Supersymmetry after Higgs discovery and its LHC phenomenology

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Dissertation Defense at the University of Tokyo

References)

M. Endo, K. Hamaguchi, SI, and N. Yokozaki,
Phys. Rev. D84 (2011) 075017 [arXiv:1108.3071],
Phys. Rev. D85 (2012) 095012 [arXiv:1112.5653],
JHEP 1206 (2012) 060 [arXiv:1202.2751],
M. Endo, K. Hamaguchi, K. Ishikawa, SI, and N. Yokozaki, arXiv:1212.3935 (accepted by JHEP).

See also)

S. Iwamoto, AIP Conf. Proc. 1467 (2012) 57-61 [arXiv:1206.0161].

V-GMSB scenario

$$=$$

$$\textbf{V}\text{-MSSM model} \left(\text{MSSM} + \mathbf{10} + \overline{\mathbf{10}} \right)$$

$$+$$

GMSB framework

①
- Higgs mass → ~ 126 GeV!
- muon $g-2$ anomaly → solved!

② LHC constraints
(SUSY search, extra quark search)

[2]

Introduction

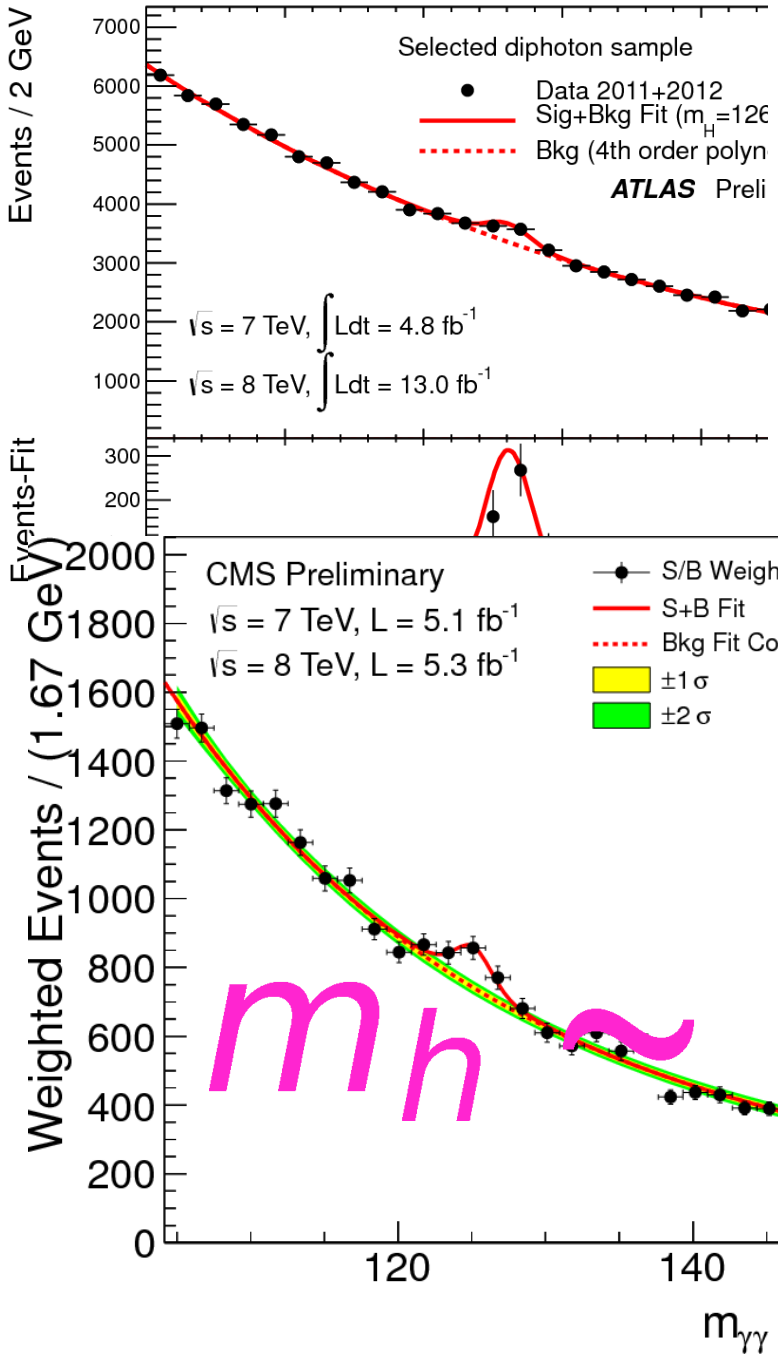
Why V-MSSM?

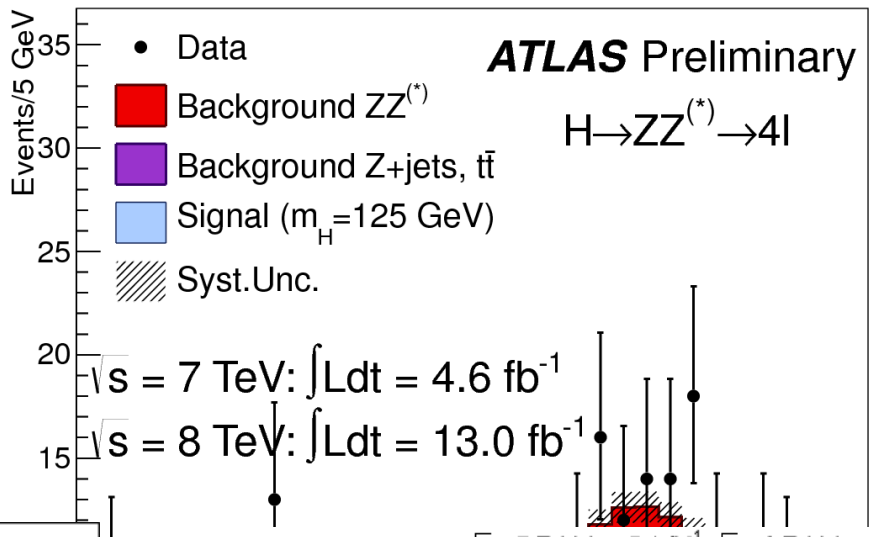
2012

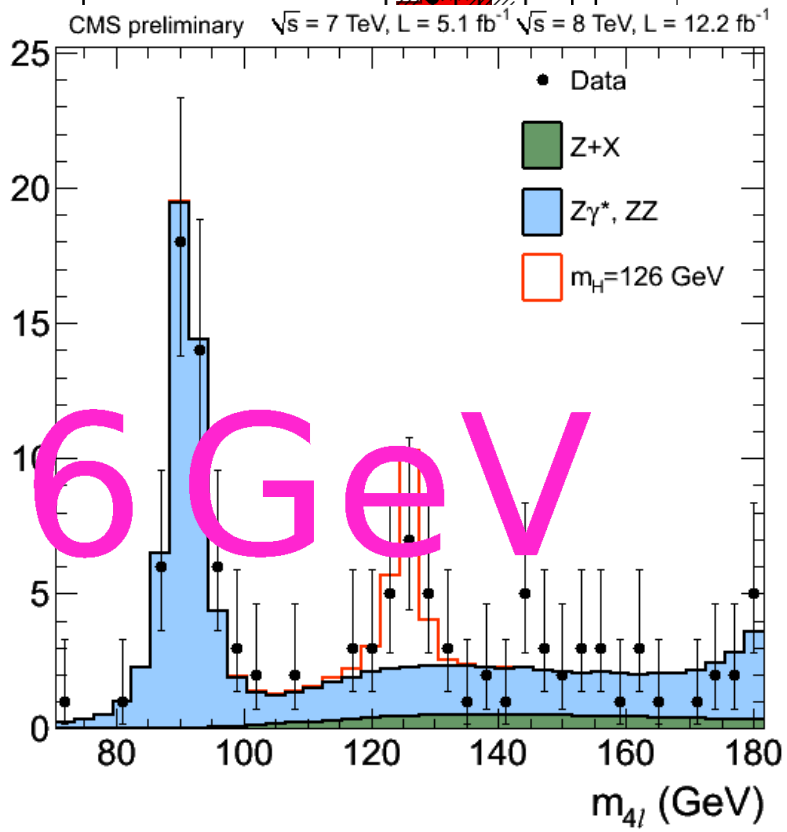
[6]

Higgs boson was Discovered!

[7]



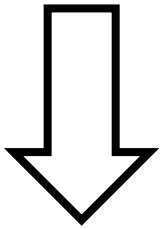




$m_h \approx 126$ GeV

Standard Model Now Completed!

- Problems
  - Hierarchy Problem, muon $g-2$ anomaly, Dark Matter, …
- Anxiety towards ultimate theory



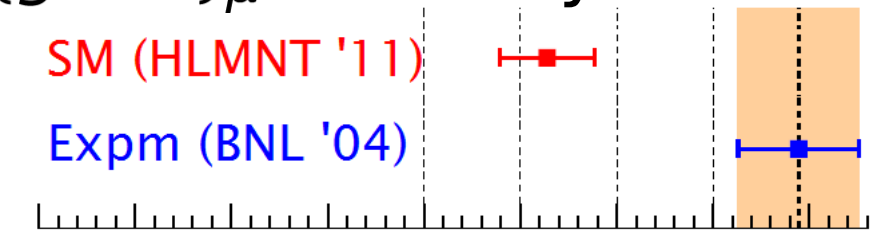
Supersymmetry (SUSY)

MSSM (Minimal SUSY Standard Model)

- Hierachy problem **Solved**
- Dark Matter Candid **Provided**
- Muon $g-2$ anomal **Explained**

$\left(a_\mu := \frac{g_\mu - 2}{2}\right)$

$(g-2)_\mu$ anomaly



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

$$a_\mu^{\mathrm{SM}} = (116\,591\,828 \pm 49) \times 10^{-11}$$

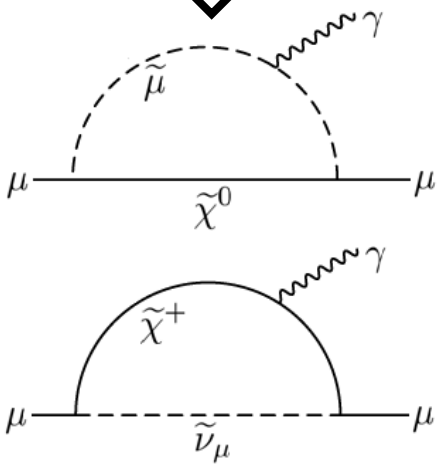
$$a_\mu^{\mathrm{exp}} = (116\,592\,089 \pm 63) \times 10^{-11}$$

3.3σ discrepancy

Can be explained with SUSY

if $\mu > 0$, $\tan\beta \gtrsim 10$,

and $m\left(\tilde{\chi}^0, \tilde{\chi}^\pm, \tilde{\mu}, \tilde{\nu}_\mu\right) \sim \mathrm{O}(100)\,\mathrm{GeV}$.



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

$$\Delta a_\mu\left(\tilde{\chi}^\pm, \tilde{\nu}\right) \approx \frac{\alpha_2 m_\mu^2}{m_{\mathrm{soft}}^2} \mathrm{sgn}(\mu M_2) \tan\beta.$$

$\left(\tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}\right)$

MSSM (Minimal SUSY Standard Model)

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$$m\left(\tilde{\chi}^0, \tilde{\chi}^{\pm}, \tilde{\mu}, \tilde{\nu}_{\mu}\right) \sim \mathrm{O}(100)\,\mathrm{GeV}??$$

in conflict!

$$m\left(\tilde{t}\right) \sim \mathrm{O}(1\text{–}10)\,\mathrm{TeV}??$$

NEW FACT!

- Higgs mass = 126 GeV!

tree — one-loop level (top-stop)

$$m_h^2 \approx m_Z^2 + \frac{3 g_W^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} - \frac{(\alpha^2-6)^2}{12} + 3\right]$$

where $\alpha := A_t/m_{\tilde{t}}$.

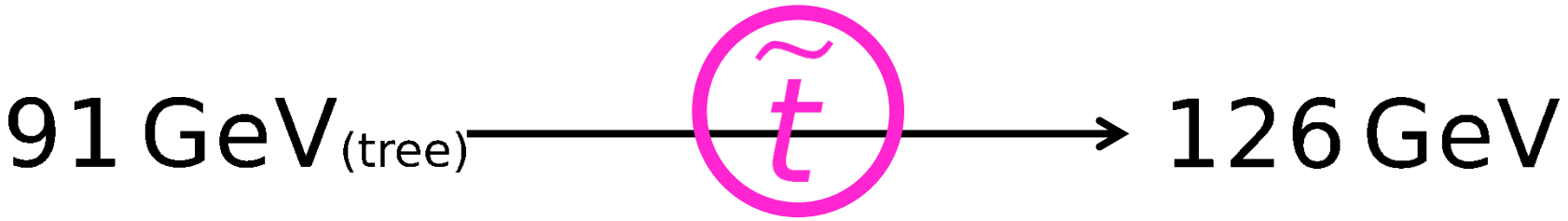
(stop mixing parameter)

heavier m_h $\Longleftrightarrow$

- $\tilde{t}$ should be *heavy*

  and/or

- stop mixing parameter α at sweet spot ($\sim \pm\sqrt{6}$).



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where $\alpha := A_t/m_{\tilde{t}}$.

(stop mixing parameter)

heavier m_h $\Longleftrightarrow$ $m_{\tilde{t}} \sim \begin{cases} 1\text{–}2\,\text{TeV} & (\alpha \sim \pm\sqrt{6}) \\ \text{O}(10)\,\text{TeV} & (\alpha \sim 0) \end{cases}$

- $\tilde{t}$ should be *heavy*

  and/or

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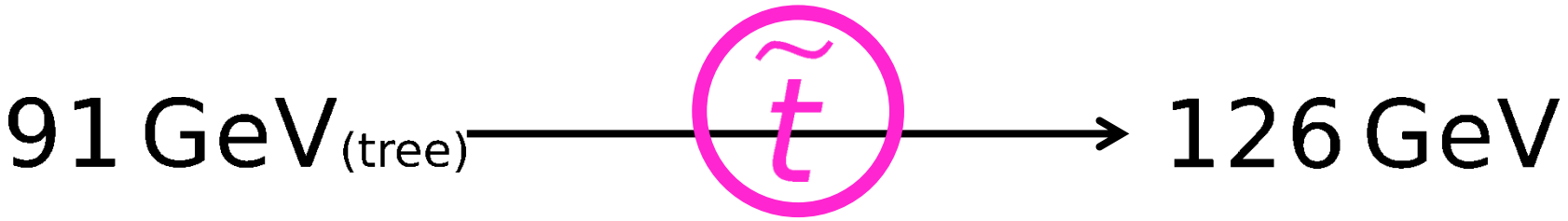

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NEW FACT!

- Higgs mass = 126 GeV!

$$m_{\tilde{t}} \sim \begin{cases} 1\text{–}2\,\mathrm{TeV} & [\alpha = A_t/m_{\tilde{t}} \sim \pm\sqrt{6} \ : \ \text{maximal-mixing (“}m_h\text{-max”) scenario}] \\ \mathrm{O}(10)\,\mathrm{TeV} & [\text{small } \alpha \text{ (small mixing)}] \end{cases}$$

e.g. **IMPOSSIBLE** in CMSSM / GMSB scenario

$m_{\tilde{q}} \Longleftrightarrow m_{\tilde{l}}$ & A_t cannot be large.

correlated

CMSSM $\rightarrow A_0$ is constrained from Br($b \rightarrow s\gamma$).
GMSB $\rightarrow A_t = 0$ at one-loop level.

$$m\left(\tilde{\chi}^0, \tilde{\chi}^{\pm}, \tilde{\mu}, \tilde{\nu}_{\mu}\right) \sim \mathrm{O}(100)\,\mathrm{GeV}??$$

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NEW FACT!

- Higgs mass = 126 GeV!

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$$m\left(\tilde{\chi}^0, \tilde{\chi}^{\pm}, \tilde{\mu}, \tilde{\nu}_{\mu}\right) \sim \mathrm{O}(100)\,\mathrm{GeV}??$$

in conflict! ➡ **How to resolve?**

$m\left(\tilde{t}\right) \sim$

- Forget $(g-2)_{\mu}$.
- Optimize ~~SUSY~~ mechanism.
- Extend the MSSM.

NEW FACT!

- Higgs mass = 126 Ge

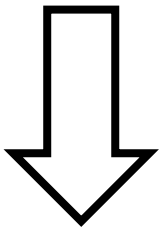
$$m_{\tilde{t}} \sim \begin{cases} 1\text{–}2\,\mathrm{TeV} & [\alpha = A_t/m_{\tilde{t}} \sim \\ \mathrm{O}(10)\,\mathrm{TeV} & [\text{small } \alpha \text{ (small mixing)}] \end{cases}$$

V-MSSM + GMSB

can explain $(g-2)_\mu$ under $m_h = 126\,\mathrm{GeV}$.

MSSM + GMSB (or mSUGRA)

$\Longrightarrow$ ~~$(g-2)_\mu$ with $m_H = 126$ GeV~~

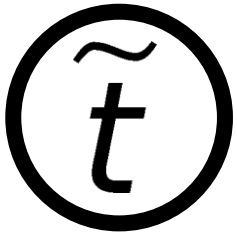


MSSM + **more complicated ~~SUSY~~**

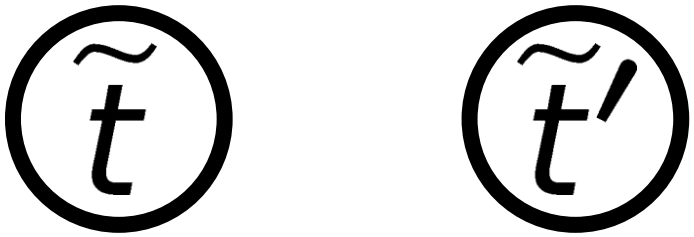
or

V-MSSM + GMSB/mSUGRA

Key Idea



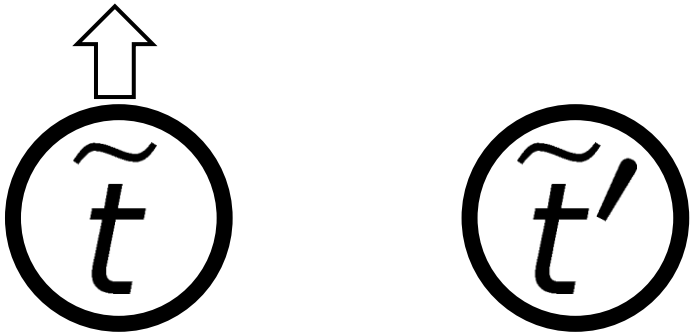
Key Idea



$(g-2)_\mu \cdots m\left(\tilde{\chi}^0, \tilde{\chi}^\pm, \tilde{\mu}, \tilde{\nu}_\mu\right) \sim \mathrm{O}(100)\,\mathrm{GeV}??$

Conflict resolved.

$m_h \sim 126\,\mathrm{GeV} \cdots$ ~~$m\left(\tilde{t}\right) \sim \mathrm{O}(1\text{–}10)\,\mathrm{TeV}??$~~ $\tilde{t}$ can be lighter.



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

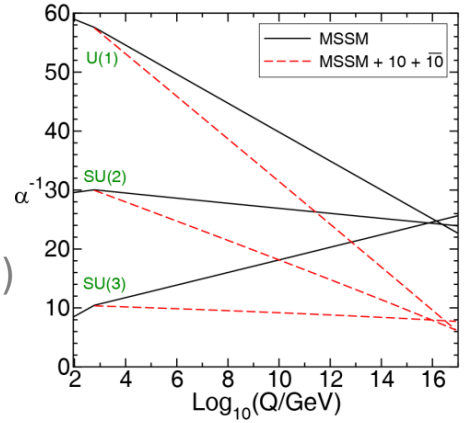
extra **V**ector-like matters

$$W_{\text{extra}} = Y'Q'H_u\bar{U}' + Y''\bar{Q}'H_dU' + M_VQ'\bar{Q}' + M_VU'\bar{U}' + M_VE'\bar{E}'$$

(cf. $W_{\text{MSSM}} \ni Y_tQH_u\bar{U}$)

$$W_{\text{mix}} = \epsilon_iQ_iH_uU' + \epsilon'_iQ'H_u\bar{U}_i + \epsilon''_iQ'H_d\bar{D}_i + \epsilon^L_iL_iH_d\bar{E}'$$

- Vector-like ⇨ • No gauge anomaly.
  • Gauge couplings unification.
- Mixings ⇨ necessary (to avoid stable particles)
  but must be tiny (to avoid large flav. viol.)
- Y' : IR fixed to ~1.05 ⇨ m_h well increased.
- Y'' : reduces m_h ⇨ assumed small.



Martin [0910.2732]

RESULT

in dissertation

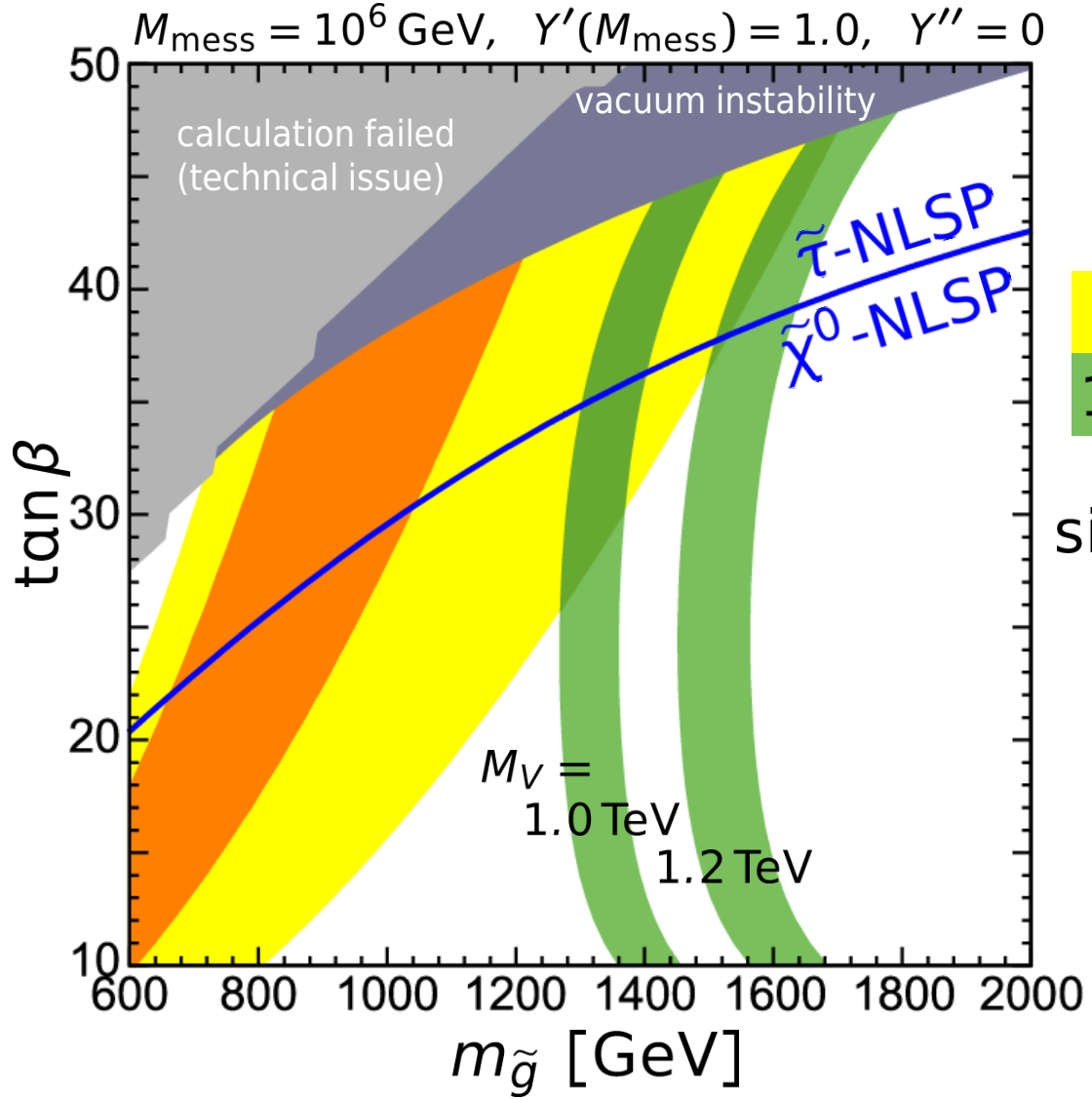
with { GMSB framework / mSUGRA framework

→ See [1112.5653]

[23]

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

$N_{\rm mess} = 1$ + $\Delta(g\text{-}2)>0$; $Y' = 1.0$ (IR fixed)



$g-2$ 1σ 2σ

$125\,{\rm GeV} < m_h < 126\,{\rm GeV}$

simultaneous realization:

$M_V \lesssim 1.2\,{\rm TeV}$,

$m_{\tilde{g}} \lesssim 1.6\,{\rm TeV}$,

$\tan\beta \sim {\rm O}(10)$

[24]

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

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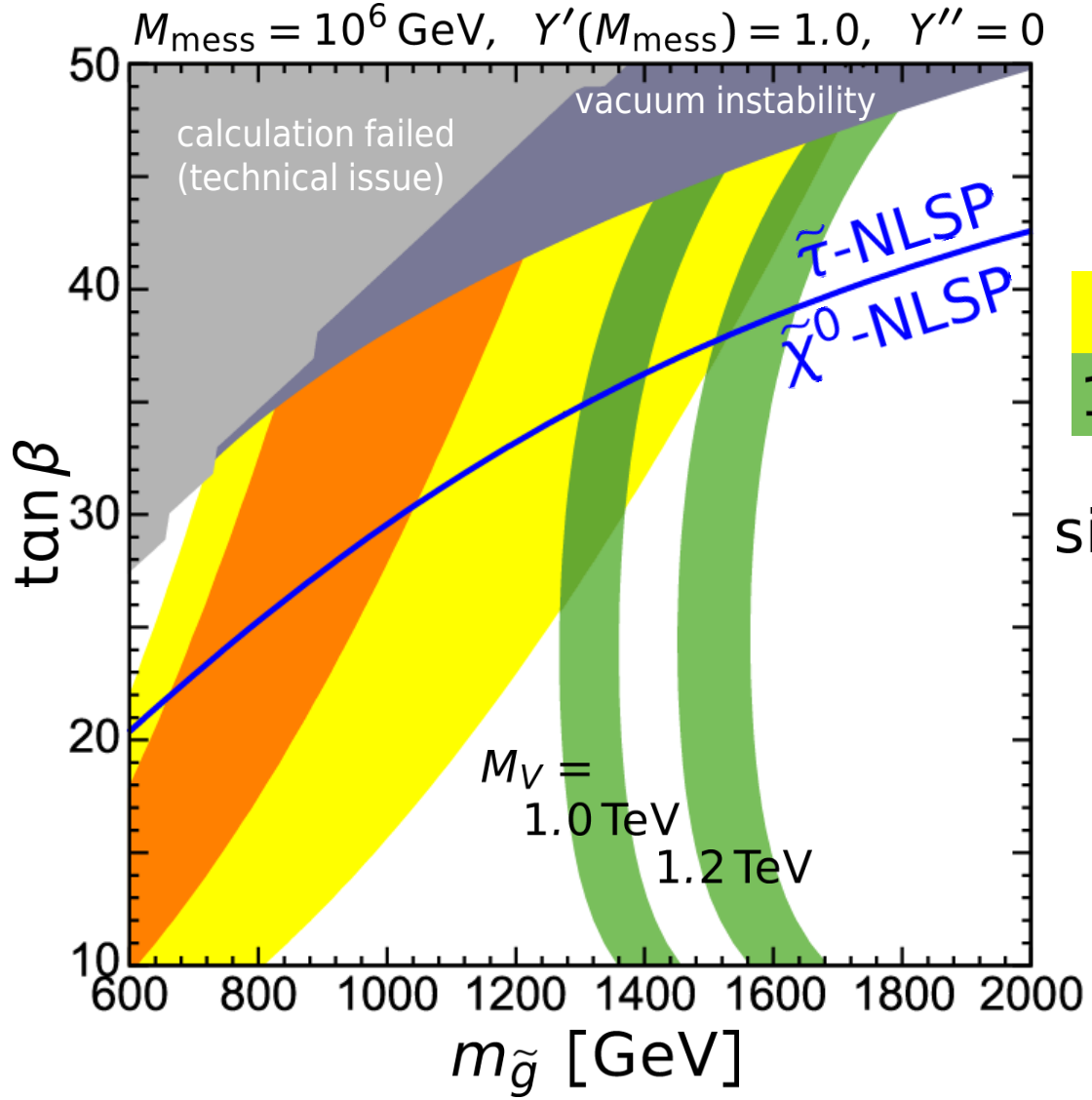

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$M_V \lesssim 1.2$ TeV,

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$\tan\beta \sim {\rm O}(10)$

➡ **LHC LIMIT!?**

[25]

LHC constraints on V-MSSM

(1) from searches for extra quarks.

(2) from searches for SUSY.

- $(Q', \bar{U}', \bar{E}') + (\bar{Q}', U', E') \to \left(\tilde{t}'_{1,2,3,4}, \tilde{b}'_{1,2}, \tilde{\tau}'_{1,2}\right)$

  $\& \left(t'_1, t'_2, b', \tau'\right)$

  - Mass

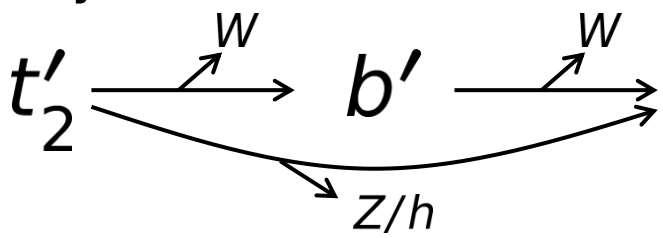
    $m_{t'} \sim M_V \pm (174\,\mathrm{GeV}/2),$

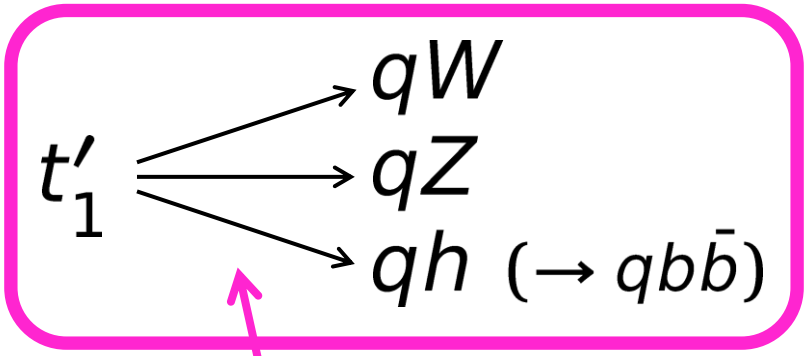
    $m_{b'} = m_{\tau'} = M_V$

  - Production

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

  - Decay





$$W_{\mathrm{extra}} = Y' Q' H_u \bar{U}' + M_V Q' \bar{Q}' + M_V U' \bar{U}' + M_V E' \bar{E}'$$

$$W_{\mathrm{mix}} = \epsilon_i Q_i H_u U' + \epsilon'_i Q' H_u \bar{U}_i + \epsilon''_i Q' H_d \bar{D}_i + \epsilon^L_i L_i H_d \bar{E}'$$

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

- $(Q', \bar{U}', \bar{E}') + (\bar{Q}', U', E') \to \left(\tilde{t}'_{1,2,3,4}, \tilde{b}'_{1,2}, \tilde{\tau}'_{1,2}\right)$

  $\& \left(t'_1, t'_2, b', \tau'\right)$

  - Current bounds

    $W_{\rm mix} = \epsilon_i Q_i H_u U' + \epsilon'_i Q' H_u \bar{U}_i + \epsilon''_i Q' H_d \bar{D}_i + \epsilon^L_i L_i H_d \bar{E}'$

    - Under "exclusive decay" assumption

3rd gen only (favored to avoid flavor constr.)

$t'_1 \to bW$ :: $m_{t'_1} > 656\,\text{GeV}$ ATLAS 7 TeV-4.7fb^{-1} [1210.5468]

$t'_1 \to tZ$ :: $m_{t'_1} > 625\,\text{GeV}$ CMS 7 TeV-5.0fb^{-1} [1210.7471]

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

$t'_1 \to q_d W$ :: $m_{t'_1} > 350\,\text{GeV}$ ATLAS 7 TeV-1.04fb^{-1} [1202.3389]

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

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

$m_{t'_1} \sim M_V - 87\,\text{GeV}$,

$pp \to t'_1 \bar{t}'_1, \qquad t'_1 \to (qW, qZ, qh)$

- Generic analysis (3rd gen. assumption : $t'_1 \to (bW, tZ, th)$)
  - Done by ATLAS (7 TeV-4.7fb^{-1} [1210.5468])

$M_V \lesssim 750\,\text{GeV}$ cases have (some) constraints.

LHC constraints on V-MSSM

(1) from searches for extra quarks.

(2) from searches for SUSY.

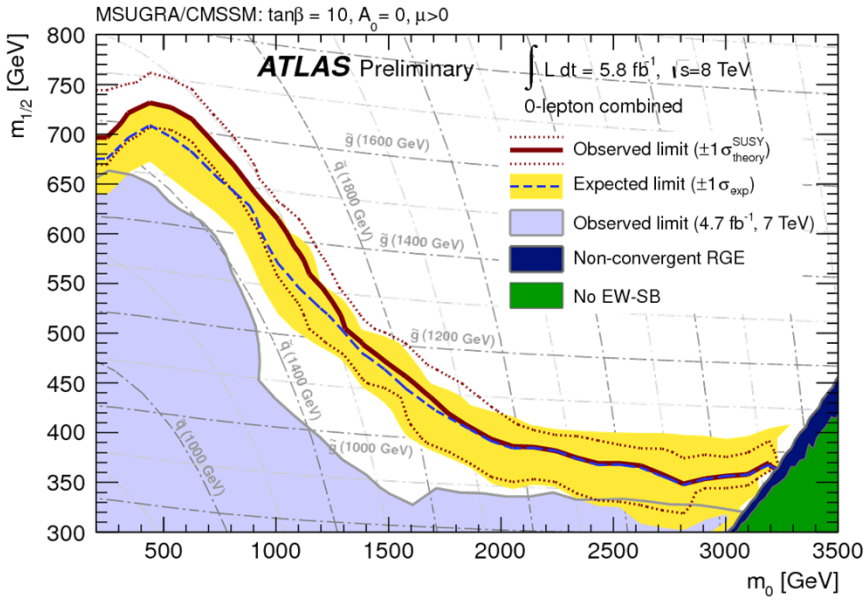
NLSP	Long-lived NLSP	NLSP prompt decay
$\tilde{\chi}_1^0$	jet + $\not{E}_T$ ($\tilde{\chi}_1^0\tilde{\chi}_1^0$) (same as mSUGRA)	jet + $\not{E}_T$ and $2\gamma + \not{E}_T$ (from $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$)
$\tilde{\tau}_1$	Long-lived stau	multi-tau

Examined in dissertation

Briefly discussed
(but left as future works)

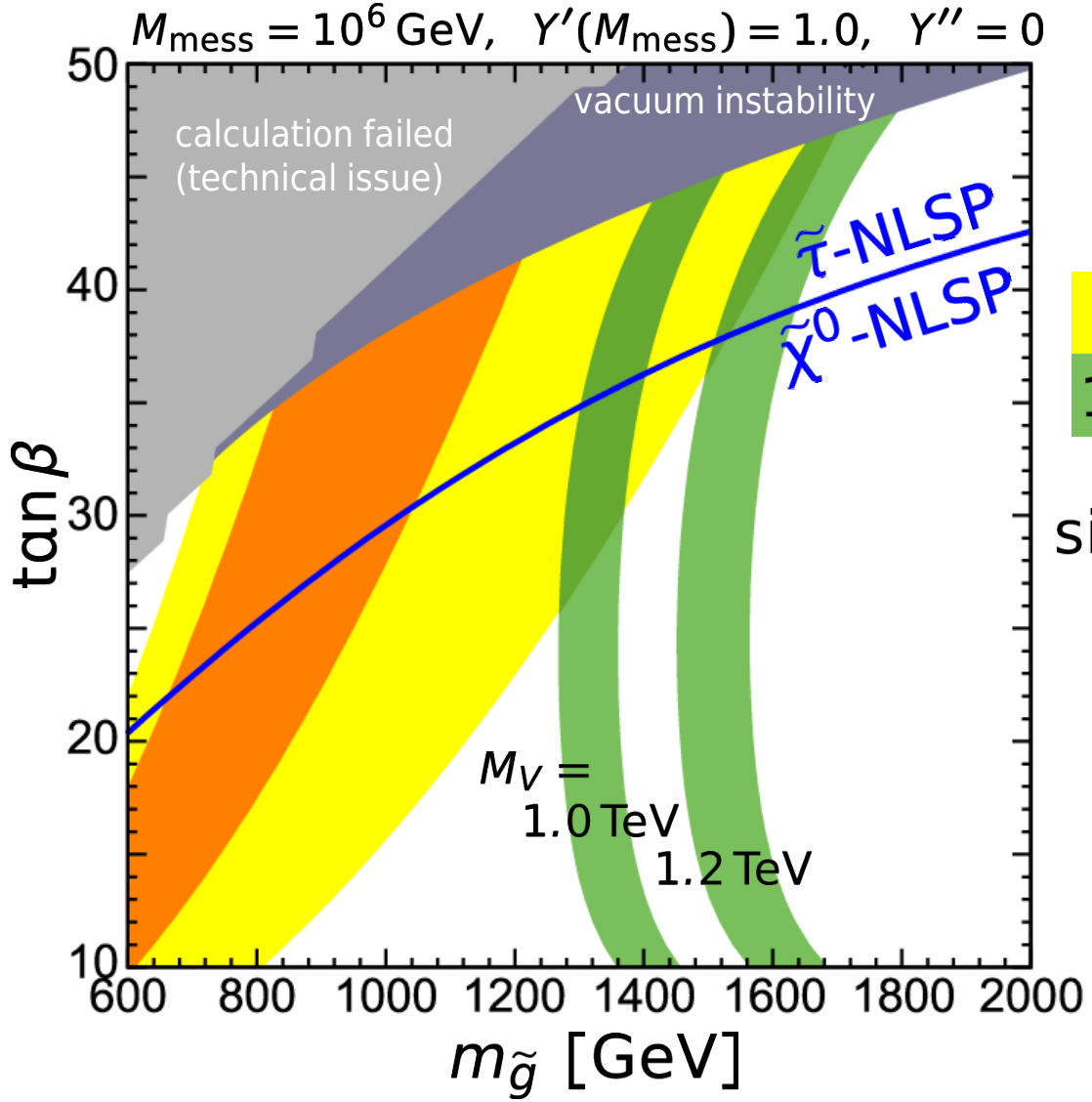
NLSP	Long-lived NLSP	NLSP prompt decay
$\tilde{\chi}_1^0$	jet + $\not{E}_T$ ($\tilde{\chi}_1^0\tilde{\chi}_1^0$) (same as mSUGRA)	jet + $\not{E}_T$ and $2\gamma + \not{E}_T$ (from $\tilde{\chi}_1^0 \to \gamma\tilde{G}$)
$\tilde{\tau}_1$	Long-lived stau	multi-tau

- Our analysis
  - Neutralino NLSP
    - → ATLAS 8 TeV-5.8 fb^{-1} (2–6 jets + $\not{E}_T$) [ATL-CONF-2012-109]
  - Stau NLSP
    - → CMS 7 TeV-5.0 fb^{-1} (assuming $pp \to \tilde{\tau}_1\tilde{\tau}_1^*$) ⇝ $m_{\tilde{\tau}_1} > 223$ GeV [1205.0272]



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

$N_{\rm mess} = 1$ + $\Delta(g\text{-}2)>0$; $Y' = 1.0$ (IR fixed)



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$125\,{\rm GeV} < m_h < 126\,{\rm GeV}$

simultaneous realization:

$M_V \lesssim 1.2\,{\rm TeV}$,

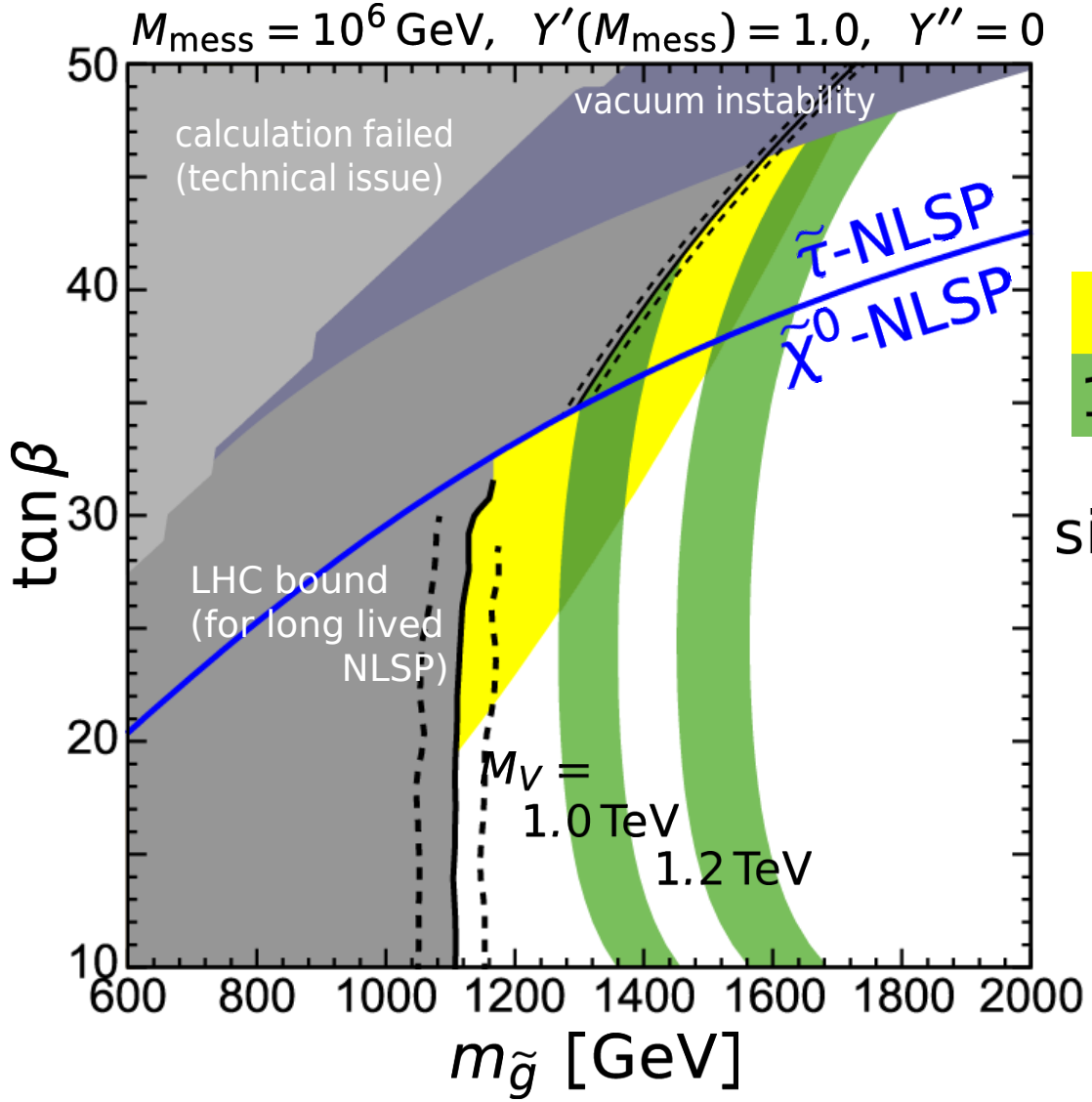
$m_{\tilde{g}} \lesssim 1.6\,{\rm TeV}$,

$\tan\beta \sim {\rm O}(10)$

[32]

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

$N_{\rm mess}$ = 1 + Δ(g-2)>0 ; Y' = 1.0 (IR fixed)



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Summary

MSSM (Minimal SUSY Standard Model)

- Hierachy problem **Solved**
- Dark Matter Candid **Provided**
- Muon $g-2$ anomal **Explained**

in conflict!

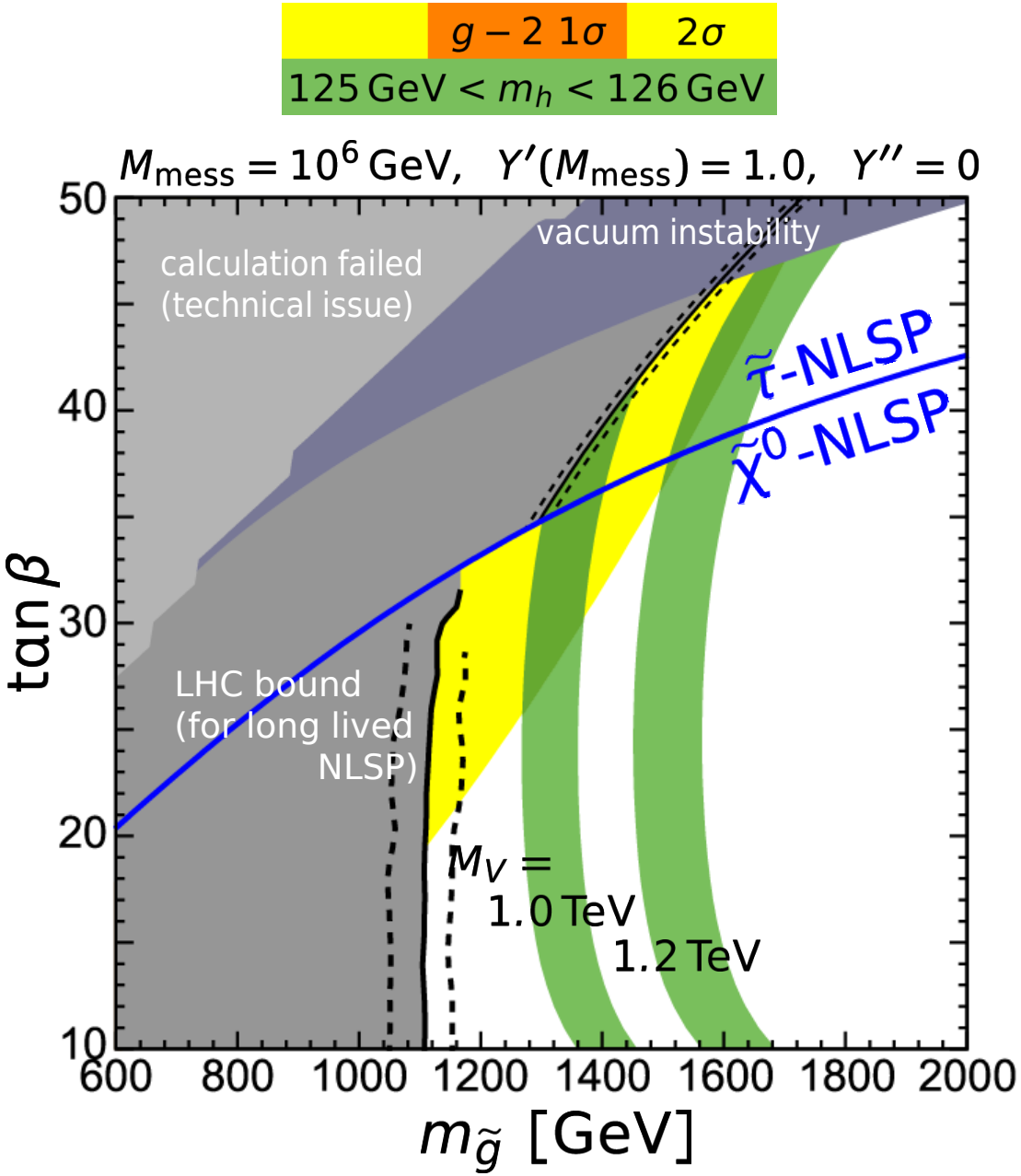
- MSSM + more complicated ~~SUSY~~
- Extended model + GMSB

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

NEW FACT!

- Higgs mass = 126 GeV!

Conflict Resolved!



LHC constraints

- Extra quark searches

  $m_{t'_1} \gtrsim 300$–$650\,\mathrm{GeV}$

  (depending on decay modes)

  $m_{t'_1} \sim M_V - 87\,\mathrm{GeV}$,
  $pp \to t'_1 \bar{t}'_1, \qquad t'_1 \to (qW, qZ, qh)$

- SUSY searches

Appendix - Historical Note

- MSSM+($\mathbf{10}+\overline{\mathbf{10}}$) model is
  - introduced in Okada and Moroi, 1992. *Mod. Phys. Lett.* **A07** (1992) 187
    - Higgs mass can be increased!
  - examined in Martin, 2010. *Phys. Rev.* **D81** (2010) 035004 [0910.2732]
    - IR fixed point behaviour of Y'.
    - Decay branching ratio of extra quarks.
  - applied to the SUSY explanation of $(g-2)_\mu$ **by us.**