g-2 と 125GeV Higgs

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9 Mar. 2012
@ 札幌ウィンタースクール2012（北大）

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

[3]

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

muon $g - 2$ anomaly

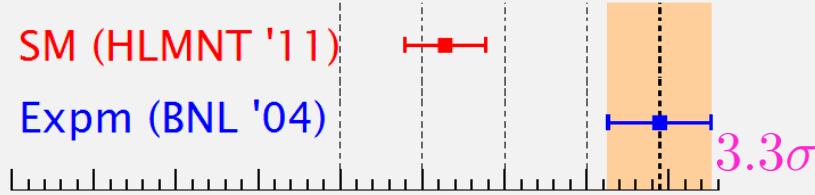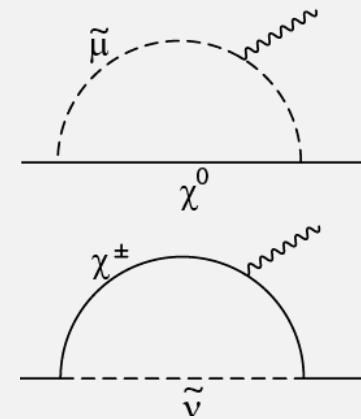SM (HLMNT '11)

Expm (BNL '04)

3.3σ

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

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mSUGRA / GMSB frameworks

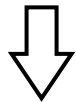# Standard Model

🙁 "hierarchy problem"

⬇ SUSY around TeV

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🙂 fermion/boson unification

🙂 GUTs, dark matter(?)

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

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mSUGRA / GMSB frameworks

However
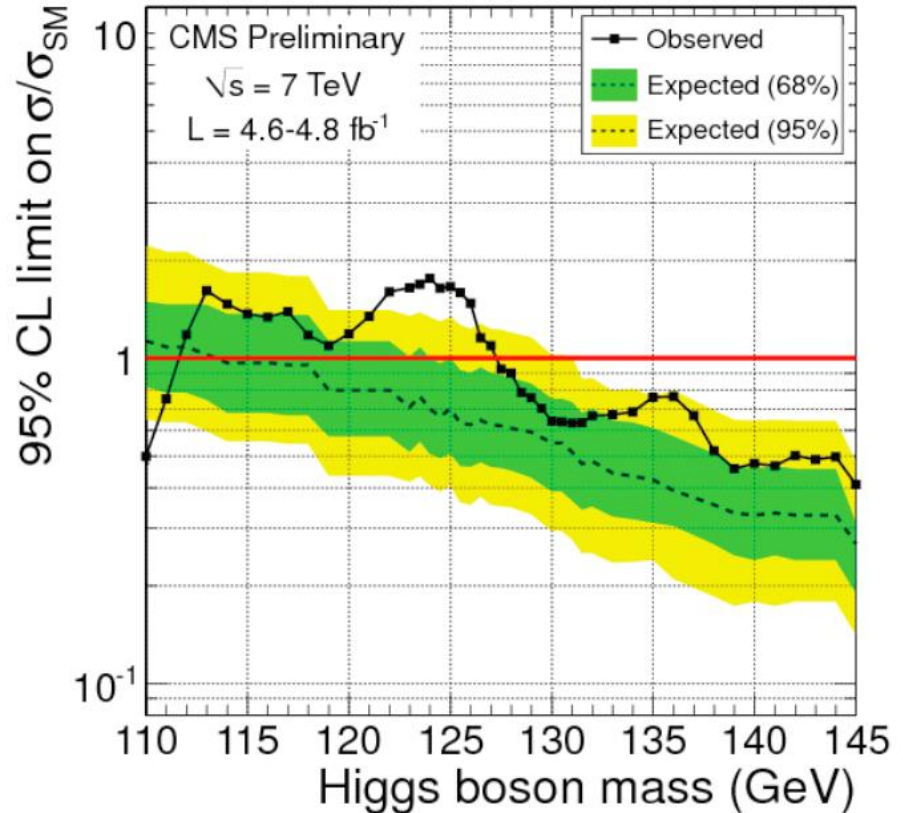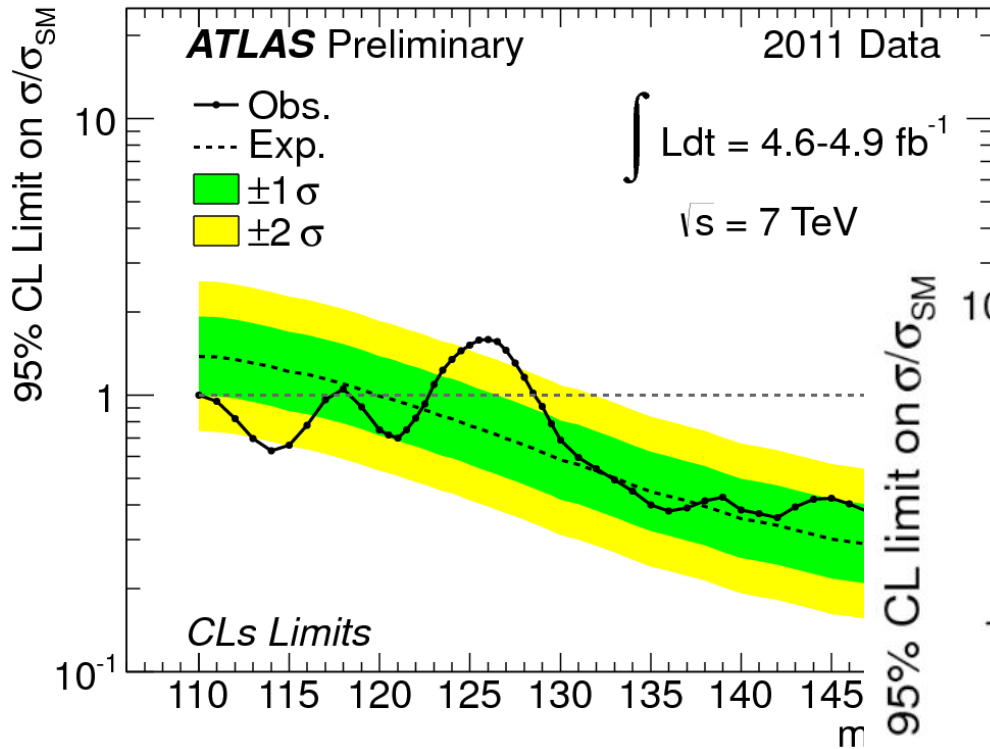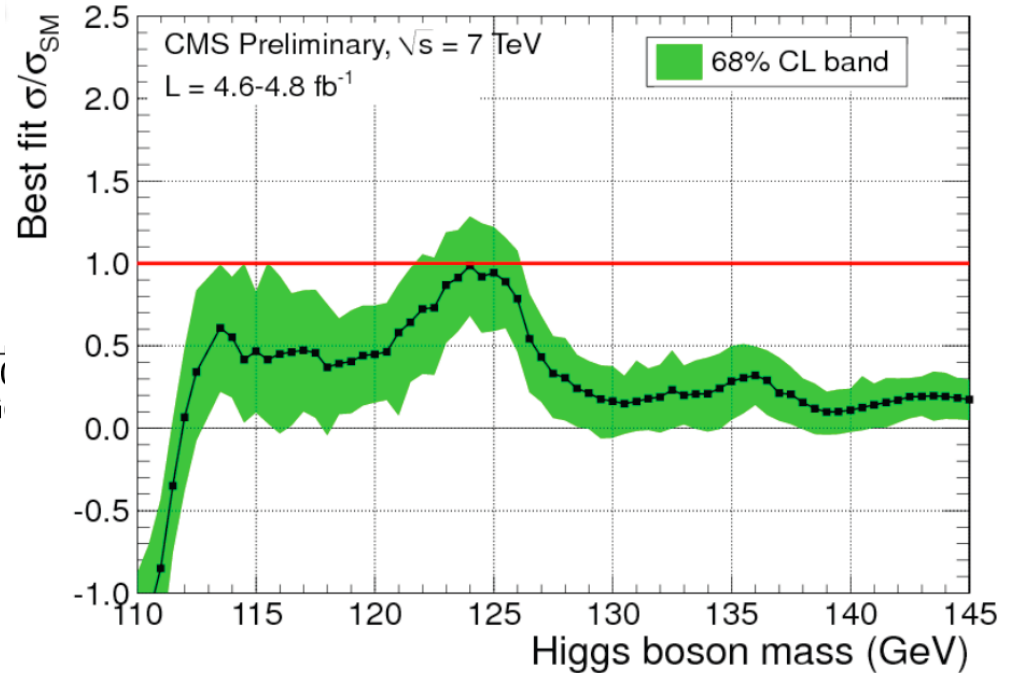
Now this "dream" is threatened by

The ~125GeV Higgs boson

The ~125GeV Higgs boson

The ~125GeV Higgs boson

**Very difficult in MSSM+mSUGRA;
Hopeless in MSSM+mGMSB.**
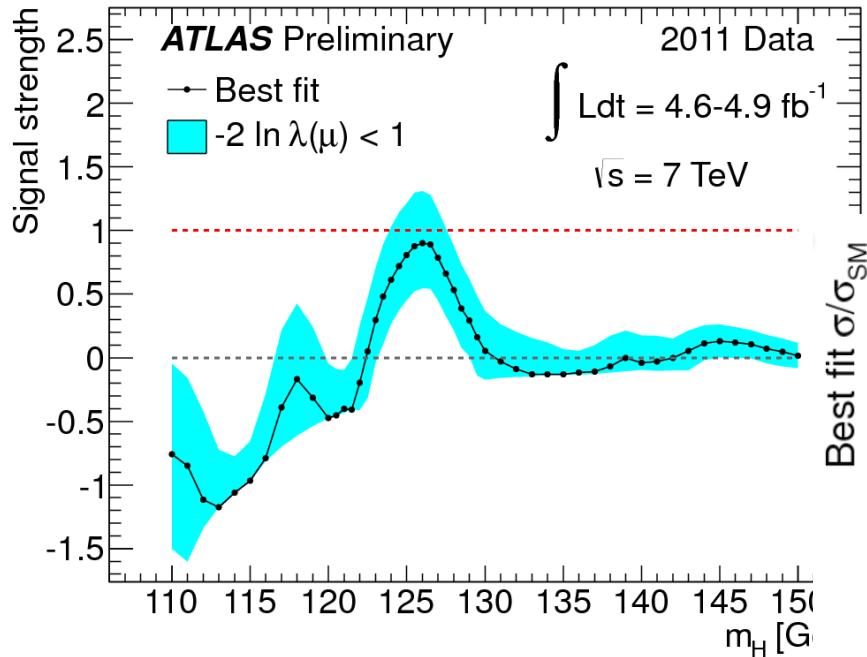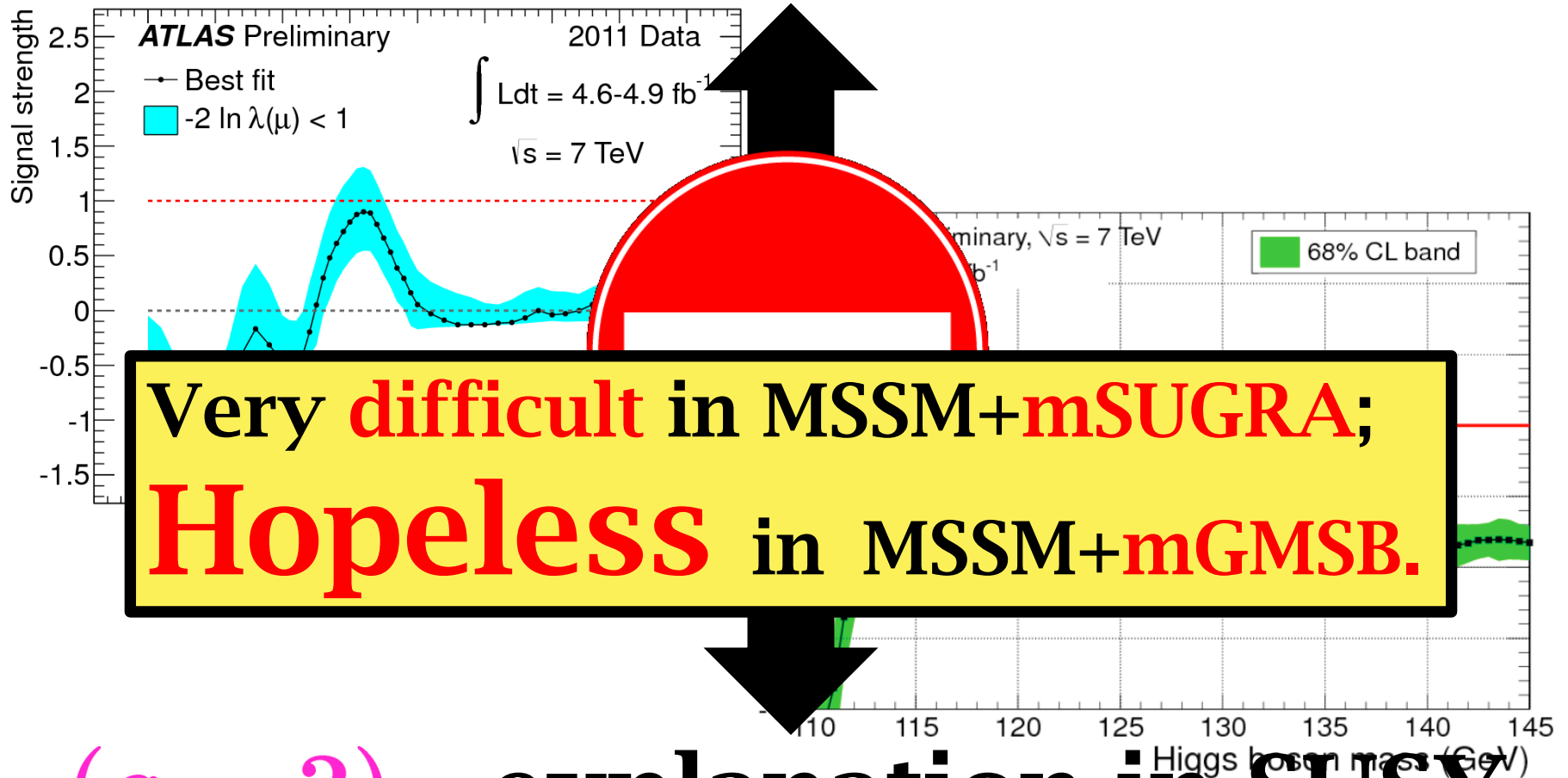
$(g-2)_\mu$ explanation in SUSY

125GeV in MSSM

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

(1-loop level)

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

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

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

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

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

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

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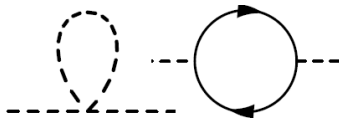- large $\tan\beta$

[10]

125Gev in MSSM

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

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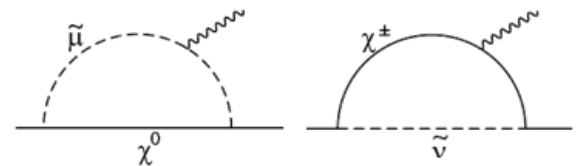# $(g-2)_\mu$ in MSSM

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

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

dilemma (GUT)

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

- large $(A_t - \mu\cot\beta)$ ⟵ - large $\tan\beta$

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

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

mSUGRA
- $b \to s\gamma$ 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 M0 for 1,2 / 3 gen.

χ^0 $\tilde{\nu}$
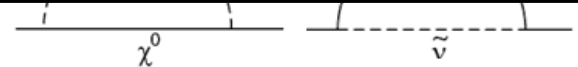
[11]

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.

[12]

For 125GeV & g−2, we must...

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⊙ **wish** a lighter Higgs.

⊙ **extend** the MSSM.

  ➢ ~~NMSSM~~ $g-2 \Rightarrow \text{large} \ \tan\beta \Rightarrow \text{NMSSM not contribute.}$

  ➢ 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]

[13]

2. The Extension we propose

Extension w. Vector–like Matters

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

$$m_h \Uparrow$$
$$W_{\text{add}} = Y' Q' H_{\text{u}} U' + Y'' \bar{Q}' H_{\text{d}} \bar{U}'$$
$$+ M_V Q' \bar{Q}' + M_V U' \bar{U}' + M_V E' \bar{E}'$$

IDEA

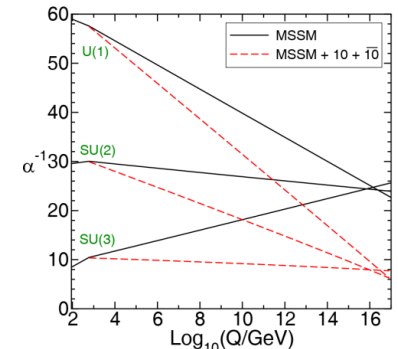MSSM: top (s)quark lifts up higgs. Okay, then…

Add another top quark!

$\Rightarrow$ Gauge anomaly…

$\Rightarrow$ Add as vector-like!

[15]

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]

$$m_h \Uparrow \qquad m_h \Downarrow \longrightarrow \text{we } assume\ Y'' \ll 1.$$

$$W_\text{add} = Y'Q'H_\text{u}U' + Y''\bar{Q}'H_\text{d}\bar{U}'$$
$$+ M_V Q'\bar{Q}' + M_V U'\bar{U}' + M_V E'\bar{E}'$$

$$W_\text{mix} = \epsilon_i Q_i H_\text{u} U' + \epsilon_i' Q' H_\text{u} \bar{U}_i + \epsilon_i'' Q' H_\text{d} \bar{D}_i$$

Mixing between SM- & vector-like quark
➢ Too large → flavor problem?
➢ No mixing → stable colored particle. $\implies$ *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.)

[16]

RESULT

in this talk

with $\begin{cases} \text{GMSB framework} \\ \text{mSUGRA framework} \end{cases}$

[17]

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

$\parallel$ $\parallel$ $\parallel$

1     $+$ 1.05

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

stau LEP bound

vacuum instable

$\tan\beta$

$\tilde\tau$ NLSP

$\tilde\chi^0$ NLSP

$M_V = 1000 \ \mathrm{GeV}$

$M_V = 600 \ \mathrm{GeV}$

$m_{\tilde g} \ (\mathrm{GeV})$

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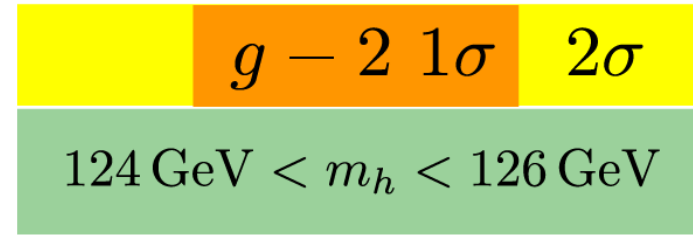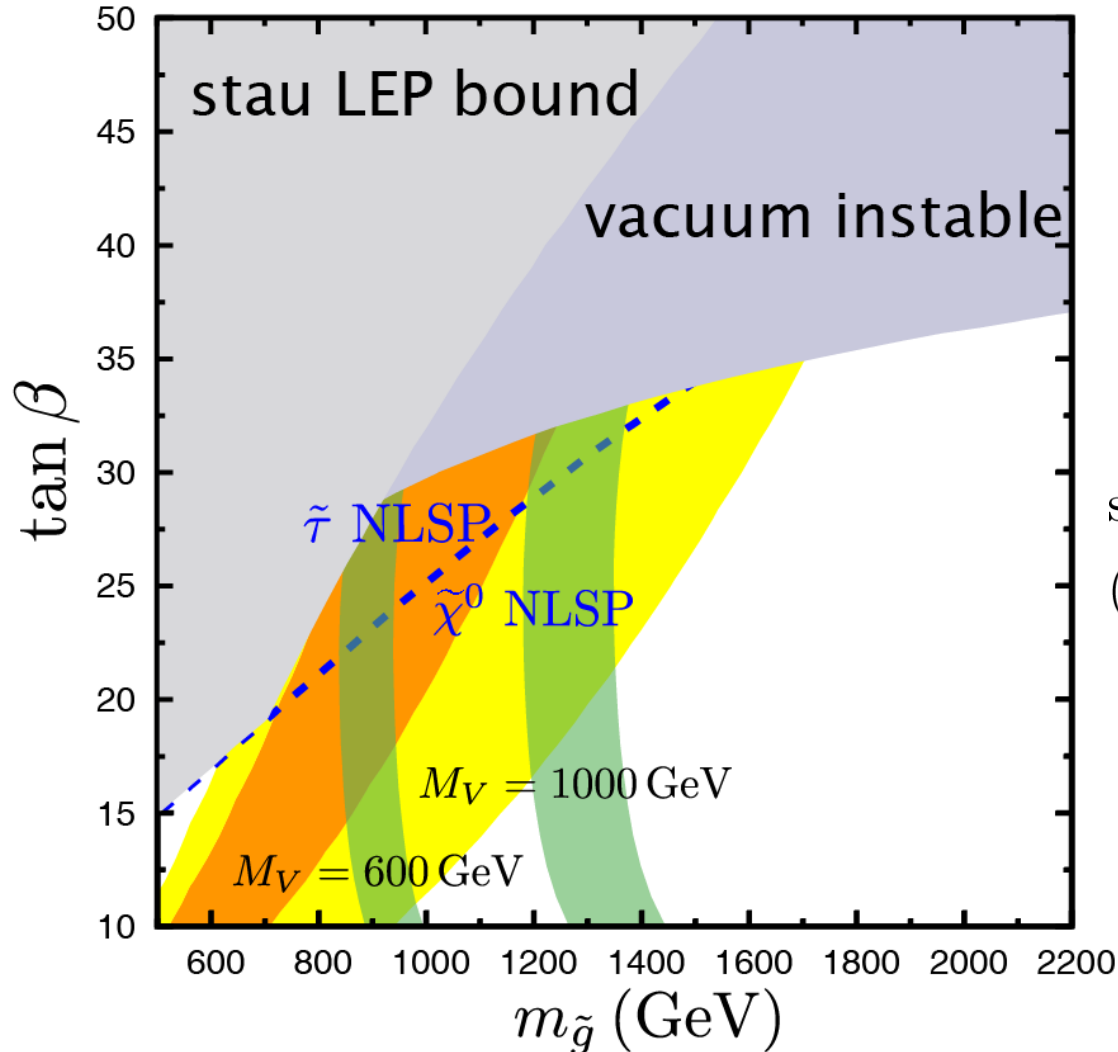
$124 \ \mathrm{GeV} < m_h < 126 \ \mathrm{GeV}$

simultaneous realization:

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

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

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

[18]

Legend (top left):
$g - 2$ 1σ 2σ
$124\,\mathrm{GeV} < m_h < 126\,\mathrm{GeV}$

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

$\parallel$ $\parallel$ $\parallel$
1   +   1.05

$M_{\mathrm{mess}} = 10^6\,\mathrm{GeV}$ $M_{\mathrm{mess}} = 10^8\,\mathrm{GeV}$ $M_{\mathrm{mess}} = 10^{10}\,\mathrm{GeV}$

stau LEP bound   vacuum instable

$\tilde{\tau}$ NLSP $\tilde{\chi}^0$ NLSP

$M_V = 1000\,\mathrm{GeV}$ $M_V = 600\,\mathrm{GeV}$

axes: $\tan\beta$ vs $m_{\tilde{g}}\,(\mathrm{GeV})$
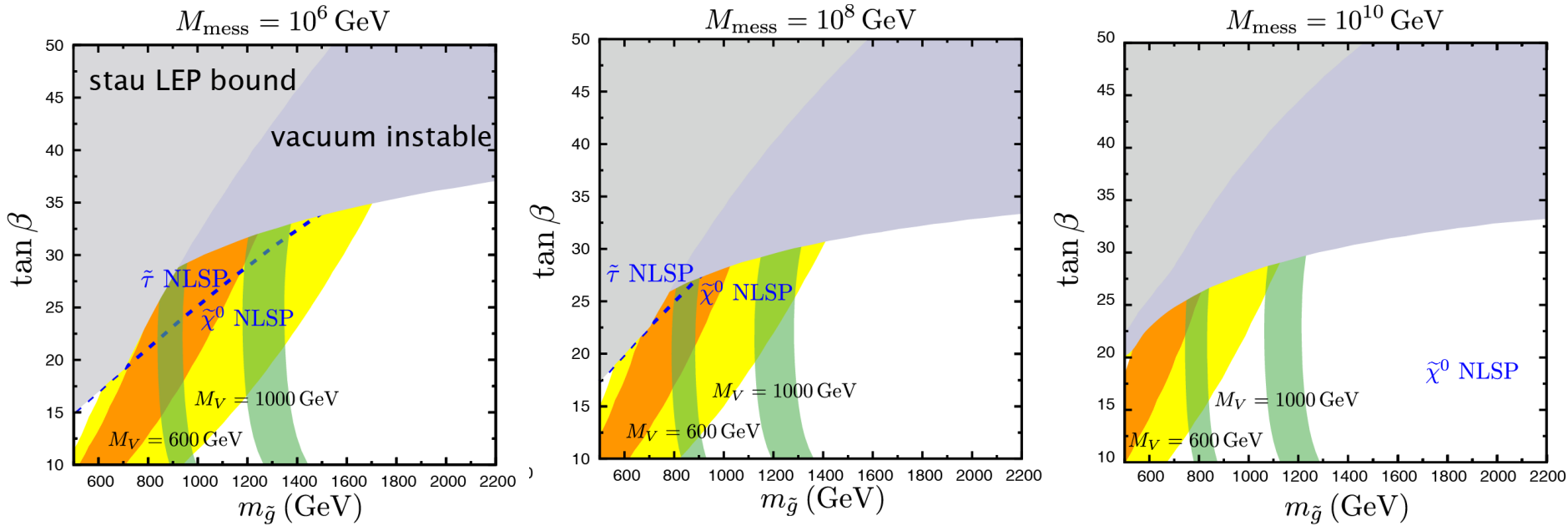
- $(g - 2)_\mu$ expm. tells us $(2\sigma$-level$)$,

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

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

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

[19]

3. LHC Phenomenology

SUSY search

$M_{\mathrm{mess}} = 10^6\,\mathrm{GeV}$ $M_{\mathrm{mess}} = 10^8\,\mathrm{GeV}$ $M_{\mathrm{mess}} = 10^{10}\,\mathrm{GeV}$
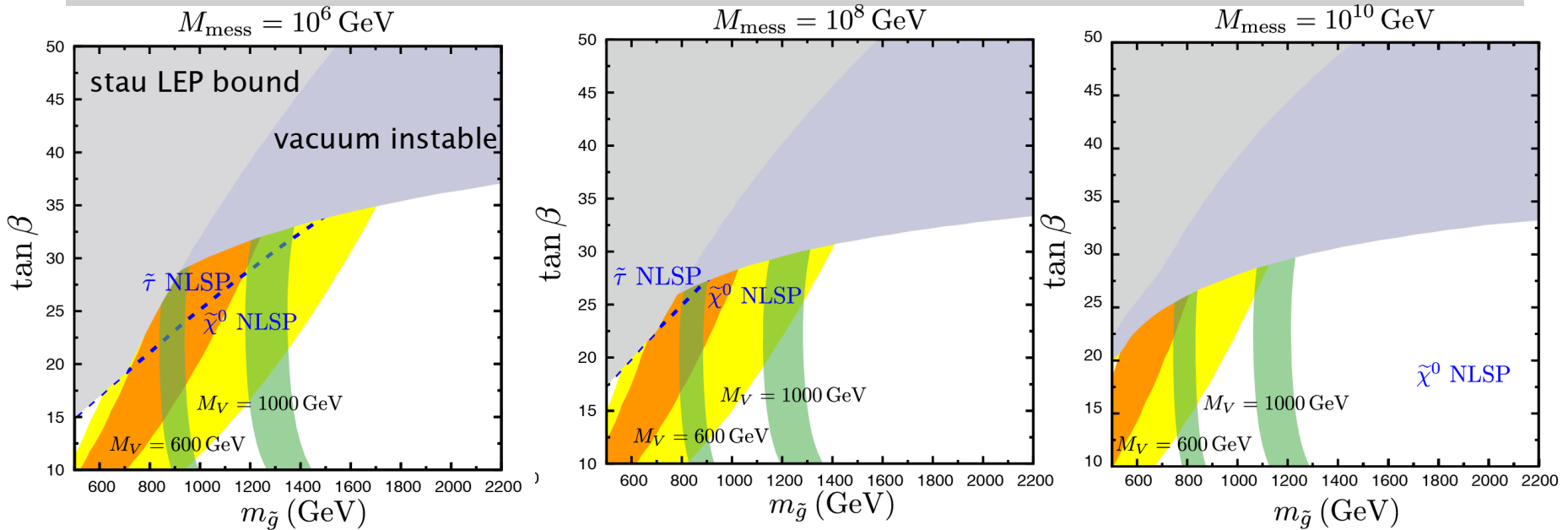
	prompt decay $(M_{\mathrm{mess}} \lesssim 10^5\,\mathrm{GeV})$	long-lived $(M_{\mathrm{mess}} \gtrsim 10^6\,\mathrm{GeV})$
$\widetilde{\chi}^0$	curr. $(1\mathrm{fb}^{-1})\ m_{\widetilde{g}} \gtrsim 1.2\,\mathrm{TeV}$ $2\gamma + \not{E}$: ATLAS[1111.4116]	curr. $(1\mathrm{fb}^{-1})\ m_{\widetilde{g}} \gtrsim 700\,\mathrm{GeV}$ $4j + \not{E}$: ATLAS[1109.6575], CMS[SUS11-008]
$\widetilde{\tau}$	will easily be covered by multi-lepton search	already excluded (CMS hvy-stbl chrgd prtcl; Seminar Jan. '12)

[21]

Vector–like Quark Search

- 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

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

Decay

$$t'_2 \xrightarrow{\;W\;} b' \xrightarrow{\;W\;} t'_1 \begin{array}{l} \rightarrow qW \\ \rightarrow qZ \\ \rightarrow qh \;\; (\rightarrow qb\bar{b}) \end{array}$$

Z/h

[22]
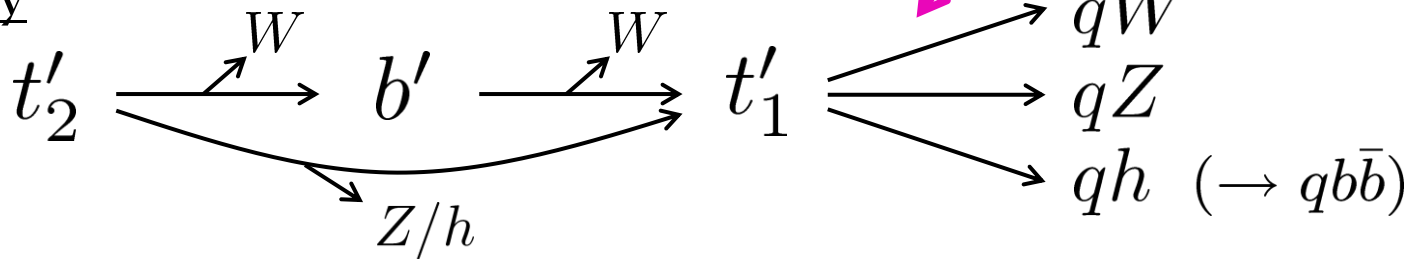
Vector–like Quark Search

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

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

Current bound

if it decays exclusively as

$t_1' \to bW \;\; :: m_{t_1'} > 552\,\text{GeV}$ CMS 4.7fb^{-1} [EXO-11-050]

$t_1' \to q_d W :: m_{t_1'} > 340\,\text{GeV}$ CDF 5.6fb^{-1} [1107.3875]

$t_1' \to tZ \;\;\; :: m_{t_1'} > 475\,\text{GeV}$ 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**

$\left. \right\}$ No general bound on t_1' yet because of these possibility.

≥ 4 b-quarks $(h \to b\bar{b})$

Interesting channel after Higgs discovery.

[23]

Vector-like Quark Search

At LHC 8TeV,
 production doubles!

$\Downarrow$

More severe bounds,
 or....?
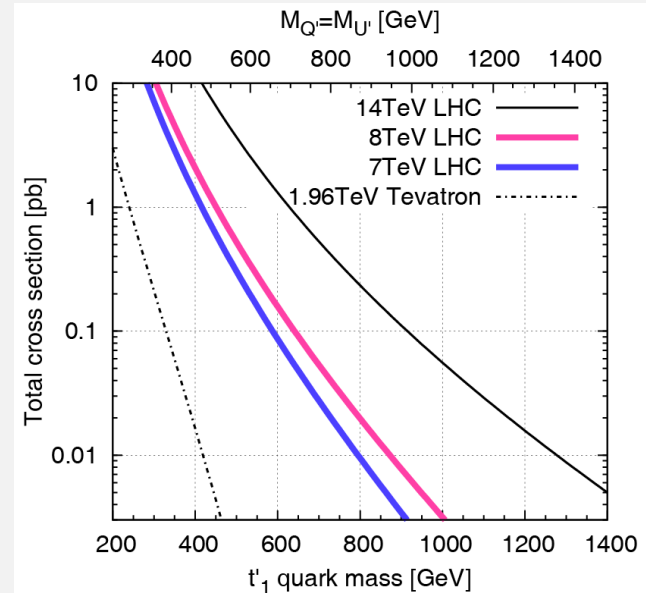
$t'_1 \to th$ :: **No bound yet**

$t'_1 \to q_u h$ :: **No bound yet**
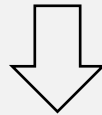
No general bound on t'_1 yet
because of these possibility.

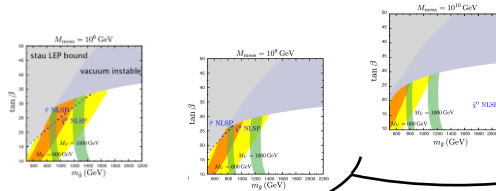$\geq 4\ b$-quarks $\quad (h \to b\bar{b})$

Interesting channel after Higgs discovery.

4. Conclusion

Conclusion

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

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

utopian theorists

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

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

[26]