

Higgs Mass and Muon $g-2$ in SUSY Models with Vector-Like Matters

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The University of Tokyo, JAPAN

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Talk Plan

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

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]

summary

To explain
 $(g - 2)_\mu$ & 125 GeV Higgs
simultaneously,
Extending the MSSM with
vector-like quarks is
a very
attractive way.

Standard Model

☹️ “hierarchy problem”

↓ SUSY around TeV

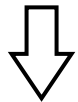
MSSM [Minimal Supersymmetric Standard Model]

😊 fermion/boson unification

😊 GUTs, dark matter(?)

😊 nicely explain **muon $g - 2$** anomaly

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



mSUGRA / GMSB frameworks



Physicists' triumph

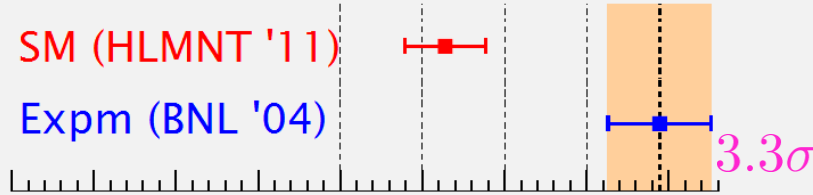
.....
Physicists' dream



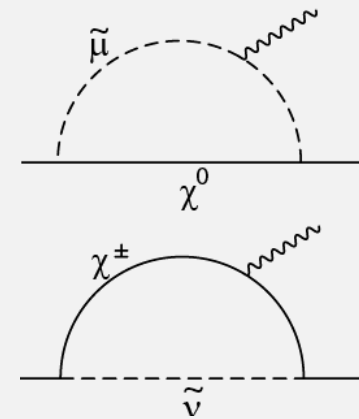
muon $g - 2$ anomaly

SM (HLMNT '11)

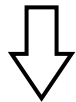
Expm (BNL '04)



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



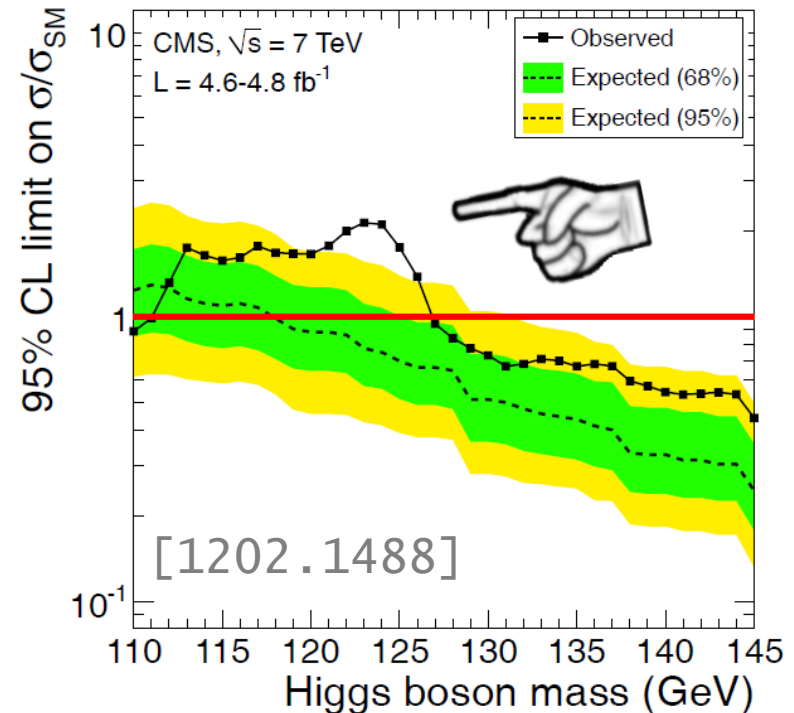
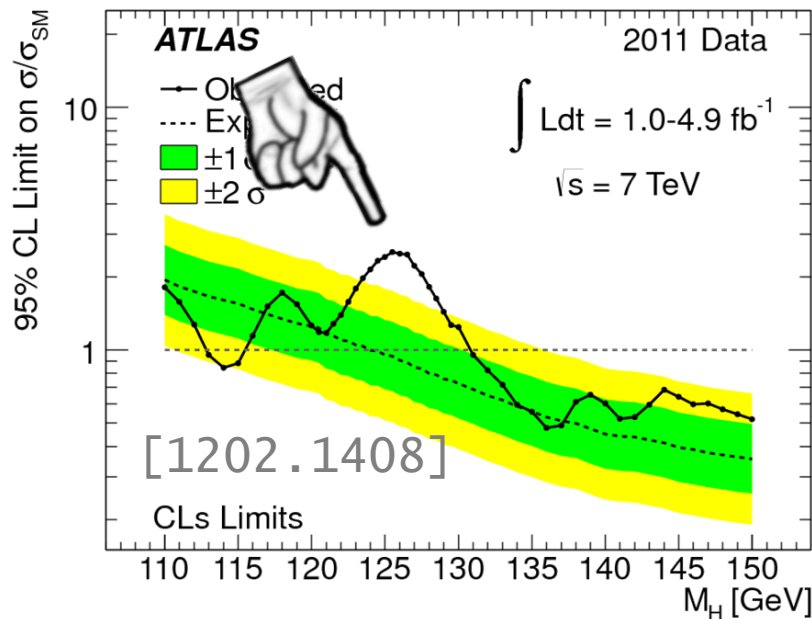
mSUGRA / GMSB frameworks

However

Now this “dream” is threatened by

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

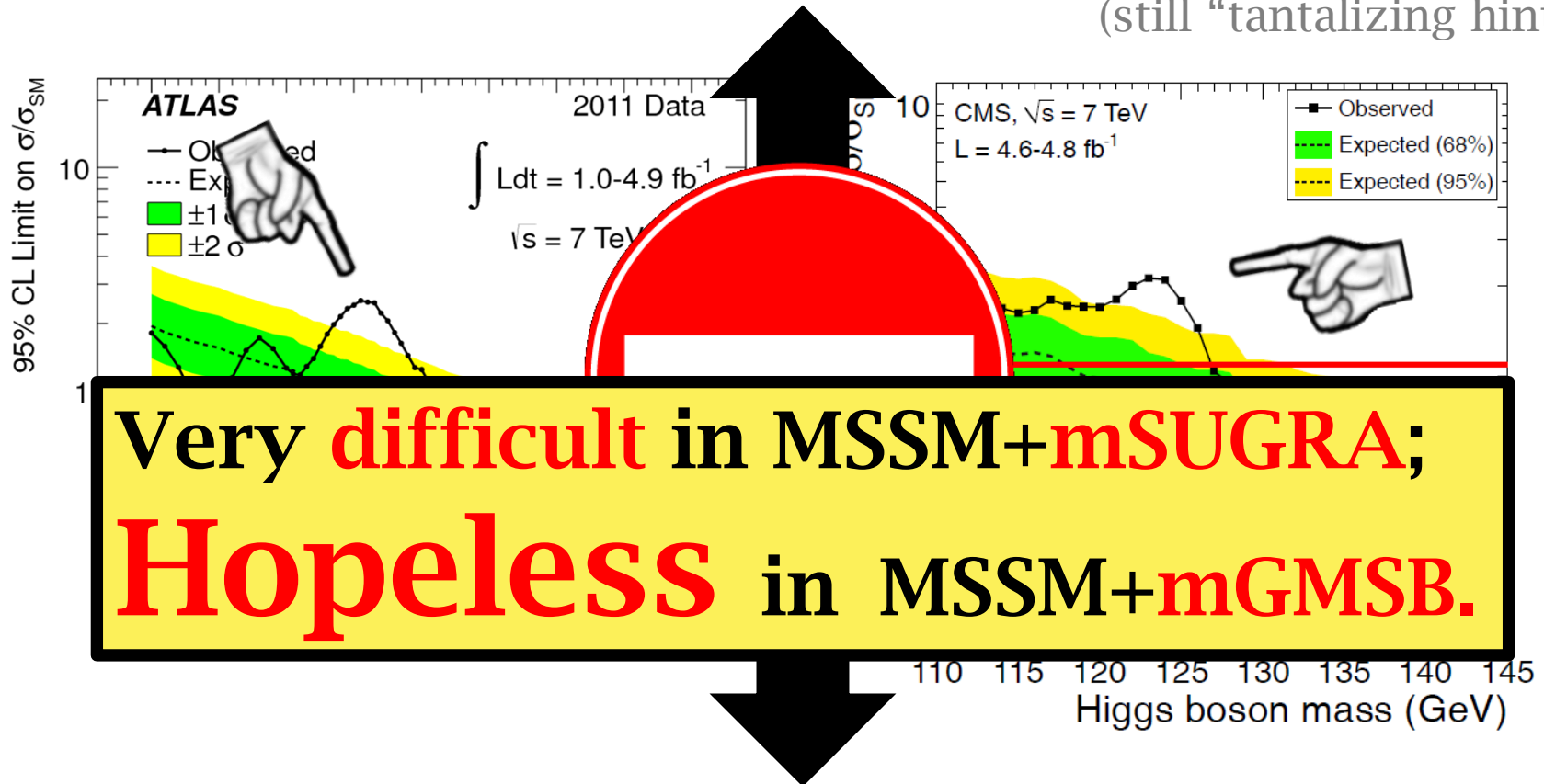
(still “tantalizing hints”)



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

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

(still “tantalizing hints”)



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

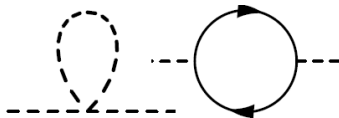
125 GeV in MSSM

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

(1-loop level)

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

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

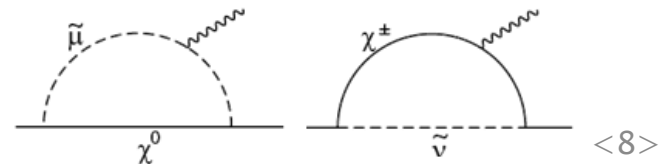


$(g - 2)_\mu$ in MSSM

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

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

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

- heavy \tilde{t}

dilemma (GUT)



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

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

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

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

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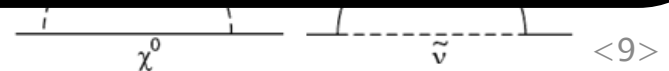
GMSB ... small A -terms \implies impossible!

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. "Non-Universal Gaugino Model" or to split M_0 for 1,2 / 3 gen.



For 125GeV & $g-2$, 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 125GeV & $g-2$, 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

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

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

IDEA

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

Add another top quark!

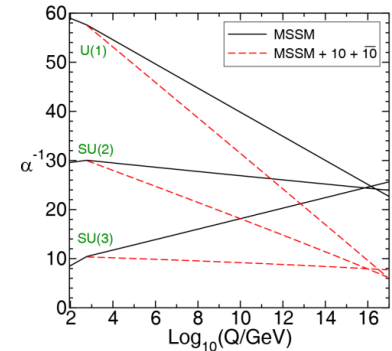
⇒ Gauge anomaly...

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

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

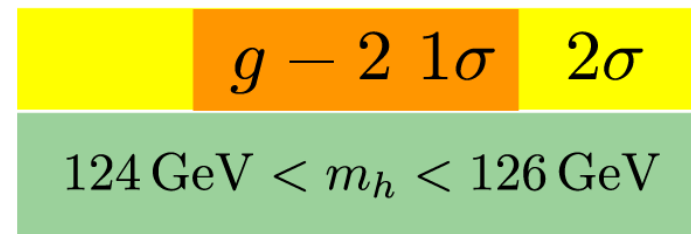
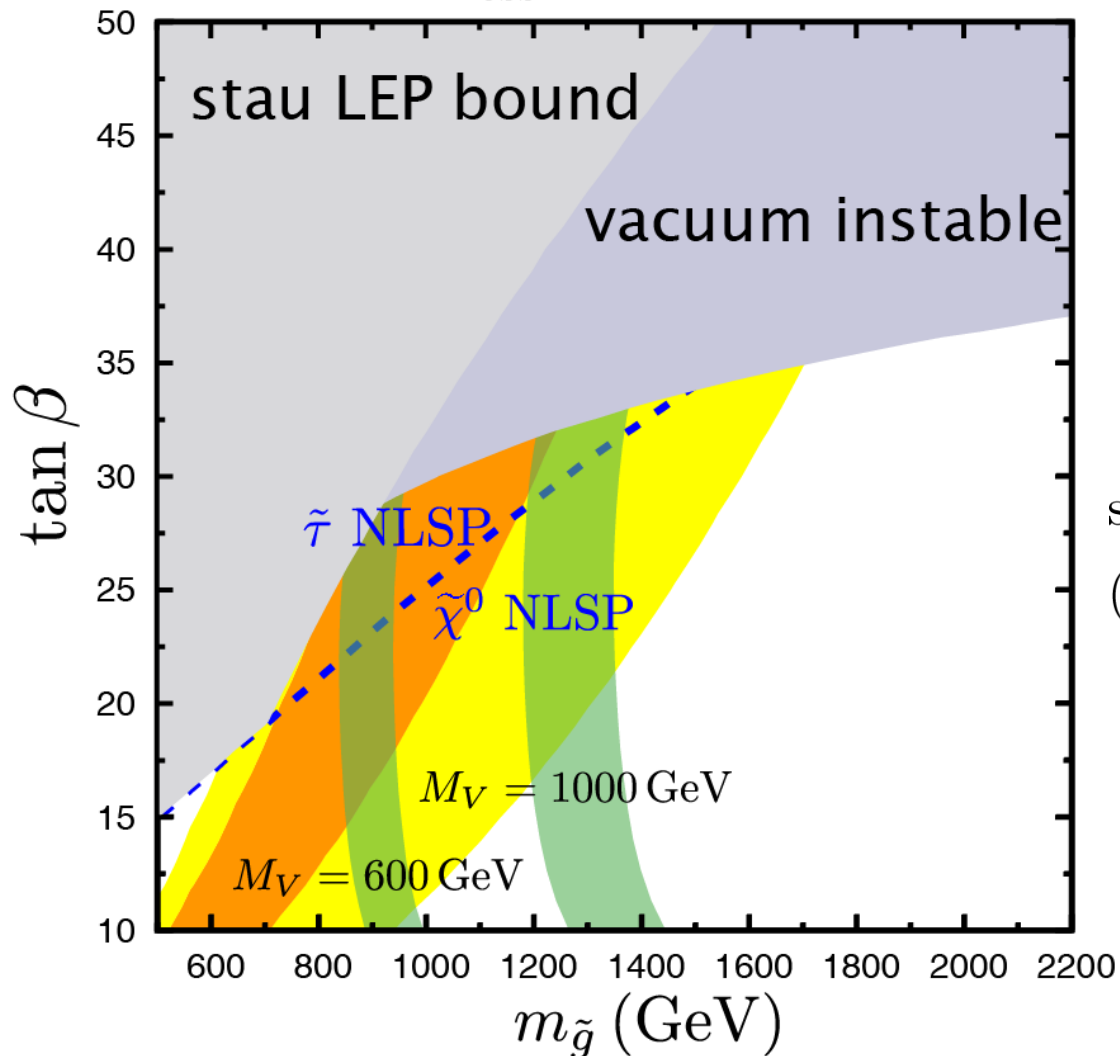
params: $(\Lambda, M_{\text{mess}}, \tan \beta, N_{\text{mess}}, \text{sgn } \mu; Y', M_V)$

\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

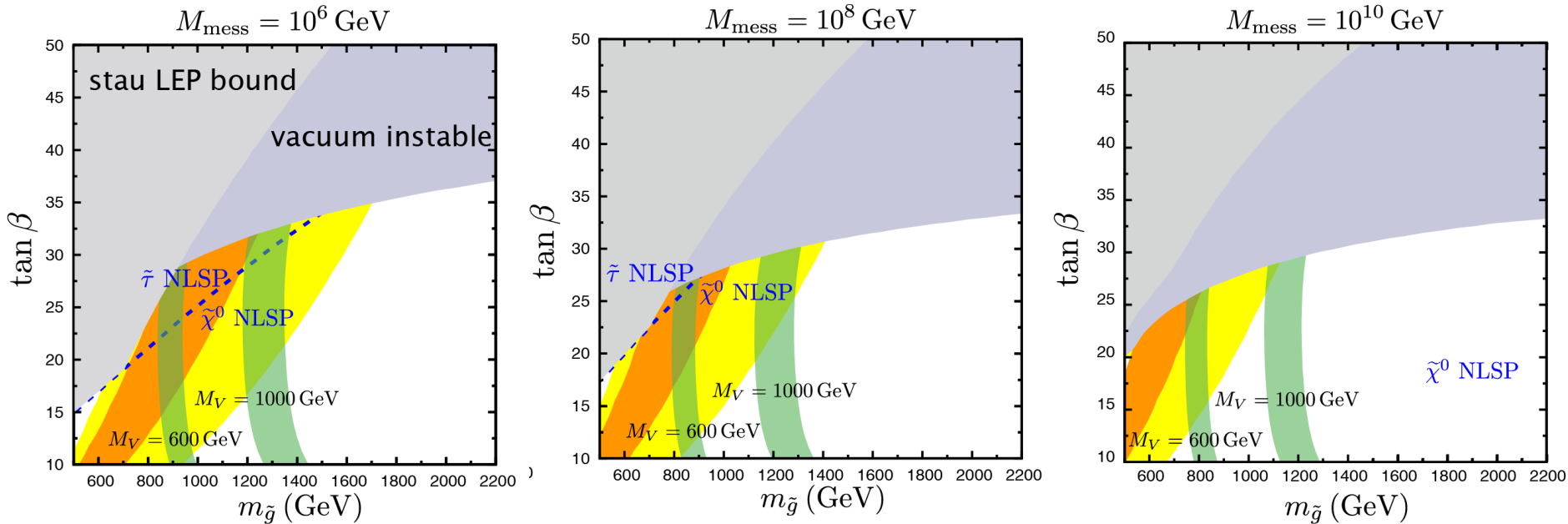
$124 \text{ GeV} < m_h < 126 \text{ GeV}$

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

\parallel
1

\parallel
+

\parallel
1.05



- $(g - 2)_\mu$ expm. tells us (2σ -level),

$$M_V \lesssim 1.5 \text{ TeV}, \quad m_{\tilde{g}} \lesssim 1.6 \text{ TeV}$$

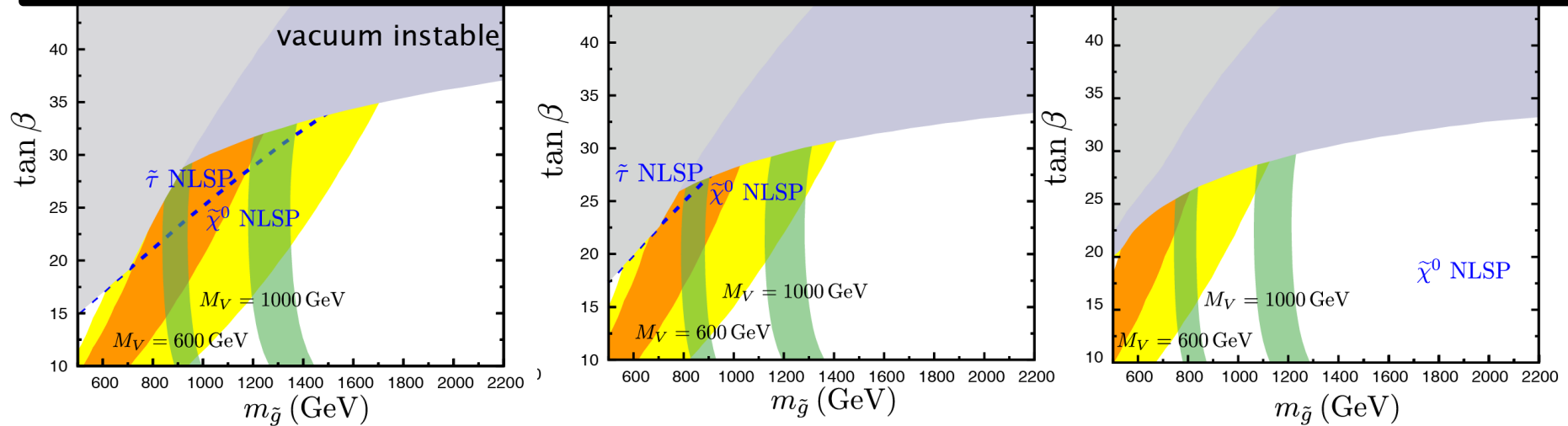
- If we take $(g - 2)_\mu$ seriously (1σ -level),

$$M_V \lesssim 1.0 \text{ TeV}, \quad m_{\tilde{g}} \lesssim 1.2 \text{ TeV}$$

3. LHC Phenomenology

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

\Rightarrow 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)
$\tilde{\chi}^0$	curr. (1fb^{-1}) $m_{\tilde{g}} \gtrsim 1.2$ TeV $2\gamma + \cancel{E}$: ATLAS[1111.4116]	curr. (1fb^{-1}) $m_{\tilde{g}} \gtrsim 700$ GeV $4j + \cancel{E}$: ATLAS1109.6575, CMS SUS11-008
$\tilde{\tau}$	will easily be covered by multi-lepton search	already excluded (CMS hvy-stbl chrgd prtcl; Seminar Jan. '12)

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

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

$$m_{b'} = M_V$$

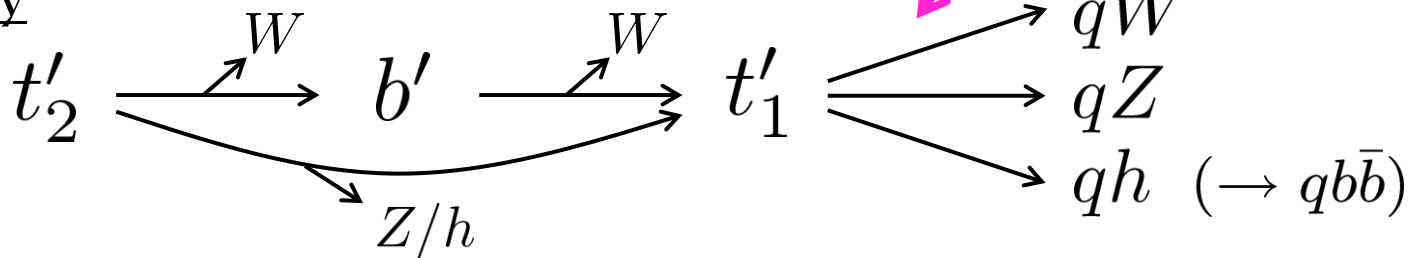
$$\begin{aligned} W_{\text{add}} &= Y' Q' H_u U' + Y'' \bar{Q}' H_d \bar{U}' \\ &\quad + M_V Q' \bar{Q}' + M_V U' \bar{U}' + M_V E' \bar{E}' \\ W_{\text{mix}} &= \epsilon_i Q_i H_u U' + \epsilon'_i Q' H_u \bar{U}_i + \epsilon''_i Q' H_d \bar{D}_i \end{aligned}$$

Production

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

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

Decay



Vector-like Quark Search

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

Current bound

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

if it decays exclusively as

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

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

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

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

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

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

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

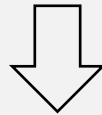
$$\geq 4 \text{ } b\text{-quarks} \quad (h \rightarrow b \bar{b})$$

Interesting channel after Higgs discovery.

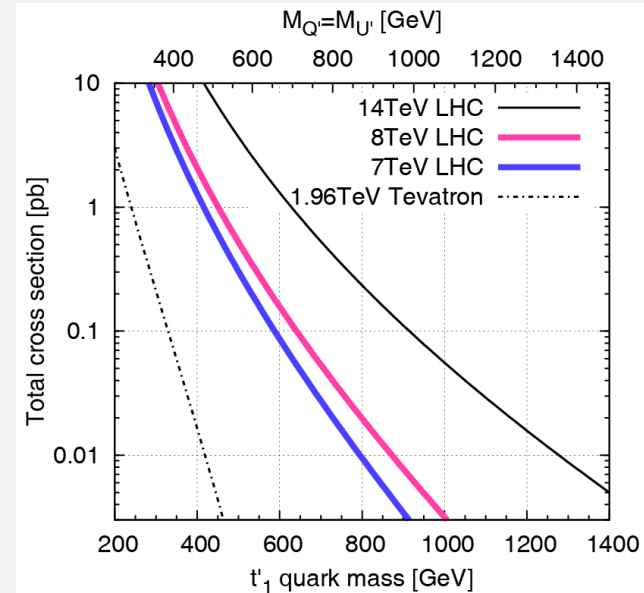
[K. Harigaya's talk]

Vector-like Quark Search

At LHC 8TeV,
production doubles!



More severe bounds,
or....?



$t'_1 \rightarrow th$:: No bound yet

$t'_1 \rightarrow q_u h$:: No bound yet

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

≥ 4 b -quarks ($h \rightarrow b\bar{b}$)

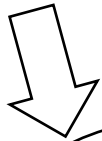
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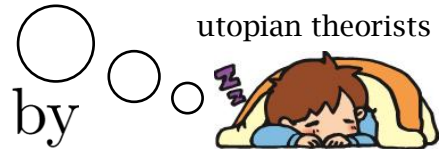
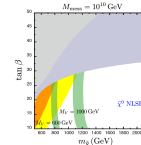
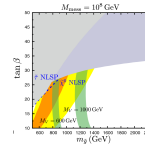
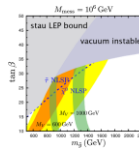
4. Conclusion

Conclusion

125GeV 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
 - $t' \rightarrow qW$
 - $t' \rightarrow qZ$
 - $t' \rightarrow qh(\rightarrow q_u b \bar{b})$

at the LHC