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

Extra vector-like quark & LHC prospects

Sho IWAMOTO（岩本　祥）

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

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

Physicists’ triumph

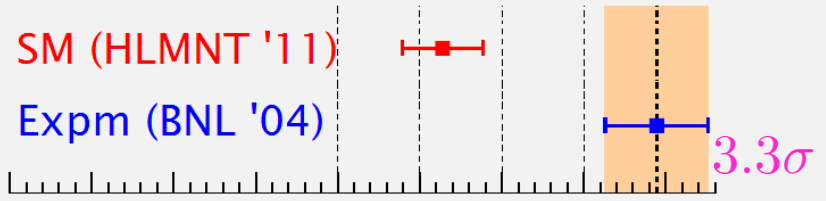
Physicists’ dream

MSSM [Minimal Supersymmetric Standard Model]

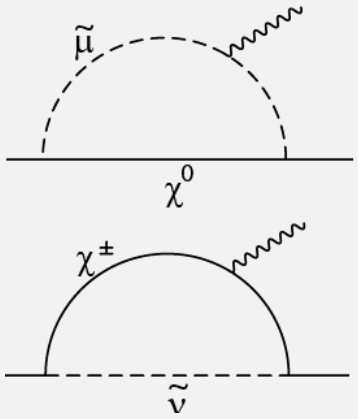
- fermion/boson unification
- GUTs, dark matter(?)
- nicely explain muon $g-2$ anomaly
- must be broken … too many ~~SUSY~~ parameters
  - ⇩

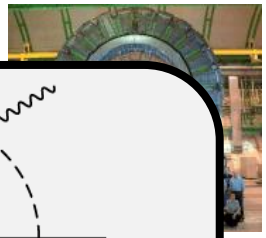
mSUGRA / GMSB frameworks

muon $g-2$ anomaly



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

⇩

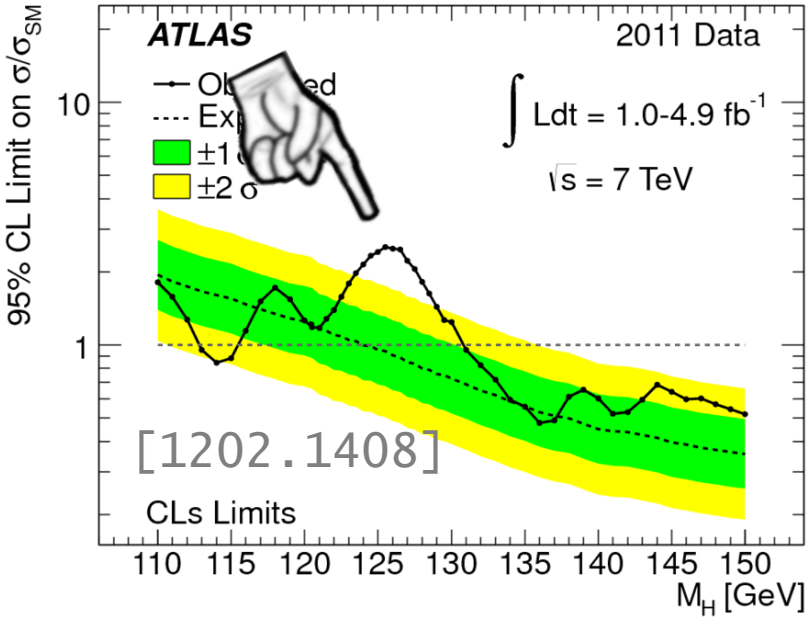
mSUGRA / GMSB frameworks

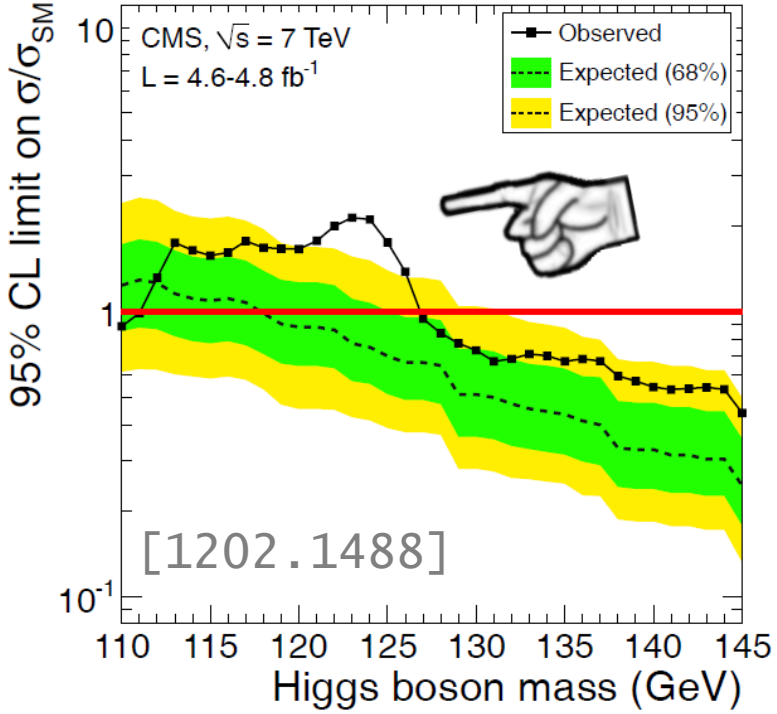
However

Now this "dream" is threatened by

The ~125GeV Higgs boson

(still "tantalizing hints")





The ~125GeV Higgs boson

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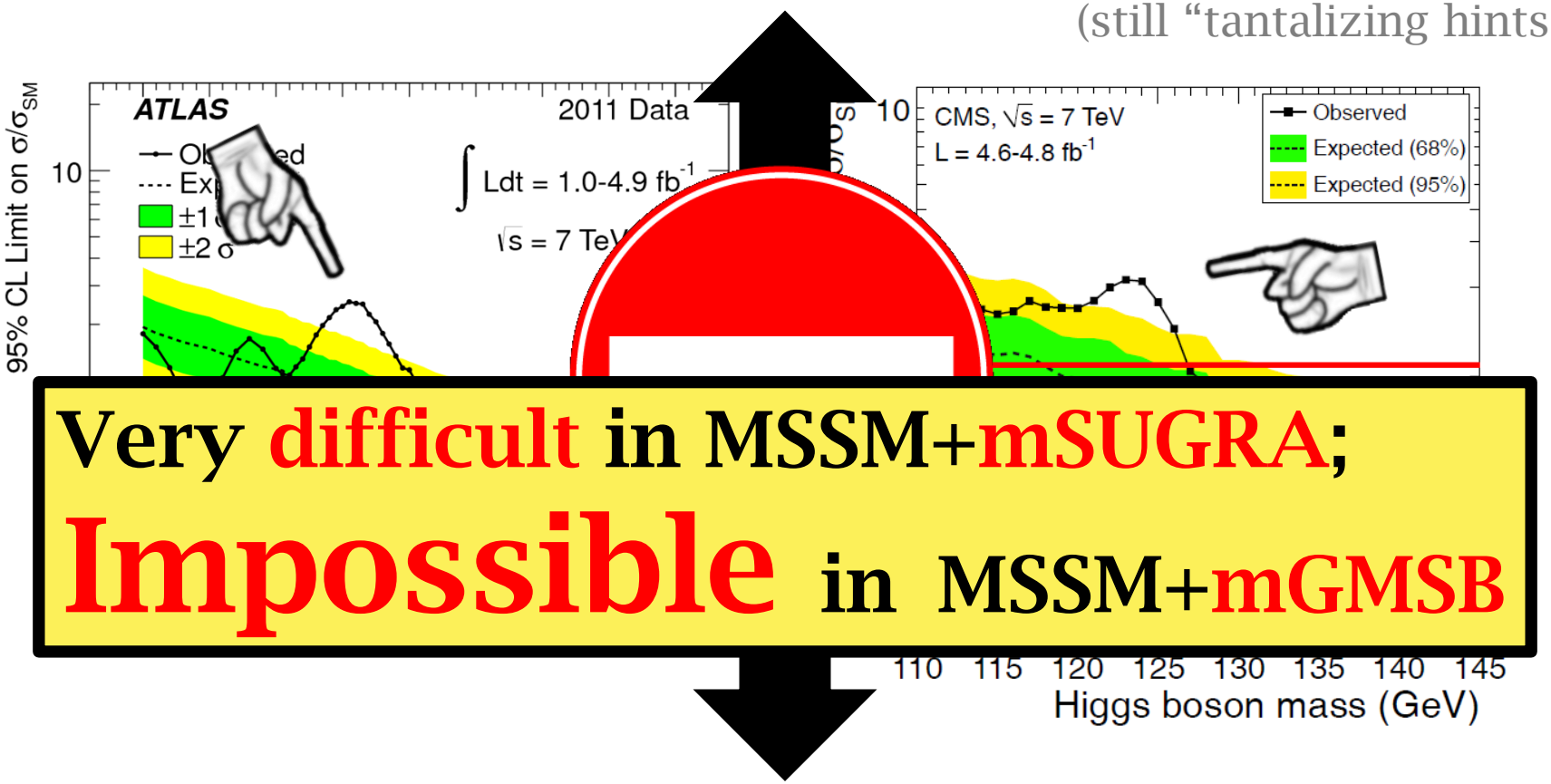


Very difficult in MSSM+mSUGRA;

Impossible in MSSM+mGMSB

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

125GeV in MSSM

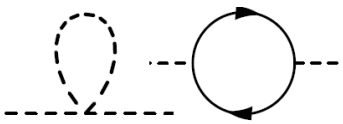
$$m_h^2 \lesssim m_Z^2 + \frac{3g_W^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\frac{M_S^2}{m_t^2} + \alpha^2\left(1-\frac{\alpha^2}{12}\right)\right]$$

where $M_S^2 := \frac{M_{\tilde{t}_1}^2 + M_{\tilde{t}_2}^2}{2}$, $\alpha := \frac{A_t - \mu\cot\beta}{M_S}$.

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

- heavy $\widetilde{t}$
- large $(A_t - \mu\cot\beta)$

  (roughly $\approx -\sqrt{6}m_{\tilde{t}}$)

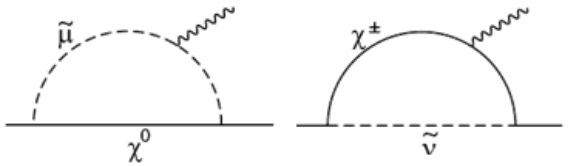


$(g-2)_\mu$ in MSSM

$$\Delta\left(\widetilde{\chi}^{\pm},\widetilde{\nu}\right) \approx \frac{\alpha_w m_\mu^2}{m_{\rm soft}^2}\,\mathrm{sgn}(\mu M_2)\tan\beta,$$

$$\Delta\left(\widetilde{\chi}^{0},\widetilde{\mu}\right) \approx \frac{\alpha_Y m_\mu^2}{m_{\rm soft}^2}\,\mathrm{sgn}(\mu M_1)\tan\beta + \cdots$$

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



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

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

dilemma (GUT)

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

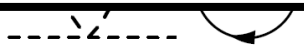
GMSB $\cdots$ small A-terms $\Longrightarrow$ impossible!

mSUGRA

- $b \to s\gamma$ forbids a huge A-term [1112.6412]
- large $\mu\tan\beta$ + small $m_{\tilde{\tau}} \Longrightarrow$ instable vacuum etc... Hisano, Sugiyama [1011.0260]

$\Longrightarrow$ Possible with parameter splitting & tuning.

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



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 $\mathbf{5}+\overline{\mathbf{5}}$
  - add $\mathbf{10}+\overline{\mathbf{10}}$
  - add a new gauge symmetry.

For 125GeV & g−2, we must…

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- **ignore** $(g-2)_\mu$ anomaly.
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- **wish** a lighter Higgs.
- **extend** the MSSM.
  - ~~NMSSM~~ $g-2 \Rightarrow$ large $\tan\beta \Rightarrow$ NMSSM not contribute.
  - ~~add $\mathbf{5}+\overline{\mathbf{5}}$~~ is still inadequate. Martin [0910.2732]
  - add $\mathbf{10}+\overline{\mathbf{10}}$ **Today's topic.** [1112.5653]
  - add a new gauge symmetry. ← See: Endo, Hamaguchi, SI, Nakayama, Yokozaki [1112.6412]

2. The Extension We Propose

Okada, Moroi (1992); we digged up again in the context “higgs & g-2”.

Extension w. Vector-like Matters

MSSM

IDEA

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

Add another top quark!

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Extension w. Vector-like Matters

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

$$W_{\mathrm{add}} = Y' Q' H_{\mathrm{u}} U' \qquad (m_h \Uparrow)$$

IDEA

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

Add another top quark!

⇨ Gauge anomaly...

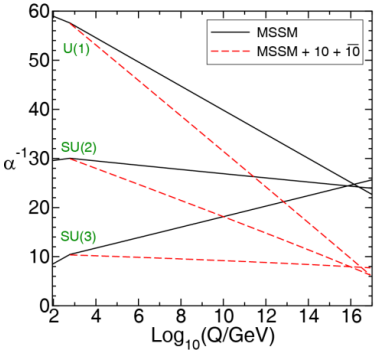
⇨ Add as vector-like!

Okada, Moroi (1992); we digged up again in the context "higgs & g-2".

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]

$m_h \Uparrow$ $\qquad$ $m_h \Downarrow \longrightarrow$ we *assume* $Y'' \ll 1$.

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

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

Mixing between SM- & vector-like quark

- Too large $\longrightarrow$ flavor problem?
- No mixing $\longrightarrow$ 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 $g-2$.
- $\mathbf{Y' = 1.05}$ **: infrared fixed point** $\Rightarrow$ **nice for 125 GeV**
  (also A_t and A' go to IR fixed point.)

RESULT

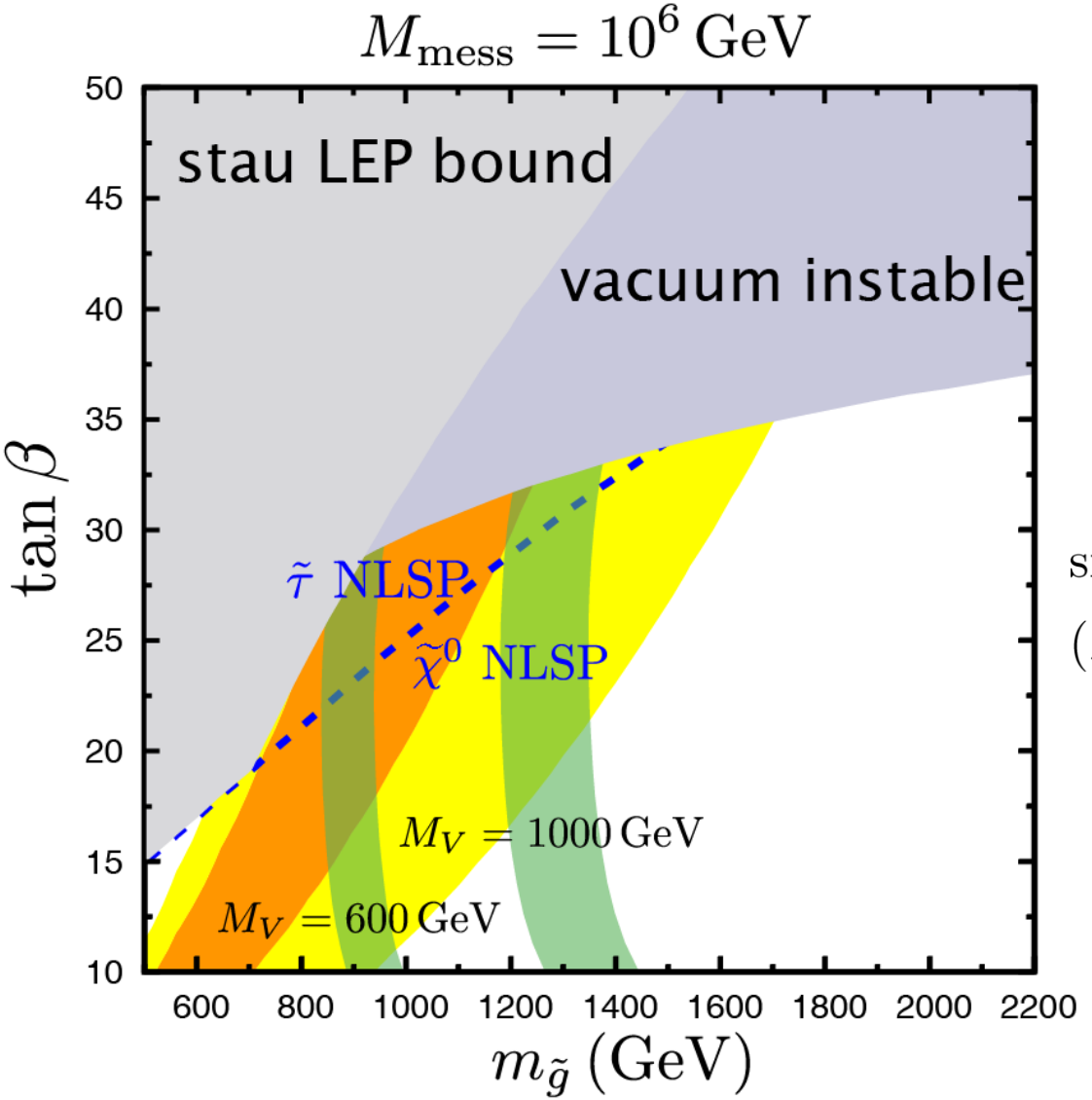
in this talk

with { GMSB framework
mSUGRA framework

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

$\|$ $\|$ $\|$

1 $+$ 1.05



$g-2$ 1σ 2σ

$124\,{\rm GeV} < m_h < 126\,{\rm GeV}$

simultaneous realization:

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

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

– $(1000\,{\rm GeV},\ 1200\,{\rm GeV},\ 30)$

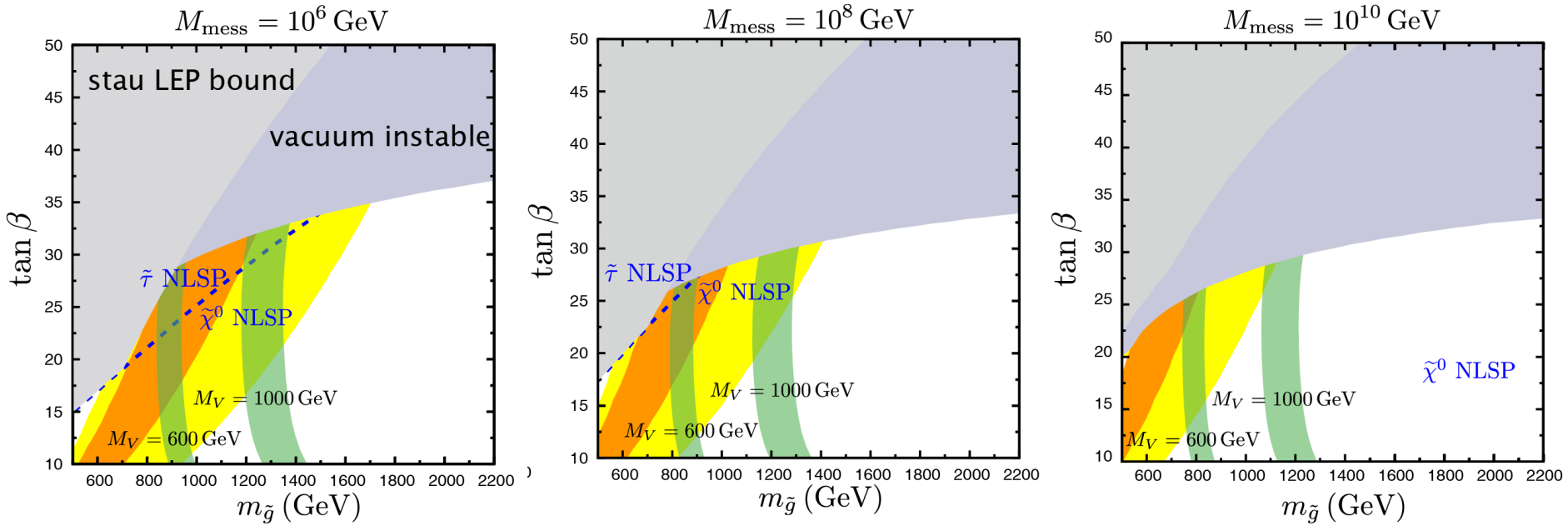
$g-2$ 1σ 2σ

$124\,\mathrm{GeV} < m_h < 126\,\mathrm{GeV}$

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

$\|\quad\quad\|\quad\quad\|$

$1\quad\ +\quad 1.05$



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

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

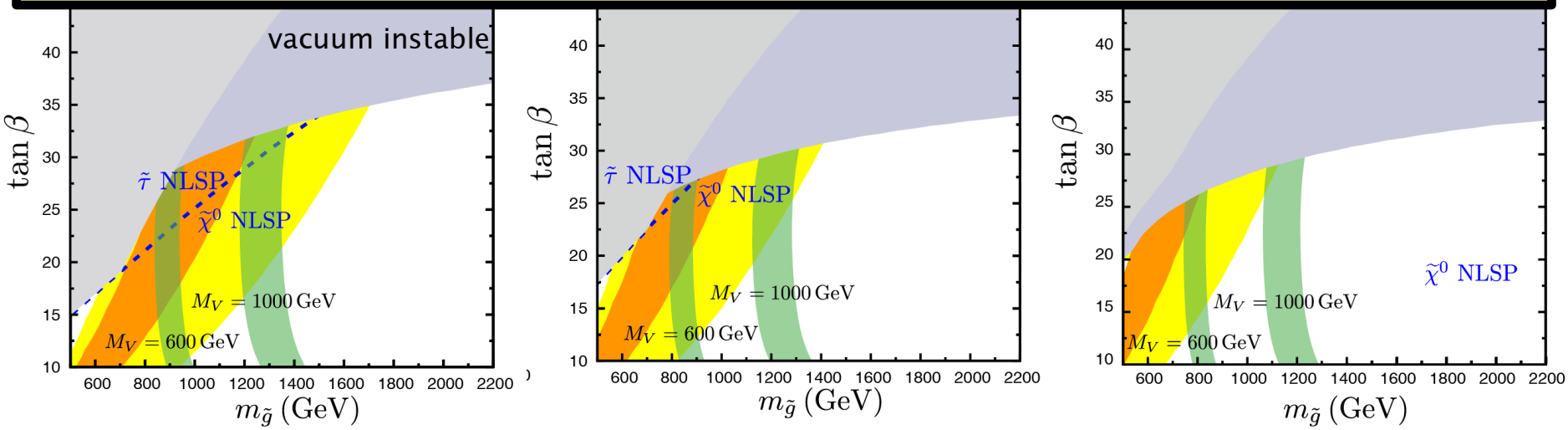
- If we take $(g-2)_\mu$ seriously (1σ-level),

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

3. LHC prospects

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

$\Longrightarrow$ Parameter space would be covered by LHC.



	prompt decay ($M_{\mathrm{mess}} \lesssim 10^5\,\mathrm{GeV}$)	long-lived ($M_{\mathrm{mess}} \gtrsim 10^6\,\mathrm{GeV}$)
$\tilde{\chi}^0$	current ($1\mathrm{fb}^{-1}$) $m_{\tilde{g}} \gtrsim 1200\,\mathrm{GeV}$ $2\gamma + \not{E}$: ATLAS[1111.4116]	current ($1\mathrm{fb}^{-1}$) $m_{\tilde{g}} \gtrsim 700\,\mathrm{GeV}$ $4j + \not{E}$: ATLAS[1109.6572], 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)

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

Mass

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

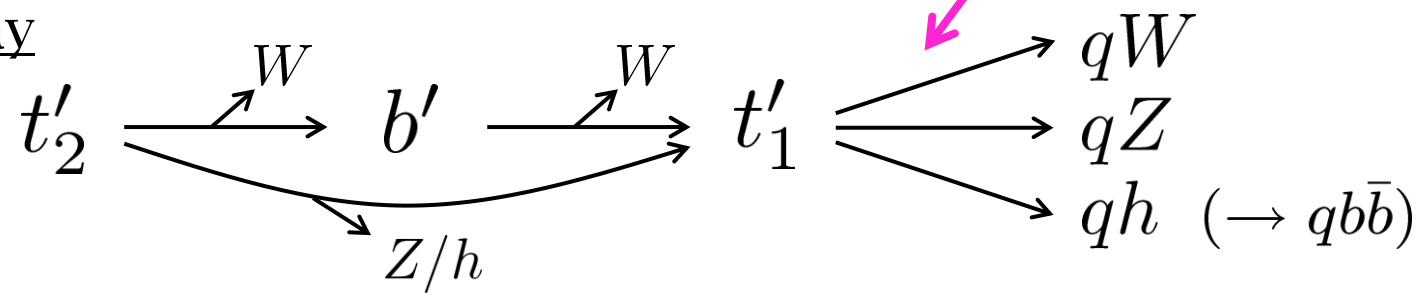
$$W_{\mathrm{add}} = Y' Q' H_{\mathrm{u}} U' + Y'' \bar{Q}' H_{\mathrm{d}} \bar{U}' + M_V Q' \bar{Q}' + M_V U' \bar{U}' + M_V E' \bar{E}'$$
$$W_{\mathrm{mix}} = \epsilon_i Q_i H_{\mathrm{u}} U' + \epsilon'_i Q' H_{\mathrm{u}} \bar{U}_i + \epsilon''_i Q' H_{\mathrm{d}} \bar{D}_i$$

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

Production

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

Decay



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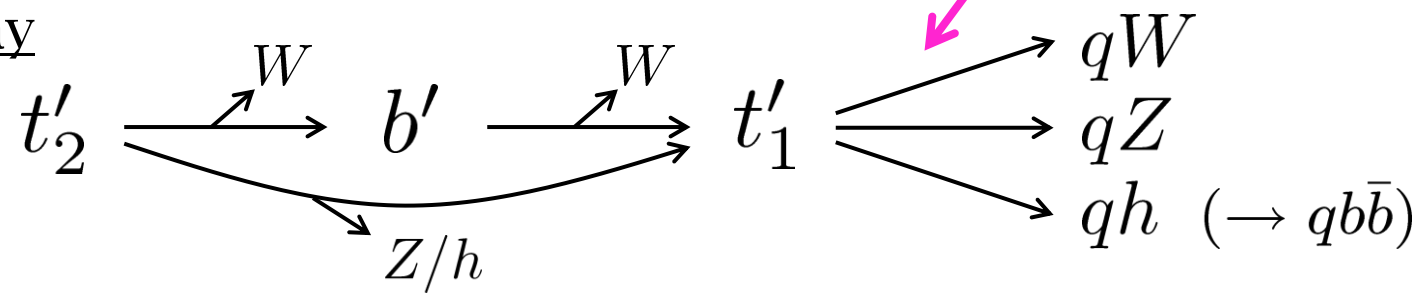


Vector-like Quark Search

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

$pp \to t'_1 \bar{t}'_1; \quad t'_1 \to qW,\ qZ,\ qh\ (\to q b\bar{b})$

Current bound

if it decays exclusively as

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

$t'_1 \to q_d W :: m_{t'_1} > 340\,\mathrm{GeV}$ CDF 5.6fb^{-1} [1107.3875]

$t'_1 \to tZ :: m_{t'_1} > 475\,\mathrm{GeV}$ CMS 1.14fb^{-1} [1109.4985]

$t'_1 \to q_u Z$ :: No bound yet

$t'_1 \to th$ :: **No bound yet**

$t'_1 \to q_u h$ :: **No bound yet**

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

≥ 4 b-quarks $(h \to b\bar{b})$

Interesting channel after Higgs discovery.

[K. Harigaya's talk (yesterday)]

Vector-like Quark Search

- New "vector-like" quark (t_1', b', t_2')

$pp \to t_1'\bar{t}_1'; \quad t_1' \to qW, qZ, qh \ (\to qb\bar{b})$

Once we have

$$t_1' \to bW :: m_{t_1'} > \mathbf{700}\,\text{GeV} \quad \text{CMS } 4.7\text{fb}^{-1} \text{ [EXO-11-050]}$$
$$t_1' \to q_d W :: m_{t_1'} > \mathbf{700}\,\text{GeV} \quad \text{CDF } 5.6\text{fb}^{-1} \text{ [1107.3875]}$$
$$t_1' \to tZ :: m_{t_1'} > \mathbf{700}\,\text{GeV} \quad \text{CMS } 1.14\text{fb}^{-1} \text{ [1109.4985]}$$
$$t_1' \to q_u Z :: m_{t_1'} > \mathbf{700}\,\text{GeV}$$
$$t_1' \to th :: m_{t_1'} > \mathbf{700}\,\text{GeV}$$
$$t_1' \to q_u h :: m_{t_1'} > \mathbf{700}\,\text{GeV}$$

} No general bound on t_1' yet because of these possibility.

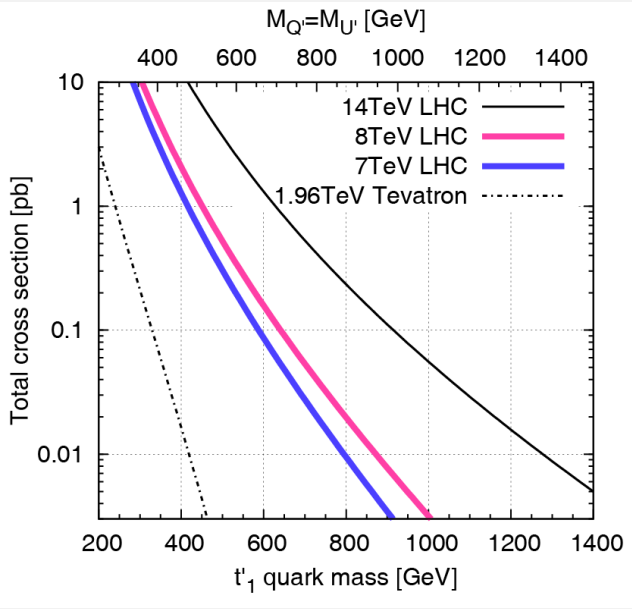
A great smash to this model;

Vector-like Quark Search

At LHC 8TeV,
production doubles!

⇩

More severe bounds,
or….?



$$t_1' \to th \quad :: m_{t_1'} > 700\,\text{GeV}$$
$$t_1' \to q_u h \quad :: m_{t_1'} > 700\,\text{GeV}$$

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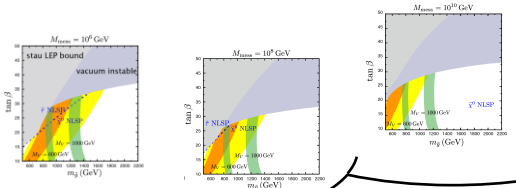
4. Conclusion

Conclusion

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

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



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

utopian theorists

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

Stay tuned & **hope new phenom. @ 8TeV LHC 2012!**