Reconcile Muon g-2 Anomaly With LHC Discoveries

郑州大学

王 飞

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- 125 GeV higgs discovered by LHC at 2012.
- Fill the last missing piece of SM.
- Problems Related To SM:

1) Hierarchy Problems.
2) Vacuum Stability problem.
3) Triviality of fundamental scalar.
4) The origin of gauge, flavor structure.
5) No dark matter candidates
6) Neutrino mass.

...

Low Energy Supersymmetry

- An elegant extension of SM is SUSY.
- Many advantages:

1. Quadratic divergence of higgs mass eliminated by introducing superpartners.
2. Natural dark matter candidates.
3. Genuine gauge coupling unification.
4. Exactly solve many strong coupling system.
5. Radiative EWSB.

SUSY Spectrum

- SUSY requires degenerate mass for particle and its superpartner.
- So SUSY must be broken.
- No Superpartners had been observed.
- Not easily to be compatible with 125 GeV higgs.

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right],$$

SUSY Breaking Mechanism

- SUSY spectrum determined by different SUSY breaking mechanism.
- Compatible with LHC discovery
- Not much fine tuning
- Successful EWSB
- Neutralino LSP
- Mediation mechanism

1. mSUGRA
2. GMSB
3. Anomaly mediation
4. gaugino mediation ....

Anomaly Mediation Mechanism

- Superconformal anomaly
- Pure gravity contributions
- Sparticle spectrum flavor blind and no flavor problem
- Sequestered---No contact term between the hidden sector and the visible sector
- In supergravity formalism with the introduction of the superweyl compensator field

$$\Phi \equiv 1 + F\theta^2 .$$

- Weyl invariant action

$$\int d^4\theta \phi\phi^\dagger \mathcal{K}\left(\frac{\phi^{1/2}}{\phi^\dagger}D_\alpha, \frac{Q}{\phi}, \frac{W_\alpha}{\phi^{3/2}}, V\right) + \mathrm{Re}\int d^2\theta \phi^3 \mathcal{W}\left(\frac{Q}{\phi}, \frac{W_\alpha}{\phi^{3/2}}\right),$$

- the soft term can be collected into the wave function superfield

$$\ln \mathcal{Z}_i(\mu) = \ln Z_i(\mu) + \left(A_i(\mu)\theta^2 + \mathrm{h.c.}\right) - m_i^2(\mu)\theta^2\bar{\theta}^2 .$$

with

$$A_i(\mu) = -\frac{\gamma_i(\mu)}{2}F_\phi ,$$

$$m_i^2(\mu) = -\frac{\dot{\gamma}_i(\mu)}{4}|F_\phi|^2 .$$

after replacement $\mathcal{Z}_i(\mu) = Z_i\left(\frac{\mu}{\sqrt{\phi\phi^\dagger}}\right)$

Similarly for gauge fields $R(\mu) = \frac{1}{g^2(\mu)} - 2\mathrm{Re}\left(\frac{m_\lambda}{g^2}(\mu)\theta^2\right) + R_D\theta^2\bar{\theta}^2 ,$

which lead to gaugino soft masses after similar replacement

$$m_\lambda = \frac{g^2}{2}\frac{dg^{-2}}{d\ln\mu}F_\phi = -\frac{\beta(g^2)}{2g^2}F_\phi$$

Properties of AMSB

- Very predictive--one parameter F_ϕ
- flavor blind
- mu-problems ---additional mechanism
- tachyonic slepton--many solutions

1. additional interactions for sleptons
2. new gauge interactions for leptons
3. large yukawa couplings
4. most elegant one:

   deflected anomaly mediation

Deflected Anomaly Mediation

- introduce new messengers to deflect RGE trajectory
- Failed for ordinary threshold-decouple.
- new light singlet X must be present

$$W = \lambda X \Psi \bar{\Psi} + \frac{X^n}{\Lambda^{n-3} \phi^{n-3}} ,$$

- Low energy wave function depends on the threshold $\tilde{X} \equiv X/\phi,$

with the soft parameters

$$\begin{aligned}
\frac{m_\lambda(\mu)}{g^2(\mu)} &= \frac{F_\phi}{2} \left(\frac{\partial}{\partial \ln \mu} + \frac{2}{n-1} \frac{\partial}{\partial \ln |X|} \right) \frac{1}{g^2(\mu, X)} , \\
A_i(\mu) &= -\frac{F_\phi}{2} \left(\frac{\partial}{\partial \ln \mu} + \frac{2}{n-1} \frac{\partial}{\partial \ln |X|} \right) \ln Z_i(\mu, X) , \\
m_i^2(\mu) &= -\frac{|F_\phi|^2}{4} \left(\frac{\partial}{\partial \ln \mu} + \frac{2}{n-1} \frac{\partial}{\partial \ln |X|} \right)^2 \ln Z_i(\mu, X) .
\end{aligned}$$

- new contributions to slepton masses.
- typical spectrum with $\frac{F_{\tilde{X}}}{\tilde{X}}$=-$F_\phi$

$$
\begin{aligned}
m_\lambda(\mu) &= \frac{\alpha(\mu)}{4\pi}(b-N)F_\phi\,, \\
A_i(\mu) &= -\frac{2c_i}{4\pi}\left[\alpha(\mu)+[\alpha(X)-\alpha(\mu)]\frac{N}{b}\right]F_\phi\,, \\
m_i^2(\mu) &= \frac{2c_i b}{(4\pi)^2}\left[\alpha^2(\mu)-\alpha^2(\mu)\frac{N}{b}+[\alpha^2(\mu)-\alpha^2(X)]\frac{N^2}{b^2}\right]|F_\phi|^2\,.
\end{aligned}
$$

- free parameters: $N,\ d,\ M_{\mathrm{Mess}},\ F_\phi,\ \tan\beta,$
- Draw back:

  1. ordinary negative d,

  2. spoil flavor no-dependence below messenger threshold--upper limit for such thresholds
- Positively deflected scenario

  lead to positive d by chosing fractional n.

Positively Deflected AMSB from SUSY QCD

- SU(N_c) SUSY QCD with N_F flavor

require N_c+1<N_F<3N_c

global symmetry of the theory: $SU(N_F)_L \times SU(N_F)_R \times U(1)_V \times U(1)_R.$

Matter contentes:

$$Q_i \sim (N, N_F, \ 1, \ 1, (N_F - N)/N_F), \quad \tilde{Q}_j \sim (\bar{N}, \ 1, \bar{N}_F, -1, (N_F - N)/N_F) \ ,$$

- introduce ISS-type superpotential $W = Tr(m_0 \tilde{Q}_i Q_i)$

Use Seiberg duality, the dual description is a SU(N_F-N_c) gauge theory with the following superpotential

$$W = -h\mu^2 Tr\Phi + hTrq\Phi\tilde{q} \ ,$$

with $q, \tilde{q}$ and Φ related to the dual baryon B and meson M, respectively.

We will not consider the metastable vauca, SUSY breaking from anomaly mediation. Concentrate on the SUSY preserving vauca at large field value.

- Integrate the messenger, we have

$$W_l = N_c(h^{N_F}\Lambda_m^{3N_c-N_F}\det\Phi)^{1/N_c} - h\mu^2 Tr(\Phi)\ .$$

- Adding compensator field, we can obtain the tree-level potential

$$V = |F_{\Phi_i^j}|^2 - N_c(h^{N_F}\Lambda_m^{3N_c-N_F}\det\Phi)^{1/N_c}(3-\frac{N_F}{N_c})F_\phi + 2h\mu^2 F_\phi Tr(\Phi)\ ,$$

- The minimum condition for $\langle\Phi\rangle \propto \tilde{m}\delta_i^j$ gives

$$2\left(N_F\Lambda_m^{3-N_F/N_c}m^{N_F/N_c-1} - \mu^2 N_F\right)(N_F/N_c-1)N_F\Lambda_m^{3-N_F/N_c}m^{N_F/N_c-2}$$
$$-\ N_F\Lambda_m^{3-N_F/N_c}m^{N_F/N_c-1}(3-\frac{N_F}{N_c})F_\phi + 2\mu^2 N_F F_\phi = 0.$$

- For large N_c=N_F-N_C with $N_c/N_F \to 1$, we have a negative deflection scenario with

$$\frac{F_\Phi}{\Phi} = -\frac{h^2 N_F(\Lambda_m^2-\mu^2)F_\phi}{(N_F-N_c)\Lambda_m^2} \approx -\frac{h^2 N_F}{(N_F-N_c)}F_\phi,$$

- The limit N_F-->3N_C which is $N_F/N_c \to 3/2$ in the dual theory, we have

$$m \approx \frac{4}{9} N_F^2 \Lambda_m^3 / F_\phi^2$$

and the (still negative) deflection parameters

$$\frac{F_{\tilde{\Phi}}}{\tilde{\Phi}} = \frac{F_\Phi}{\Phi} - F_\phi \approx -(\frac{3}{2}h^2 + 1)F_\phi.$$

- In the limit N_F-->3/2 N_c which is $N_F/N_c \to 3$ in the dual theory, we can have

$$\begin{aligned} \frac{F_\Phi}{\Phi} &= -\frac{h^2 N_F (m^2 - \mu^2)}{m} \equiv c h^2 F_\phi, \\ &\approx 0.53 h^2 N_F \mu \approx 0.26 h^2 F_\phi, \qquad \text{when } m \approx -1.3\mu, F_\phi = 2N_F\mu, \\ &\approx 0.04 h^2 N_F \mu \approx 0.4 h^2 F_\phi, \qquad \text{when } m \approx -1.02\mu, F_\phi = 0.1 N_F \mu, \end{aligned}$$

So the deflection parameters $d \equiv \frac{F_{\tilde{\Phi}}}{\tilde{\Phi} F_\phi} = \frac{F_\Phi}{\Phi F_\phi} - 1 \approx c h^2 - 1.$

with 0<c<1. So d can be positive for large h.

- Smooth tranisition between positive and negative deflection parameter in SUSY QCD.
- No need to introduce additional messenger sector--appear automatically from Seiberg dual.
- More easily to realize positive slepton masses with less messenger numbers.
- Can split the gaugino hierarchy.

Muon g-2 anomaly

- anomalous magnetic moment for muon is

$$a_\mu \equiv \frac{g_\mu - 2}{2} , \quad \vec{\mu}_\mu = g_\mu \left(\frac{Qe}{2m_\mu} \right) \vec{S} ,$$

- with the SM predictions

$$a_\mu^{\rm SM}[e^+e^-] = 116591834(49) \times 10^{-11} ,$$

- Experimental results of Brookhaven AGS

$$a_\mu = 116592089(63) \times 10^{-11} .$$

- The different

$$\Delta a_\mu \equiv a_\mu(\exp) - a_\mu(\rm SM) = (28.6 \pm 8.0) \times 10^{-10}$$

has a 3 sigma deviation.

Many solutions....

SUSY contributions to muon g-2

- Dominantly chargino-sneutrino loop and neutralino smuon loop

$$\Delta a_\mu(\tilde{W},\tilde{H},\tilde{\nu}_\mu) \simeq 15\times 10^{-9}\left(\frac{\tan\beta}{10}\right)\left(\frac{(100\mathrm{GeV})^2}{\mu\ M_2}\right)\left(\frac{f_C}{1/2}\right),$$

$$\Delta a_\mu(\tilde{W},\tilde{H},\tilde{\mu}_L) \simeq -2.5\times 10^{-9}\left(\frac{\tan\beta}{10}\right)\left(\frac{(100\mathrm{GeV})^2}{\mu\ M_2}\right)\left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{B},\tilde{H},\tilde{\mu}_L) \simeq 0.76\times 10^{-9}\left(\frac{\tan\beta}{10}\right)\left(\frac{(100\mathrm{GeV})^2}{\mu\ M_1}\right)\left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{B},\tilde{H},\tilde{\mu}_R) \simeq -1.5\times 10^{-9}\left(\frac{\tan\beta}{10}\right)\left(\frac{(100\mathrm{GeV})^2}{\mu\ M_1}\right)\left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{\mu}_L,\tilde{\mu}_R,\tilde{B}) \simeq 1.5\times 10^{-9}\left(\frac{\tan\beta}{10}\right)\left(\frac{(100\mathrm{GeV})^2(\mu\ M_1)}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2}\right)\left(\frac{f_N}{1/6}\right),$$

- Need low SUSY scale O(100 GeV) to account for muon g-2

LHC discoveries

- Null search results of new particles

$$\mathcal{B}r\left(B_s^0 \to \mu^+\mu^-\right) = \left(3.2^{+1.5}_{-1.2}\right) \times 10^{-9},$$

in excellent agreements with SM predictions.
SUSY contributions must very small.
Contribution mediated by flavor changing squarks loop.

- Possibly excess of diphoton rate not disapperar

$$R_{\gamma\gamma} = \frac{\sigma(pp \to H)_{\rm obs}}{\sigma(pp \to H)_{\rm SM}} \times \frac{\Gamma(H \to \gamma\gamma)_{\rm obs}}{\Gamma(H \to \gamma\gamma)_{\rm SM}}$$

$$\mu_{\gamma\gamma} = 1.14^{+0.26}_{-0.23} \quad \text{CMS}$$

$$\mu_{\gamma\gamma} = 1.17 \pm 0.27 \quad \text{ATLAS}$$

largest contributions from stau triangle. So may be light.

- Apparently conflict with the scale of SUSY
- Also possible that SUSY spectrum is not ordinary:

sleptons are light

colord particles are heavy.

not heavy Bino,Wino,higgsino to give DM.

Many realization:

1. gluino SUGRA

Sujeet Akula, Pran Nath,Phys. Rev. D 87, 115022 (2013)

Fei Wang, Wenyu Wang, Jin Min Yang, JHEP 1506 (2015) 079

2. EWSUSY

Tianjun Li, Shabbar Raza,Phys. Rev. D 91, 055016 (2015)

3. Generalized Natural SUSY

B. Paul Padley, Kuver Sinha, Kechen Wang, 1505.05877

We realize such spectrum from positively deflected AMSB scenario.

- Chose different deflection parameter with different messenger numbers.
- The whole spectrum at messenger scale:

$$\frac{m^2_{\tilde{Q}_L}}{|F_\phi|^2} = \frac{\alpha_3^2(M)}{(4\pi)^2} 8G_3 - \frac{\alpha_2^2(M)}{(4\pi)^2}\frac{3}{2}G_2 - \frac{\alpha_1^2(M)}{(4\pi)^2}\frac{11}{50}G_1,$$

$$\frac{m^2_{\tilde{U}^c_L}}{|F_\phi|^2} = \frac{\alpha_3^2(M)}{(4\pi)^2} 8G_3 - \frac{\alpha_1^2(M)}{(4\pi)^2}\frac{88}{25}G_1, \qquad m_{\lambda_i}(M) = \frac{\alpha_i(M)}{4\pi}F_\phi(b_i + dN_F),$$

$$\frac{m^2_{\tilde{D}^c_L}}{|F_\phi|^2} = \frac{\alpha_3^2(M)}{(4\pi)^2} 8G_3 - \frac{\alpha_1^2(M)}{(4\pi)^2}\frac{22}{25}G_1, \qquad G_i = \left(\frac{N_F}{b_i} - \frac{N_F^2}{b_i^2}\right)d^2 + \left(\frac{N_F}{b_i}d + 1\right)^2,$$

$$\frac{m^2_{\tilde{L}_L}}{|F_\phi|^2} = -\frac{\alpha_2^2(M)}{(4\pi)^2}\frac{3}{2}G_2 - \frac{\alpha_1^2(M)}{(4\pi)^2}\frac{99}{50}G_1,$$

$$\frac{m^2_{\tilde{E}^c_L}}{|F_\phi|^2} = -\frac{\alpha_1^2(M)}{(4\pi)^2}\frac{198}{25}G_1, \qquad \frac{m^2_{\tilde{H}_d}}{|F_\phi|^2} = \frac{m^2_{\tilde{L}_L}}{|F_\phi|^2},$$

$$\frac{m^2_{\tilde{H}_u}}{|F_\phi|^2} = \frac{m^2_{\tilde{L}_L}}{|F_\phi|^2} - 3\frac{y_t^2}{(16\pi^2)^2}\left(\frac{16}{3}g_3^2 + 3g_2^2 + \frac{13}{15}g_1^2 - 6y_t^2\right),$$

- The third generation:

$$\frac{m^2_{\tilde{Q}_{L,3}}}{|F_\phi|^2} = \frac{m^2_{\tilde{Q}_L}}{|F_\phi|^2} - \frac{y_t^2}{(16\pi^2)^2}(\frac{16}{3}g_3^2 + 3g_2^2 + \frac{13}{15}g_1^2 - 6y_t^2) \ ,$$

$$\frac{m^2_{\tilde{t}^c_L}}{|F_\phi|^2} = \frac{m^2_{\tilde{U}^c_L}}{|F_\phi|^2} - 2\frac{y_t^2}{(16\pi^2)^2}(\frac{16}{3}g_3^2 + 3g_2^2 + \frac{13}{15}g_1^2 - 6y_t^2) \ ,$$

$$\frac{A_t}{\frac{F_\phi}{2\pi}} = -\frac{8}{3}\alpha_3(M) - \frac{3}{2}\alpha_2(M) - \frac{13}{30}\alpha_1(M) + \frac{1}{8\pi}\left(6|y_t(M)|^2 + |y_b(M)|^2\right) ,$$

$$\frac{A_b}{\frac{F_\phi}{2\pi}} = -\frac{8}{3}\alpha_3(M) - \frac{3}{2}\alpha_2(M) - \frac{7}{30}\alpha_1(M) + \frac{1}{8\pi}\left(|y_t(M)|^2 + 6|y_b(M)|^2 + |y_\tau(M)|^2\right)$$

$$\frac{A_\tau}{\frac{F_\phi}{2\pi}} = -\frac{3}{2}\alpha_2(M) - \frac{9}{10}\alpha_1(M) + \frac{1}{8\pi}\left(3|y_b(M)|^2 + 4|y_\tau(M)|^2\right) ,$$

- Scan the parameters to solve the discrepancy:

Input: $10\text{TeV} < F_\phi < 600\text{TeV}.$ $\quad 50 \geq \tan\beta \geq 1$

$N_F \geq 4$ and $3 \geq d \geq -3.$

messenger scale 10TeV< M<10^{16} GeV.

- higgs mass bound

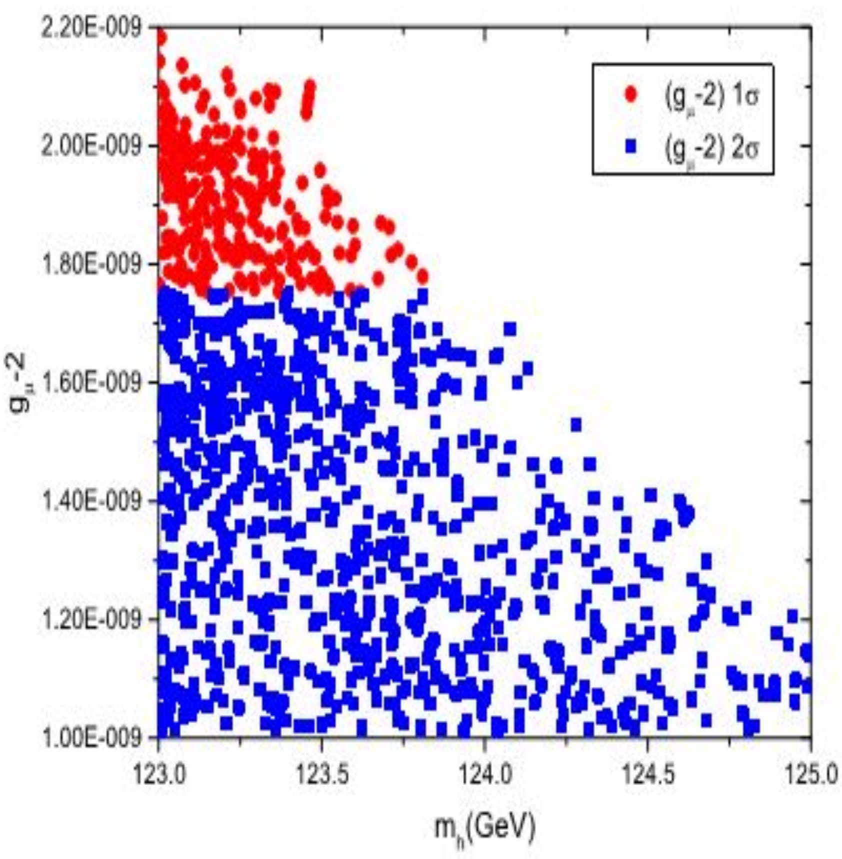
$$123\text{GeV} < M_h < 127\text{GeV}$$

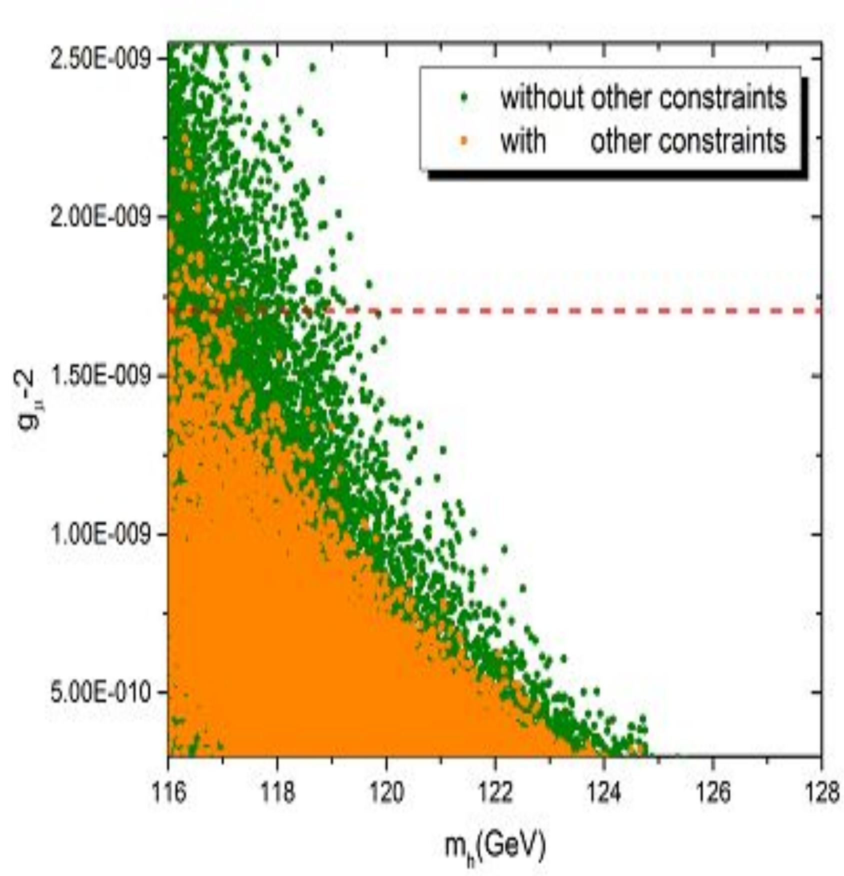
- dark matter relic density

$$\Omega_{DM} = 0.1199 \pm 0.0027$$

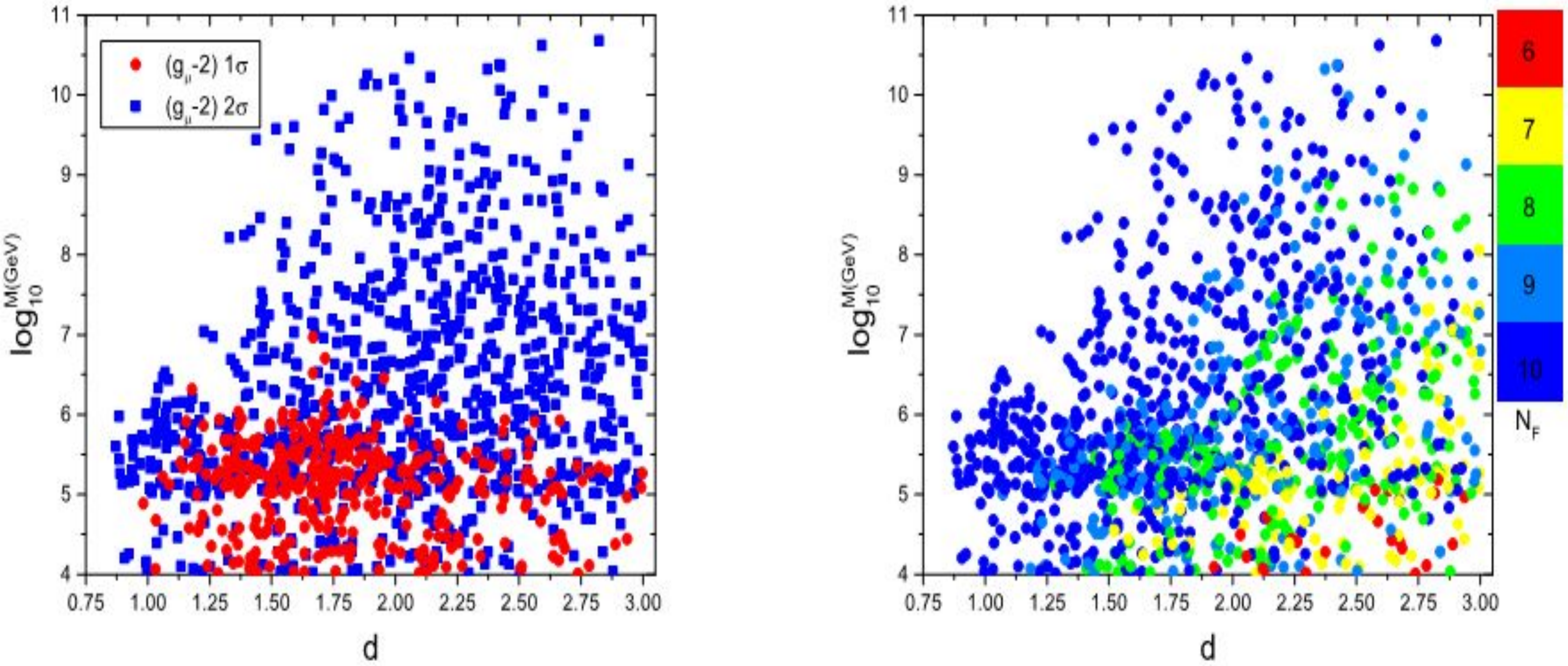
- precision measurement.
- LEP lower bound.
- positive slepton masses
- solve the muon g-2 discrepancy.

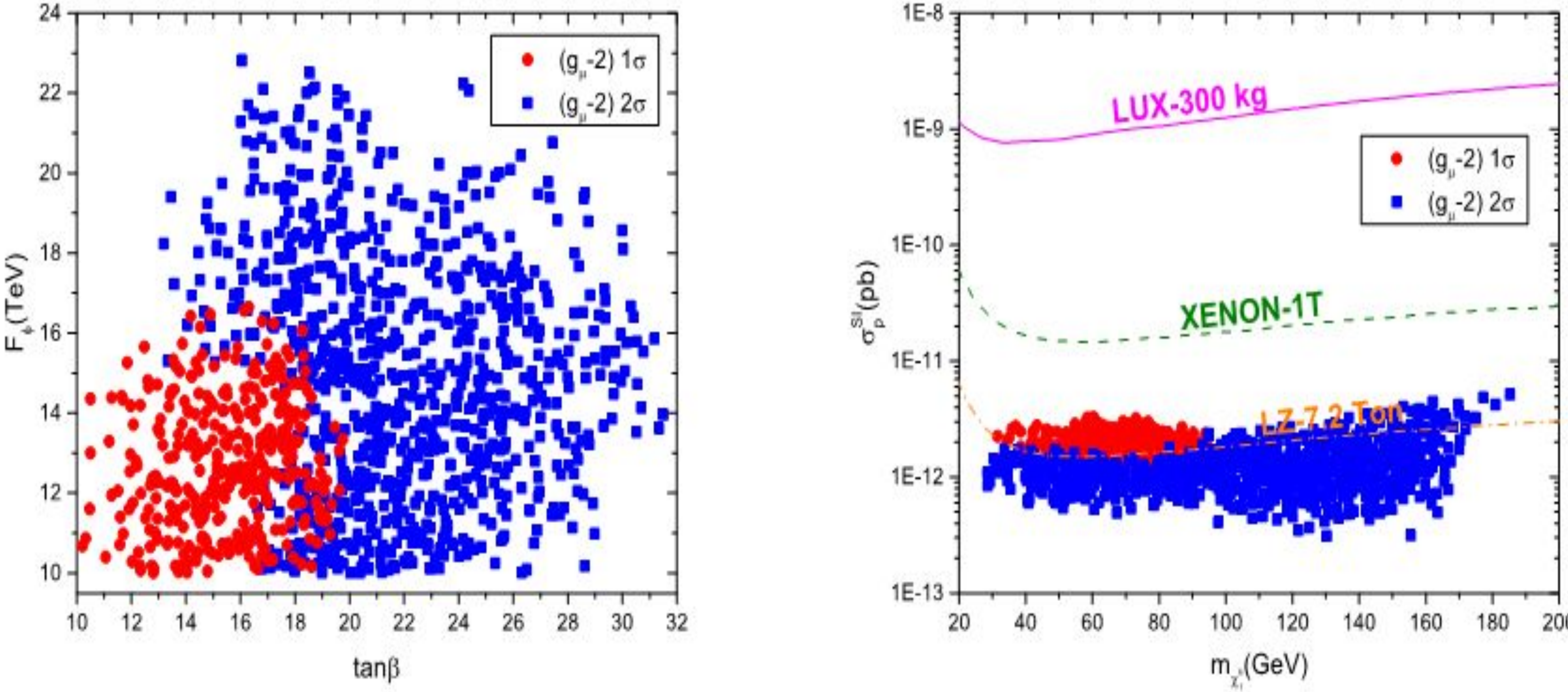
- Our Scenario v.s. MSSM





- deflection parameter v.s. M and N_F





(g_μ-2) 1σ
(g_μ-2) 2σ
F_ϕ(TeV)
tanβ
LUX-300 kg
XENON-1T
LZ-7.2 Ton
σ_p^SI(pb)
m_χ1^0(GeV)

Table 1: Benchmark point I. $d > 0$. All the quantities with mass dimension are in GeV.

N_F	d	M	F_ϕ	$tan\beta$
10	1.59	1.09×10^4	1.33×10^4	15.0
$m^2_{\tilde{H}_u}$	$m^2_{\tilde{H}_d}$	M_1	M_2	M_3
6.98×10^4	1.20×10^5	1.82×10^2	5.48×10^2	1.88×10^3
$m_{\tilde{Q}_L}$	$m_{\tilde{U}_L}$	$m_{\tilde{D}_L}$	$m_{\tilde{L}_L}$	$m_{\tilde{E}_L}$
1.30×10^3	1.26×10^3	1.26×10^3	3.46×10^2	1.53×10^2
$m_{\tilde{Q}_{L,3}}$	$m_{\tilde{U}_{L,3}}$	$m_{\tilde{D}_{L,3}}$	A_U	A_D
1.30×10^3	1.25×10^3	1.26×10^3	-6.58×10^2	-6.50×10^2
A_L	A_τ	A_t	A_b	
-1.46×10^2	-1.17×10^2	-2.28×10^2	-5.34×10^2	
$Br(B \to X_S\gamma)$	$Br(B^0_S \to \mu^+\mu^-)$	$g_\mu - 2$	$\Omega_\chi h^2$	σ_P^{SI}
3.25×10^{-4}	3.40×10^{-9}	1.82×10^{-9}	0.117	1.09×10^{-12} pb
m_{h_1}	$m_{\tilde{\chi}^0_1}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{\chi}^\pm_1}$	$m_{\tilde{g}}$
124.4	84.1	100.2	464.5	3949.4

Table 2: Benchmark point II. $d < 0$. All the quantities with mass dimension are in GeV. Since the LSP is $\tilde{\tau}$, $\Omega_\chi h^2$ and σ_P^{SI} can not be calculated.

N_F	d	M	F_ϕ	$tan\beta$
10	-2.66	4.57×10^6	1.83×10^4	12.2
$m^2_{\tilde{H}_u}$	$m^2_{\tilde{H}_d}$	M_1	M_2	M_3
4.78×10^3	7.12×10^4	-1.02×10^3	-1.44×10^3	-2.54×10^3
$m_{\tilde{Q}_L}$	$m_{\tilde{U}_L}$	$m_{\tilde{D}_L}$	$m_{\tilde{L}_L}$	$m_{\tilde{E}_L}$
8.40×10^2	8.01×10^2	7.99×10^2	2.67×10^2	1.11×10^2
$m_{\tilde{Q}_{L,3}}$	$m_{\tilde{U}_{L,3}}$	$m_{\tilde{D}_{L,3}}$	A_U	A_D
8.27×10^2	7.73×10^2	7.99×10^2	-7.57×10^2	-7.45×10^2
A_L	A_τ	A_t	A_b	
-2.12×10^2	-1.93×10^2	-2.73×10^2	-6.38×10^2	
$Br(B \to X_S\gamma)$	$Br(B^0_S \to \mu^+\mu^-)$	$g_\mu - 2$	$\Omega_\chi h^2$	σ_P^{SI}
3.27×10^{-4}	3.38×10^{-9}	-2.0×10^{-10}	-	-
m_{h_1}	$m_{\tilde{\chi}^0_1}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{\chi}^\pm_1}$	$m_{\tilde{g}}$
125.6	476.8	383.5	1231.4	5229.1

Thank You!