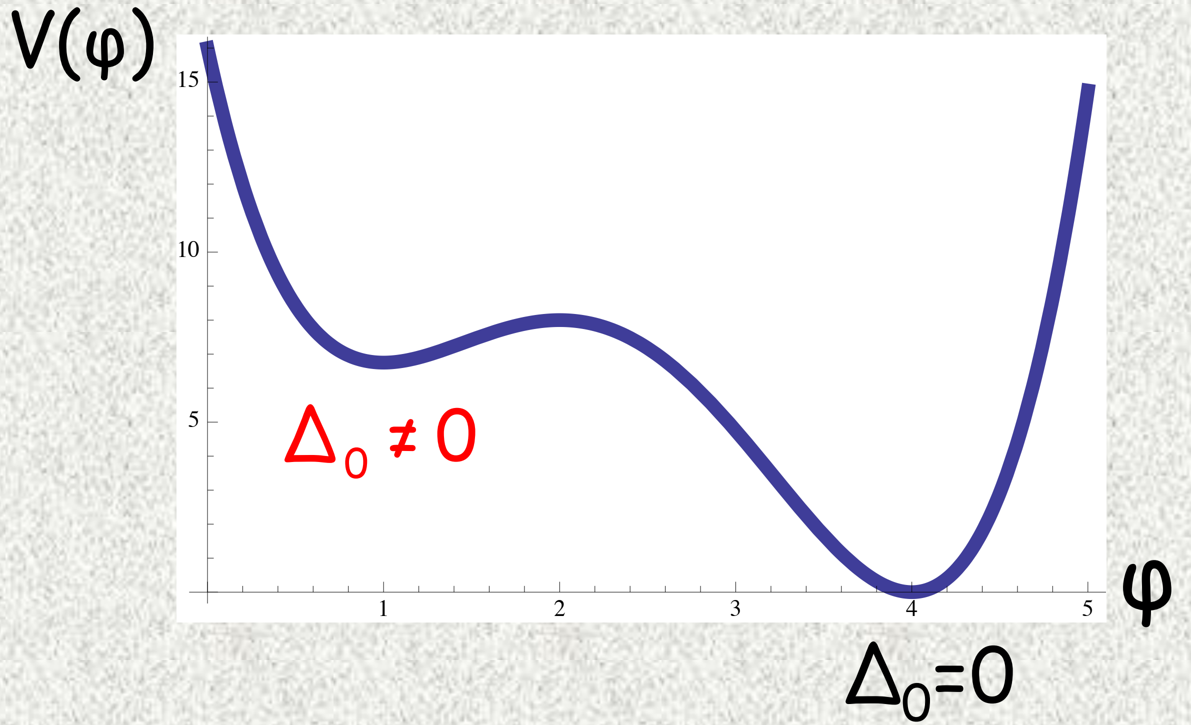
$(\Delta_{0*}, \varphi_* = \bar{\varphi}_*)$ determined as the intersection point of two real curves in the $(\Delta_{0*}, \varphi = \bar{\varphi})$ plane



$E \geqq 0$ in SUSY

⇒ Trivial solution Δ_0=0 is NOT lifted

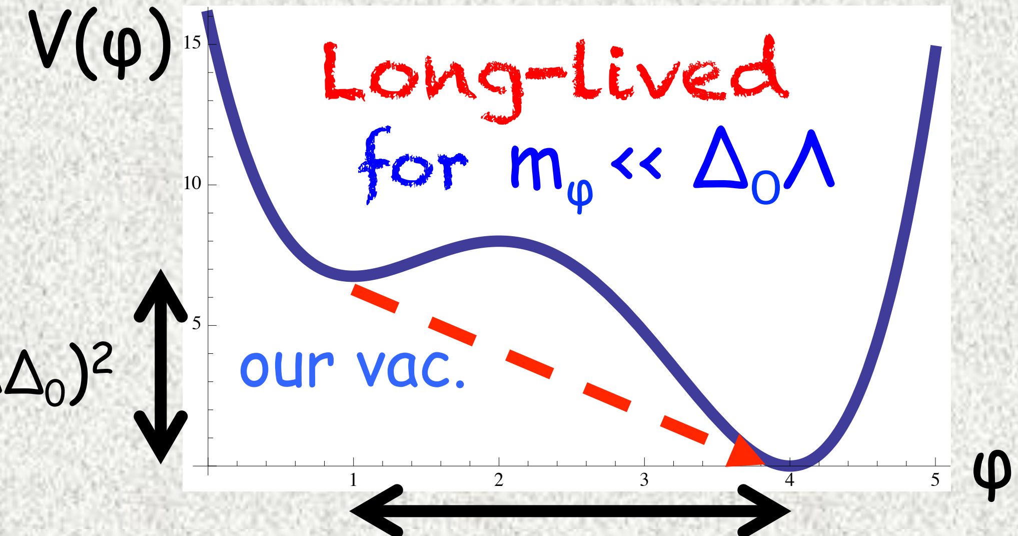
⇒ Our SUSY breaking vac. is a local min.



Metastability of our false vacuum

<D> = 0 vacuum is not lifted

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



$\Delta V \sim (m_\varphi \Lambda\Delta_0)^2$

$\Delta\varphi \sim \Delta_0\Lambda$ (Λ: cutoff scale)

Coleman & De Luccia(1980)

Decay rate of our vacuum

$$\propto \exp\left[-\frac{\langle\Delta\phi\rangle^4}{\langle\Delta V\rangle}\right] \approx \exp\left[-\frac{(\Delta_0\Lambda)^2}{m_\varphi^2}\right] \ll 1$$

$\Delta_0\Lambda \gg m_\varphi$

Numerical samples of solutions for the gap equation & the stationary condition for φ

$c' + \frac{1}{64\pi^2}$	$\tilde{A}/(4\cdot 32\pi^2)$	Δ_{0*}	φ_*/M $(-\frac{N^2}{\mathrm{Im}(i+\Lambda)})$	$\|F_*/D_*\|$	$\|f_{3*}\|$
0.002	0.0001	0.477	0.707 (10000)	2.621 $(m = M)$	1.77
0.002	0.0001	0.477	0.707 (10000)	0.524 $(m \ll M)$	0.35
0.002	0.0001	0.477	0.707 (10000)	0.860 $(m = 0.4M)$	0.58
0.003	0.001	1.3623	0.8639 (2000)	0.825 $(m = M)$	>1
0.003	0.001	1.3623	0.8639 (2000)	0.224 $(m \ll M)$	0.43
0.003	0.001	1.3623	0.5464 (5000)	1.092 $(m = M)$	>1
0.003	0.001	1.3623	0.5464 (5000)	0.142 $(m \ll M)$	0.27
0.003	0.001	1.3623	0.5464 (5000)	0.911 $(m = 0.9M)$	1.76
0.003	0.001	1.3623	0.3863 (10000)	1.444 $(m = M)$	>1
0.003	0.001	1.3623	0.3863 (10000)	0.100 $(m \ll M)$	0.19
0.003	0.001	1.3623	0.3863 (10000)	0.960 $(m = 0.8M)$	1.85

Higgs Mass via D-term Effects

Itoyama & NM (2013)

Higgs Lagrangian

$$\mathcal{L}_{Higgs} = \int d^4\theta \left[H_u^\dagger e^{-g_Y V_1 - g_2 V_2 - 2 q_u g V_0} H_u + H_d^\dagger e^{g_Y V_1 - g_2 V_2 - 2 q_d g V_0} H_d \right]$$
$$+ \left[\left(\int d^2\theta \mu H_u H_d \right) - B\mu H_u H_d + h.c. \right]$$

$H_{u,d}$ with U(1) charges $q_{u,d}$ assumed

μ-term → $q_u + q_d = 0$

$\langle V_0 \rangle = \theta^4 \langle D^0 \rangle$ → additional Higgs mass@tree

Higgs potential

$$V_H = \frac{g_2^2}{2\left(1+\mathrm{Im}\,\mathcal{F}_{0YY}\langle\varphi^0\rangle\right)}\sum_a\left(H_u^\dagger\frac{\sigma^a}{2}H_u + H_d^\dagger\frac{\sigma^a}{2}H_d\right)^2$$

$$+\frac{g_Y^2}{8\left(1+\mathrm{Im}\,\mathcal{F}_{0YY}\langle\varphi^0\rangle\right)}\left(|H_u|^2-|H_d|^2\right)^2$$

$$+\frac{1}{2\left(1+\mathrm{Im}\,\mathcal{F}_{0YY}\langle\varphi^0\rangle\right)}\left(q_u g|H_u|^2+q_d g|H_d|^2-\langle D^0\rangle\right)^2$$

$$+|\mu|^2\left(|H_u|^2+|H_d|^2\right)+\left(B\mu H_u H_d + h.c.\right)$$

$$\simeq\frac{g_2^2+g_Y^2}{8}\left(|H_u^0|^2-|H_d^0|^2\right)^2+\frac{1}{2}\left(q_u g|H_u^0|^2+q_d g|H_d^0|^2-\langle D^0\rangle\right)^2$$

$$+|\mu|^2\left(|H_u^0|^2+|H_d^0|^2\right)-\left(B\mu H_u^0 H_d^0 + h.c.\right)$$

$\mathrm{Im}\,\mathcal{F}_{0YY}\langle\varphi^0\rangle \approx \langle\varphi^0\rangle/\Lambda \ll 1$

Higgs mass

$$m_{Higgs}^2 = \frac{1}{2}\left[\tilde{M}_Z^2 + M_A^2 - \sqrt{\left(\tilde{M}_Z^2 + M_A^2\right)^2 - 4\tilde{M}_Z^2 M_A^2 \cos^2 2\beta}\right]$$

$$\tilde{M}_Z^2 \equiv M_Z^2 + q_u^2 g^2 v^2 : q_u = 0 \Rightarrow m_{Higgs}^2 = m_{MSSM\ Higgs}^2$$

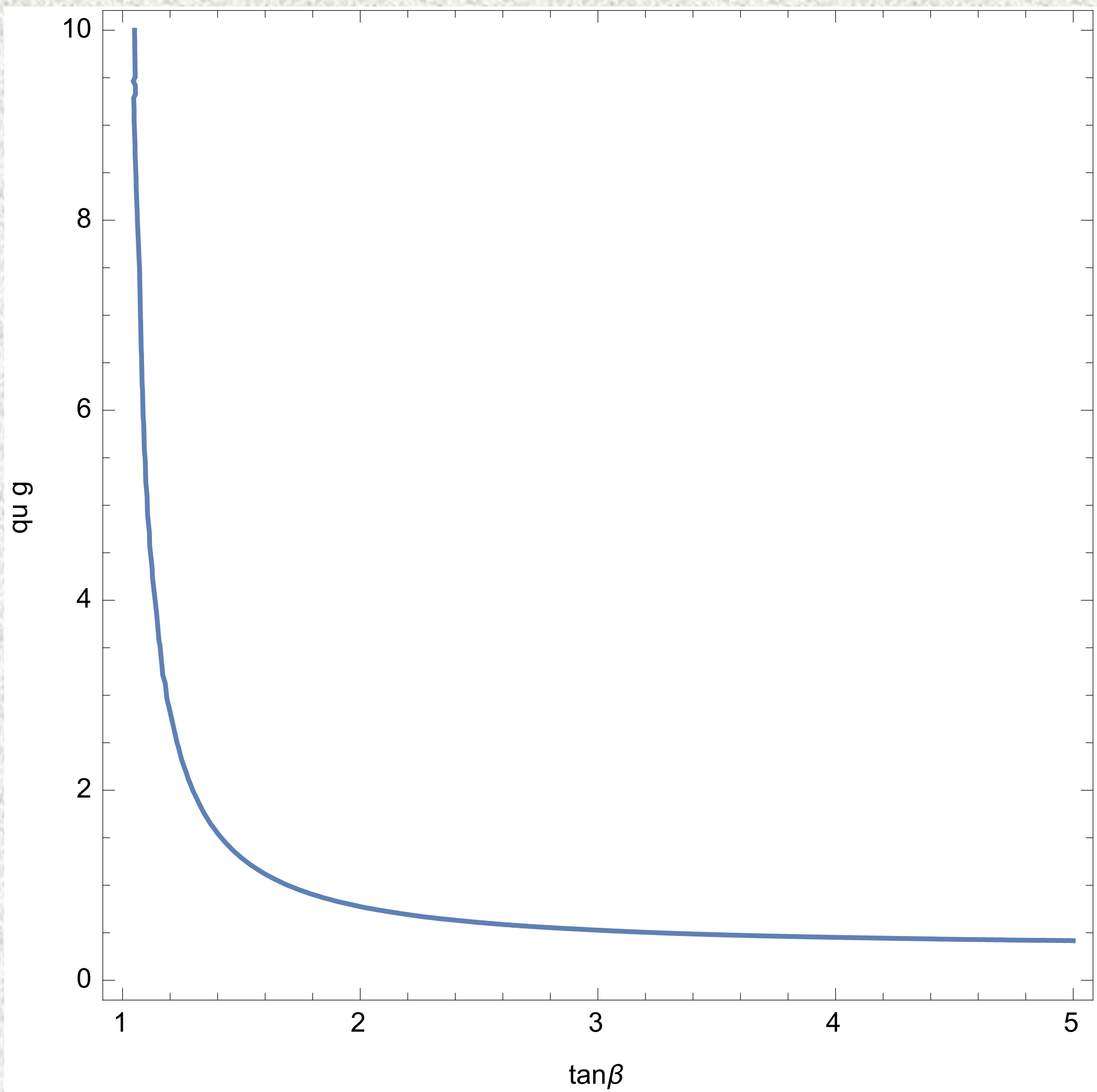
Minimization conditions

$$\mu^2 + \frac{M_Z^2}{2} = \frac{q_u g}{\cos 2\beta}\left(-q_u g v^2 \cos 2\beta - 2\left\langle D^0 \right\rangle\right)$$

$$M_A^2 \equiv \frac{2B\mu}{\sin 2\beta} = 2\mu^2 = -M_Z^2 - \frac{q_u g}{\cos 2\beta}\left(-q_u g v^2 \cos 2\beta - 2\left\langle D^0 \right\rangle\right)$$

$$m_{Higgs}^2 = \frac{1}{2}\left[-\frac{2q_u g}{\cos 2\beta}\left\langle D^0 \right\rangle - \sqrt{\left(-\frac{2q_u g}{\cos 2\beta}\left\langle D^0 \right\rangle\right)^2 + 8q_u g\left\langle D^0 \right\rangle \tilde{M}_Z^2 \cos 2\beta + 4\tilde{M}_Z^4 \cos^2 2\beta}\right]$$

A plot for 126 GeV Higgs



Summary

- Dirac gaugino scenario is one of the interesting alternatives
- A new dynamical mechanism of D-term DSB proposed
- 126 GeV Higgs mass possible via D-term tree level effects

Work in progress
(w/ Itoyama & Shindou)

Possibility of 126 GeV Higgs mass via top-stop loop effects