

$(g-2)_\mu$ anomaly & 125_{GeV} Higgs : Extra vector-like quark & LHC prospects

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The University of Tokyo, JAPAN

18th Feb. 2012

@ KEK, Tsukuba

Talk Plan

1. Background
2. The extension we propose
3. LHC prospects

Based on

Higgs mass, muon $g-2$, and LHC prospects

in gauge mediation models with vector-like matters

M. Endo, K. Hamaguchi, S.I., N. Yokozaki. [1112.5653]

Also See: Endo, Hamaguchi, SI, Yokozaki. [1108.3071] [1202.2751]
Endo, Hamaguchi, SI, Nakayama, Yokozaki. [1112.6412]

To explain $(g-2)_\mu$ anomaly & 125 GeV Higgs : simultaneously

Adding Extra vector-like quark & LHC prospects is a very attractive way, and is interesting.

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Standard Model

☹️ “hierarchy problem”

↓ SUSY around TeV

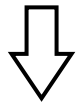
MSSM [Minimal Supersymmetric Standard Model]

😊 fermion/boson unification

😊 GUTs, dark matter(?)

😊 nicely explain muon $g - 2$ anomaly

☹️ must be broken ... too many ~~SUSY~~ parameters



mSUGRA / GMSB frameworks



Physicists' triumph

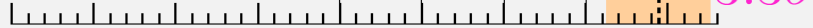
.....
Physicists' dream



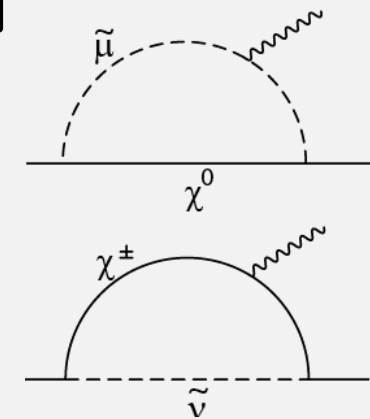
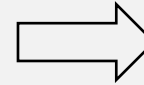
muon $g - 2$ anomaly

SM (HLMNT '11)

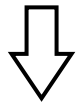
Expm (BNL '04)



Hagiwara, Liao, Martin, Nomura, Teubner [1105.3149]



- 😊 fermion/boson unification
- 😊 GUTs, dark matter(?)
- 😊 nicely explain muon $g - 2$ anomaly
- 😞 must be broken ... too many ~~SUSY~~ parameters



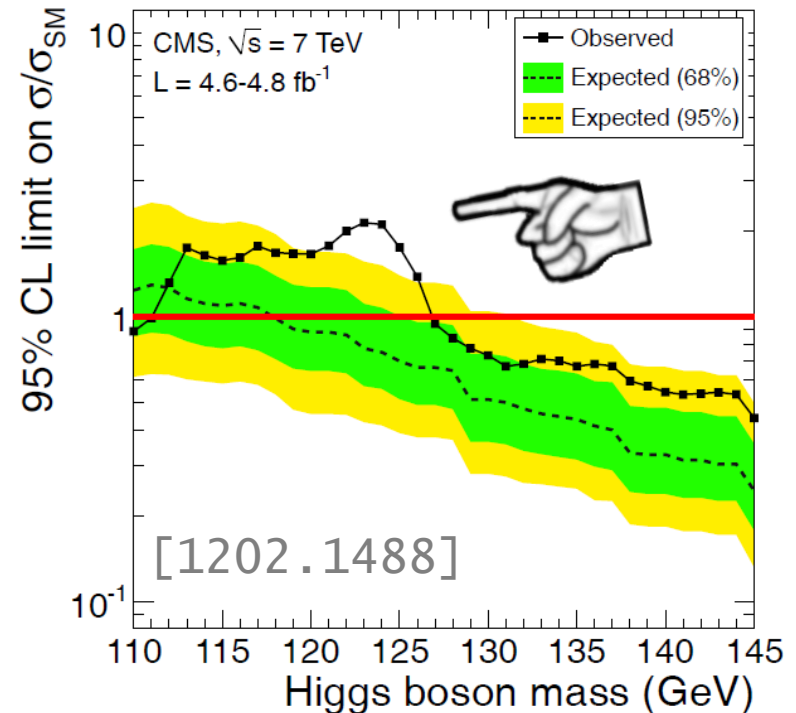
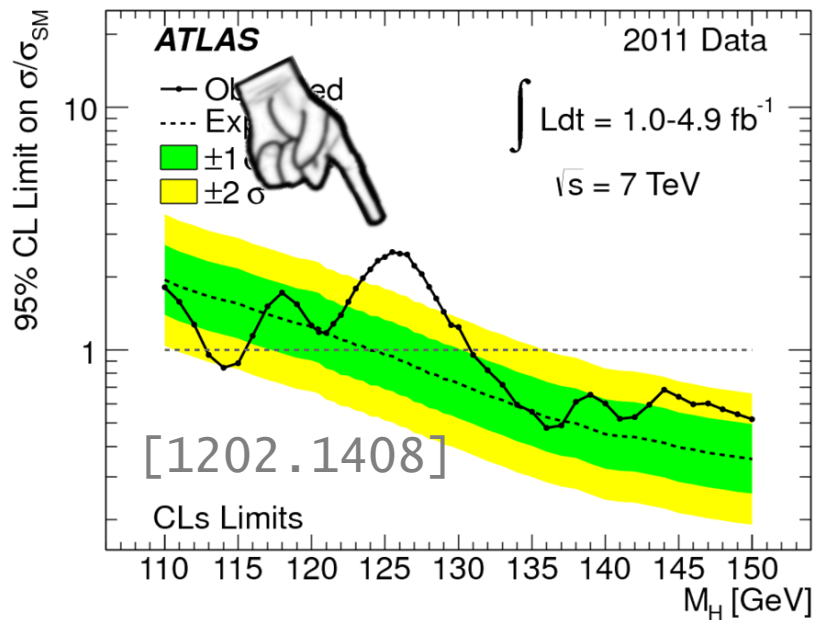
mSUGRA / GMSB frameworks

However

Now this “dream” is threatened by

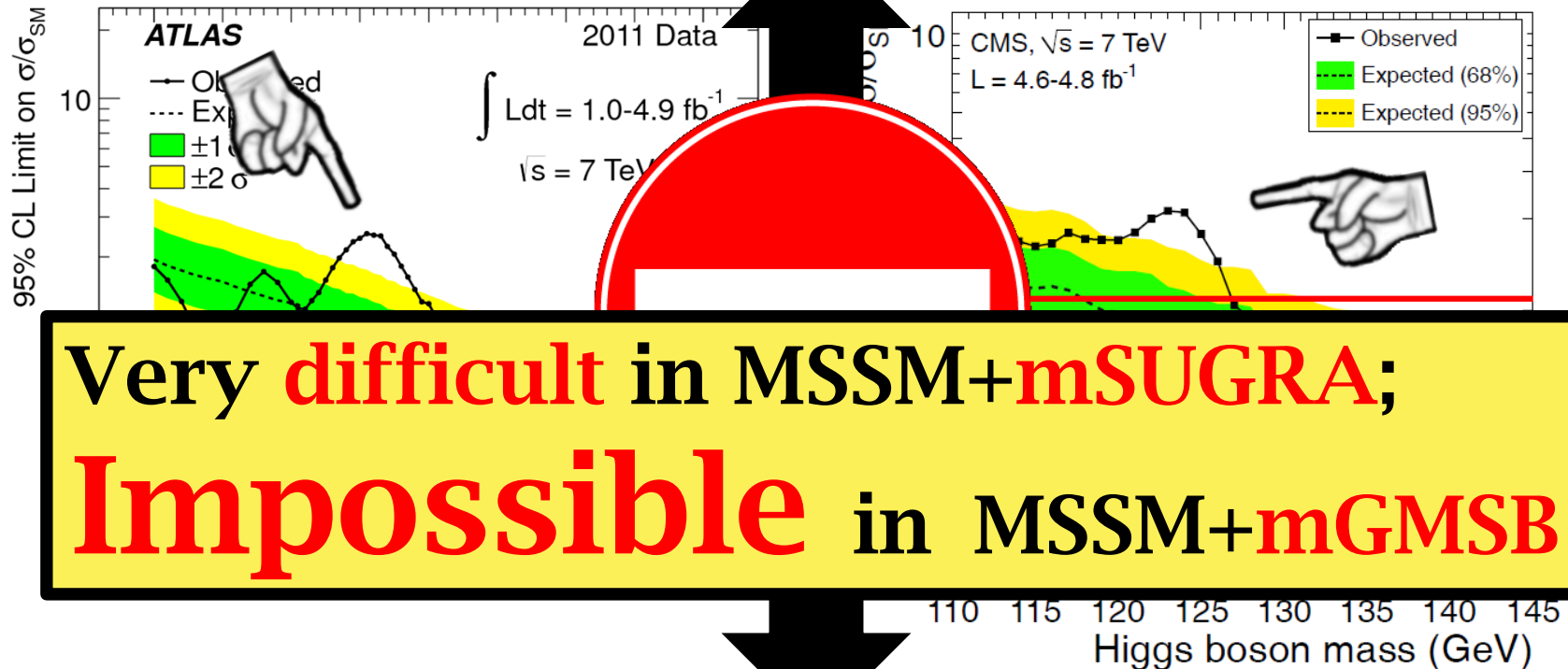
The $\sim 125\text{GeV}$ Higgs boson

(still “tantalizing hints”)



The $\sim 125\text{GeV}$ Higgs boson

(still “tantalizing hints”)



Very difficult in MSSM+mSUGRA;
Impossible in MSSM+mGMSB

$(g - 2)_\mu$ explanation in SUSY

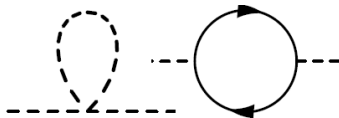
125 GeV in MSSM

$$m_h^2 \lesssim m_Z^2 + \frac{3g_W^2 m_t^4}{8\pi^2 m_W^2} \left[\ln \frac{M_S^2}{m_t^2} + \alpha^2 \left(1 - \frac{\alpha^2}{12} \right) \right]$$

where $M_S^2 := \frac{M_{t_1}^2 + M_{t_2}^2}{2}$, $\alpha := \frac{A_t - \mu \cot \beta}{M_S}$.

(1-loop level; Carena&Haber [0208209], Djouadi [0503173])

- heavy \tilde{t}
- large $(A_t - \mu \cot \beta)$
(roughly $\approx -\sqrt{6}m_{\tilde{t}}$)

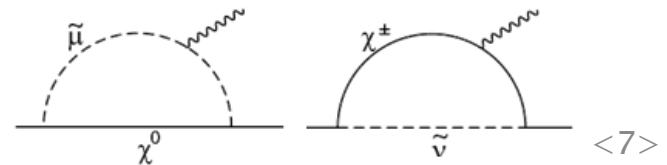


$(g - 2)_\mu$ in MSSM

$$\Delta(\tilde{\chi}^\pm, \tilde{\nu}) \approx \frac{\alpha_w m_\mu^2}{m_{\text{soft}}^2} \text{sgn}(\mu M_2) \tan \beta,$$

$$\Delta(\tilde{\chi}^0, \tilde{\mu}) \approx \frac{\alpha_Y m_\mu^2}{m_{\text{soft}}^2} \text{sgn}(\mu M_1) \tan \beta + \dots$$

- light $(\tilde{\nu}_\mu, \tilde{\chi}^\pm)$ or $(\tilde{\mu}, \tilde{\chi}^0)$
- large $\tan \beta$



125 GeV in MSSM

$$m_h^2 \lesssim m_Z^2 + \frac{3g_W^2 m_t^4}{8\pi^2 m_W^2} \left[\ln \frac{M_S^2}{m_t^2} + \alpha^2 \left(1 - \frac{\alpha^2}{12} \right) \right]$$

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(1-loop level; Carena&Haber [0208209], Djouadi [0503173])

- heavy \tilde{t}

dilemma (GUT)



- light $(\tilde{\nu}_\mu, \tilde{\chi}^\pm)$ or $(\tilde{\mu}, \tilde{\chi}^0)$

- large $(A_t - \mu \cot \beta)$
(roughly $\approx -\sqrt{6}m_{\tilde{t}}$)



- large $\tan \beta$

GMSB ... small A -terms \implies impossible!

mSUGRA

- $b \rightarrow s\gamma$ forbids a huge A -term [1112.6412]
- large $\mu \tan \beta$ + small $m_{\tilde{\tau}}$ \implies instable vacuum etc...

Hisano, Sugiyama [1011.0260]

\implies Possible with parameter splitting & tuning.

e.g. "NUGM" in P. Myeonghun's talk.

$(g - 2)_\mu$ in MSSM

$$\Delta(\tilde{\chi}^\pm, \tilde{\nu}) \approx \frac{\alpha_w m_\mu^2}{m_{\text{soft}}^2} \text{sgn}(\mu M_2) \tan \beta,$$

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For 125 GeV & $g-2$, we must...

- ◎ **tune** the parameter in ~~SUSY~~ models
- ◎ **ignore** $(g - 2)_\mu$ anomaly.
 - “It is just from hadronical uncertainty, theorists’ fault!!”
- ◎ **wish** a lighter Higgs.
- ◎ **extend** the MSSM.
 - NMSSM
 - add $5 + \bar{5}$
 - add $10 + \overline{10}$
 - add a new gauge symmetry.

For 125 GeV & $g-2$, we must...

◎ **tune** the parameter in ~~SUSY~~ models

◎ **ignore** $(g-2)_\mu$ anomaly.

➤ “It is just from hadronical uncertainty, theorists’ fault!”

◎ **wish** a lighter Higgs.

◎ **extend** the MSSM.

➤ ~~NMSSM~~ $g-2 \Rightarrow$ large $\tan\beta \Rightarrow$ NMSSM not contribute.

➤ ~~add $5 + \bar{5}$~~ is still inadequate. Martin [0910.2732]

➤ **add $10 + \bar{10}$** **Today’s topic.** [1112.5653]

➤ add a new gauge symmetry. ← See: Endo, Hamaguchi, SI, Nakayama, Yokozaki [1112.6412]

2. The Extension We Propose

Extension w. Vector-like Matters

MSSM

IDEA

MSSM: top (s)quark lifts up higgs. Okay, then...

Add another top quark!

Extension w. Vector-like Matters

$$\text{MSSM} + (\mathbf{10} \quad \quad), \text{ i.e. } \begin{cases} \mathbf{10} = (Q', U', E') \end{cases}$$

$$W_{\text{add}} = Y' Q' H_u U' \quad m_h \uparrow$$

IDEA

MSSM: top (s)quark lifts up higgs. Okay, then...

Add another top quark!

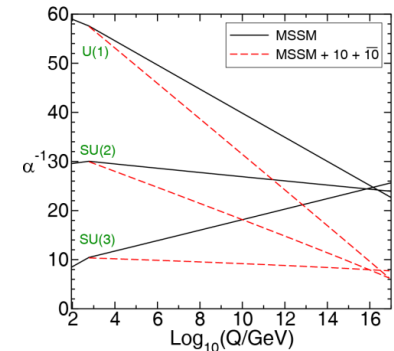
⇒ Gauge anomaly...

⇒ Add as vector-like!

Extension w. Vector-like Matters

$$\text{MSSM} + (\mathbf{10} + \overline{\mathbf{10}}), \text{ i.e. } \begin{cases} \mathbf{10} = (Q', U', E') \\ \overline{\mathbf{10}} = (\bar{Q}', \bar{U}', \bar{E}') \end{cases}$$

- No gauge anomaly.
- Gauge couplings unification.



Martin [0910.2732]

$$W_{\text{add}} = \overset{m_h \uparrow}{Y'} Q' H_u U' + \overset{m_h \downarrow}{Y''} \bar{Q}' H_d \bar{U}' + M_V Q' \bar{Q}' + M_V U' \bar{U}' + M_V E' \bar{E}'$$

$m_h \downarrow \rightarrow \text{we assume } Y'' \ll 1.$

$$W_{\text{mix}} = \epsilon_i Q_i H_u U' + \epsilon'_i Q' H_u \bar{U}_i + \epsilon''_i Q' H_d \bar{D}_i$$

Mixing between SM- & vector-like quark

- Too large \rightarrow flavor problem?
- No mixing \rightarrow stable colored particle. \Rightarrow *assumed very small.*

params: $(\Lambda, M_{\text{mess}}, \tan \beta, N_{\text{mess}}, \text{sgn } \mu, Y', M_V)$

(GMSB framework)

- $N_{\text{mess}} = 1$ to keep perturbative up to M_{GUT} .
- $\text{sgn } \mu = +$ to explain $g - 2$.
- $Y' = 1.05$: infrared fixed point \Rightarrow nice for 125 GeV (also A_t and A' go to IR fixed point.)

RESULT

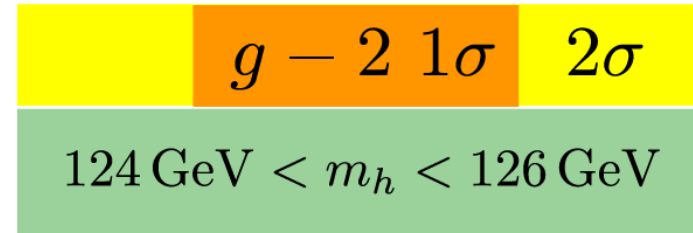
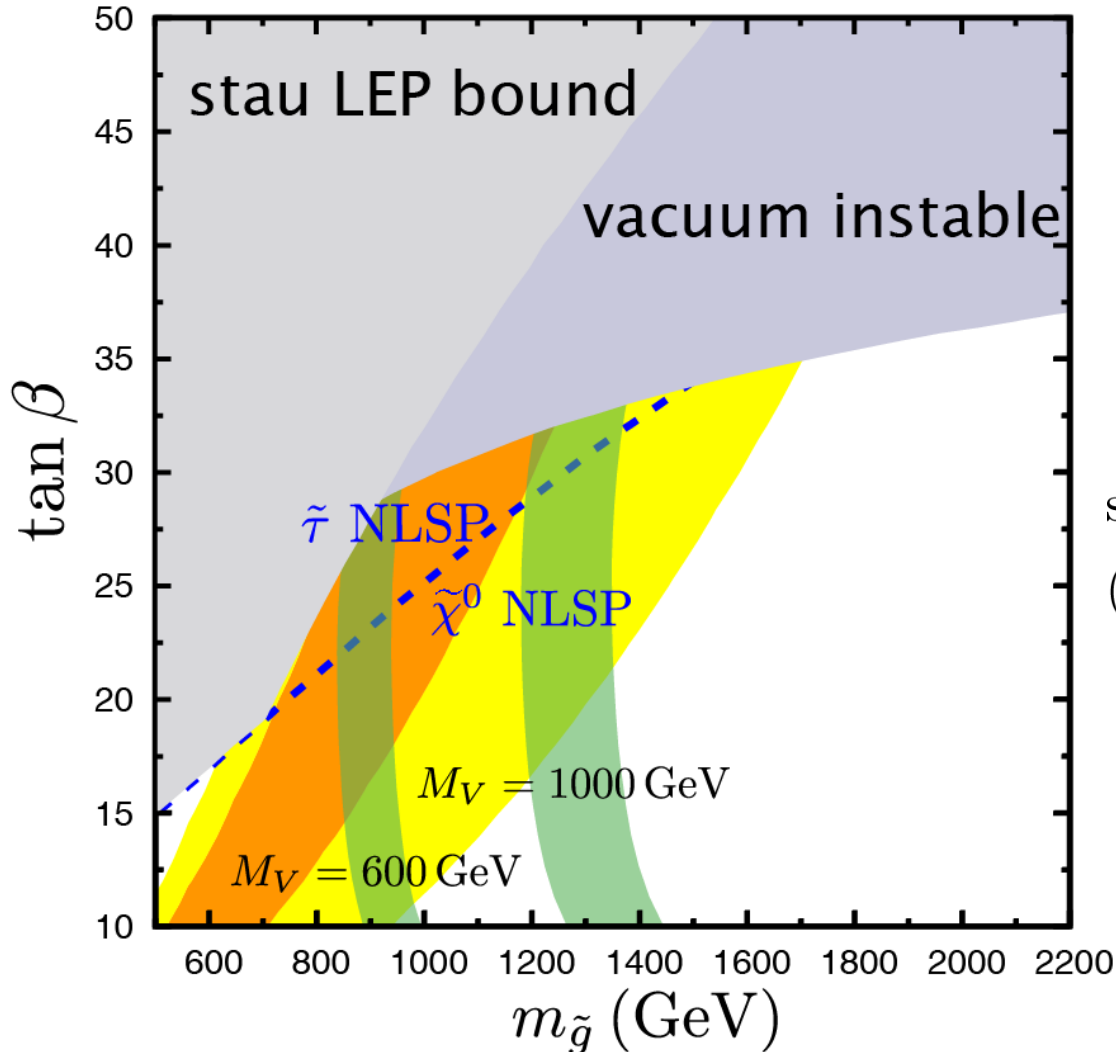
in this talk

with $\left\{ \begin{array}{l} \text{GMSB framework} \\ \text{mSUGRA framework} \end{array} \right.$

params: $(\Lambda, M_{\text{mess}}, \tan \beta, N_{\text{mess}}, \text{sgn } \mu; Y', M_V)$

\parallel
1 \parallel
+ \parallel
1.05

$M_{\text{mess}} = 10^6 \text{ GeV}$



simultaneous realization:

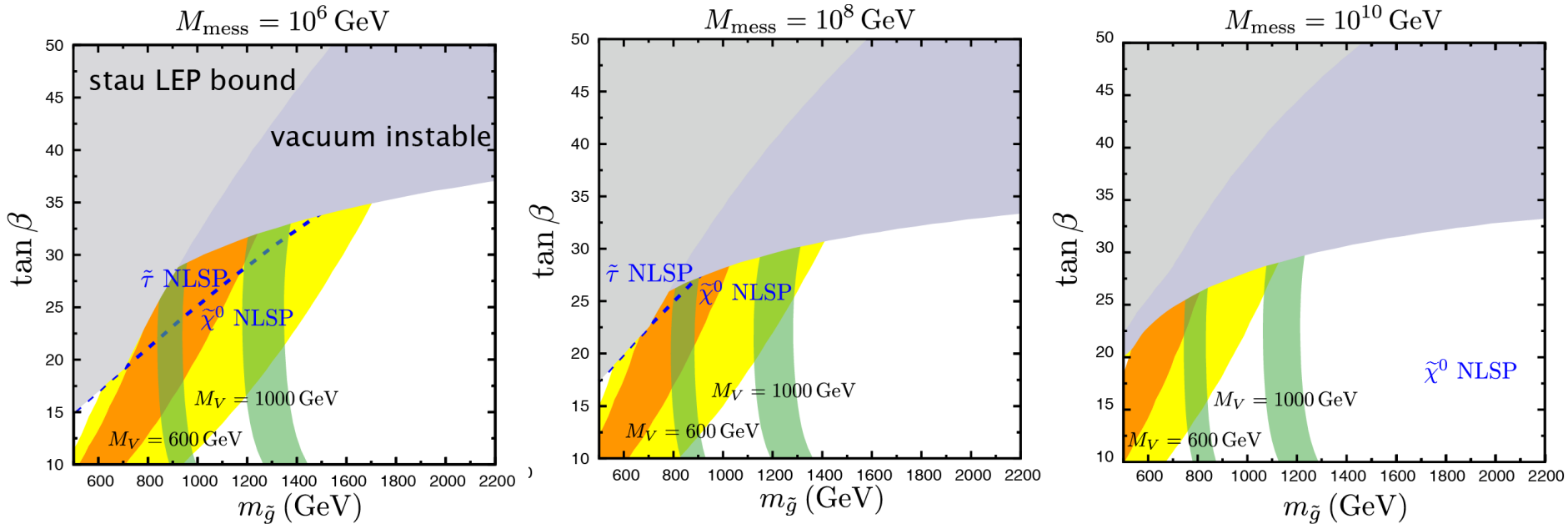
$$(M_V, m_{\tilde{g}}, \tan \beta) \approx$$

$$(600 \text{ GeV}, 900 \text{ GeV}, 20)$$

$$- (1000 \text{ GeV}, 1200 \text{ GeV}, 30)$$

$g - 2$ 1σ 2σ
 $124 \text{ GeV} < m_h < 126 \text{ GeV}$

params: $(\Lambda, M_{\text{mess}}, \tan\beta, N_{\text{mess}}, \text{sgn}\mu; Y', M_V)$
|| || ||
1 + 1.05

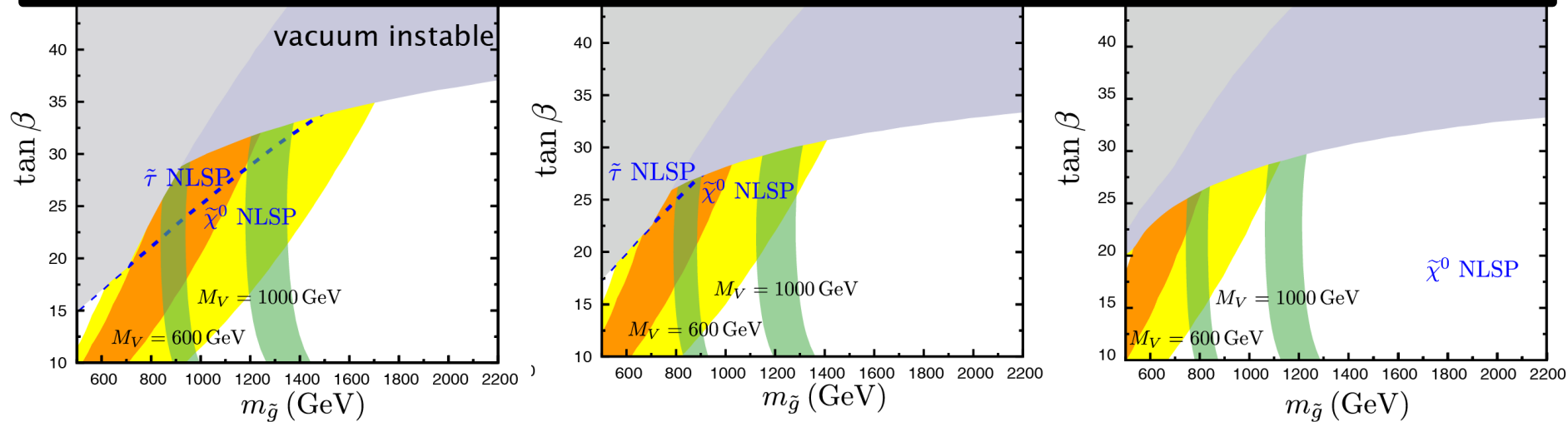


- $(g - 2)_\mu$ expm. tells us (2σ -level),
 $M_V \lesssim 1.5 \text{ TeV}, m_{\tilde{g}} \lesssim 1.6 \text{ TeV}$
- If we take $(g - 2)_\mu$ seriously (1σ -level),
 $M_V \lesssim 1.0 \text{ TeV}, m_{\tilde{g}} \lesssim 1.2 \text{ TeV}$

3. LHC prospects

Sparticle mass = lighter ($\because g - 2$)

\implies Parameter space would be covered by LHC.



	prompt decay ($M_{\text{mess}} \lesssim 10^5$ GeV)	long-lived ($M_{\text{mess}} \gtrsim 10^6$ GeV)
$\tilde{\chi}^0$	current (1fb^{-1}) $m_{\tilde{g}} \gtrsim 1200$ GeV $2\gamma + \cancel{E}$: ATLAS[1111.4116]	current (1fb^{-1}) $m_{\tilde{g}} \gtrsim 700$ GeV $4j + \cancel{E}$: ATLAS[1109.6575], CMS SUS-11-008
$\tilde{\tau}$	will easily be covered by multi-lepton search	already excluded (CMS heavy-stable charged particle; Seminar Jan. 2012)

Vector-like Quark Search

direct proof!

- ◉ New “vector-like” quark (t'_1, b', t'_2)

$$10 = (Q', U', E')$$

$$\bar{10} = (\bar{Q}', \bar{U}', \bar{E}')$$

Mass

$$m_{t'} \sim M_V \pm (174 \text{ GeV}/2),$$

$$m_{b'} = M_V$$

$$W_{\text{add}} = Y' Q' H_u U' + Y'' \bar{Q}' H_d \bar{U}' + M_V Q' \bar{Q}' + M_V U' \bar{U}' + M_V E' \bar{E}'$$

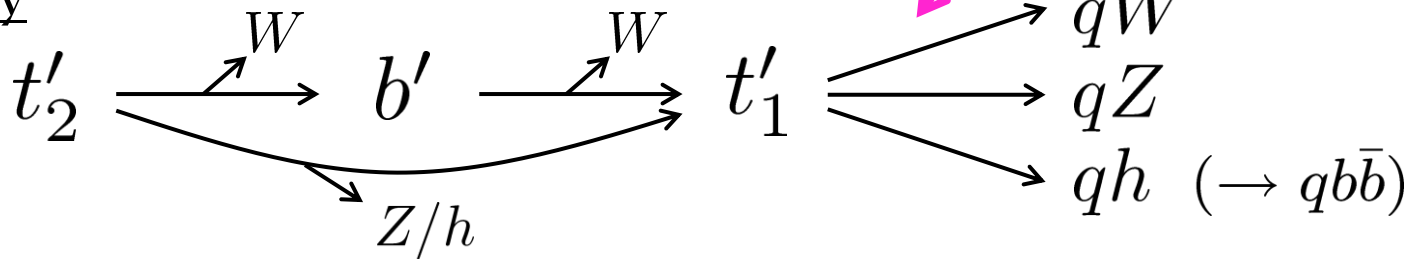
$$W_{\text{mix}} = \epsilon_i Q_i H_u U' + \epsilon'_i Q' H_u \bar{U}_i + \epsilon''_i Q' H_d \bar{D}_i$$

depending on mixing
btw. vec-like/SM quark.

Production

$$pp \rightarrow t'_1 \bar{t}'_1 \text{ etc. (pair production)}$$

Decay



Vector-like Quark Search

- New “vector-like” quark (t'_1, b', t'_2)

Current bound

$$pp \rightarrow t'_1 \bar{t}'_1; \quad t'_1 \begin{cases} \rightarrow qW \\ \rightarrow qZ \\ \rightarrow qh \quad (\rightarrow q\bar{b}\bar{b}) \end{cases}$$

if it decays exclusively as

$$t'_1 \rightarrow bW \quad :: \quad m_{t'_1} > 552 \text{ GeV} \quad \text{CMS } 4.7\text{fb}^{-1} \text{ [EXO-11-050]}$$

$$t'_1 \rightarrow q_d W \quad :: \quad m_{t'_1} > 340 \text{ GeV} \quad \text{CDF } 5.6\text{fb}^{-1} \text{ [1107.3875]}$$

$$t'_1 \rightarrow tZ \quad :: \quad m_{t'_1} > 475 \text{ GeV} \quad \text{CMS } 1.14\text{fb}^{-1} \text{ [1109.4985]}$$

$$t'_1 \rightarrow q_u Z \quad :: \quad \text{No bound yet}$$

$$t'_1 \rightarrow th \quad :: \quad \text{No bound yet}$$

$$t'_1 \rightarrow q_u h \quad :: \quad \text{No bound yet}$$

} No general bound on t'_1 yet because of these possibility.

$$\geq 4 \text{ } b\text{-quarks} \quad (h \rightarrow \bar{b}b)$$

Interesting channel after Higgs discovery.

[K. Harigaya's talk (yesterday)]

Vector-like Quark Search

- ◉ New “vector-like” quark (t'_1, b', t'_2)

$$pp \rightarrow t'_1 \bar{t}'_1; \quad t'_1 \begin{cases} \rightarrow qW \\ \rightarrow qZ \\ \rightarrow qh \quad (\rightarrow q\bar{b}\bar{b}) \end{cases}$$

Once we have

$$t'_1 \rightarrow bW \quad :: m_{t'_1} > 700 \text{ GeV} \quad \text{CMS } 4.7\text{fb}^{-1} \text{ [EXO-11-050]}$$

$$t'_1 \rightarrow q_d W \quad :: m_{t'_1} > 700 \text{ GeV} \quad \text{CDF } 5.6\text{fb}^{-1} \text{ [1107.3875]}$$

$$t'_1 \rightarrow tZ \quad :: m_{t'_1} > 700 \text{ GeV} \quad \text{CMS } 1.14\text{fb}^{-1} \text{ [1109.4985]}$$

$$t'_1 \rightarrow q_u Z \quad :: m_{t'_1} > 700 \text{ GeV}$$

$$t'_1 \rightarrow th \quad :: m_{t'_1} > 700 \text{ GeV}$$

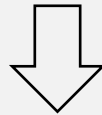
$$t'_1 \rightarrow q_u h \quad :: m_{t'_1} > 700 \text{ GeV}$$

} No general bound on t'_1 yet because of these possibility.

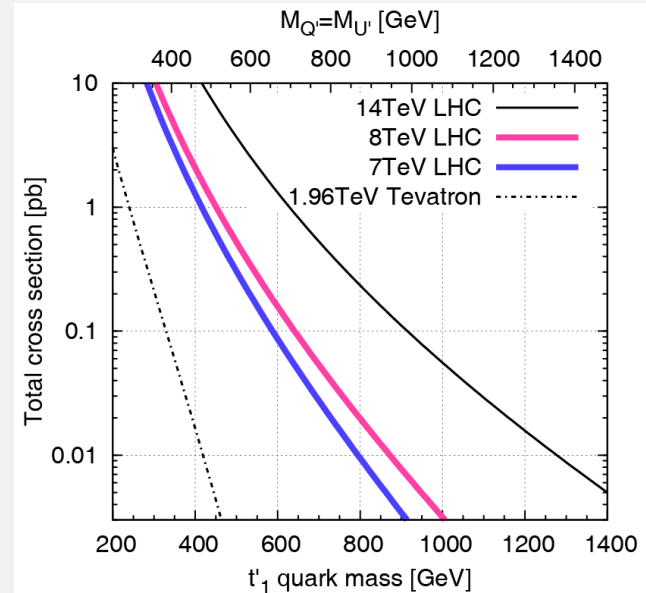
A great smash to this model;

Vector-like Quark Search

At LHC **8** TeV,
production **doubles!**



More severe bounds,
or....?



$$t'_1 \rightarrow th \quad :: m_{t'_1} > 700 \text{ GeV}$$

$$t'_1 \rightarrow q_u h \quad :: m_{t'_1} > 700 \text{ GeV}$$

No general bound on t'_1 yet
because of these possibility.

A great smash to this model;

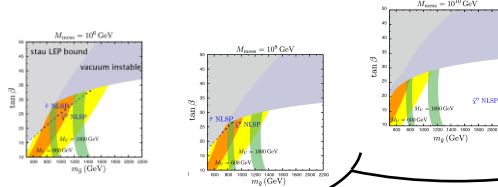
3. Conclusion

Conclusion

125 GeV higgs? + $(g - 2)_\mu$



MSSM + **10** + $\overline{\mathbf{10}}$: vector-like quarks



Our ~~delusion~~ dream will be smashed/proved by

- SUSY search ($\tilde{\chi}_1^0$ -(N)LSP / $\tilde{\tau}$ -(N)LSP)
- 4th gen. quark search
 - $t' \rightarrow q_d W$
 - $t' \rightarrow q_u Z$
 - $t' \rightarrow q_u h (\rightarrow q_u b \bar{b})$ at the LHC

utopian theorists



Stay tuned & hope new phenom. @ 8_{TeV} LHC 2012!