



SUSY (with explaining $(g - 2)_\mu$) at the LHC

Sho IWAMOTO (岩本 祥)

Kavli IPMU, the University of Tokyo

1 May 2013
ACP Seminar @ Kavli IPMU

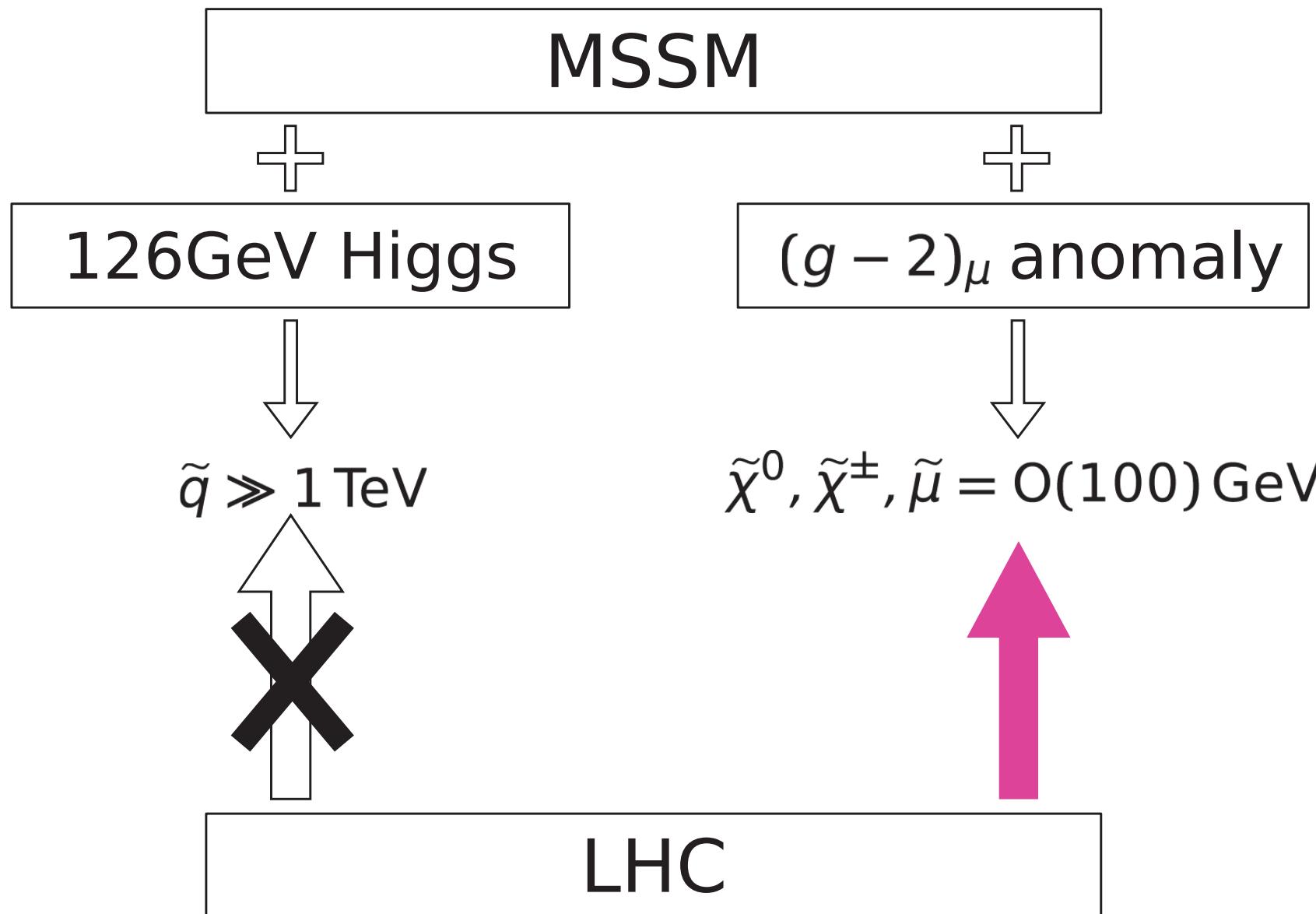
References

Endo, Hamaguchi, SI, Yoshinaga [[1203.4256](#)].

Endo, Hamaguchi, SI, Yokozaki [[1108.3071](#)][[1112.5653](#)][[1202.2751](#)];
Endo, Hamaguchi, Ishikawa, SI, Yokozaki [[1212.3935](#)].

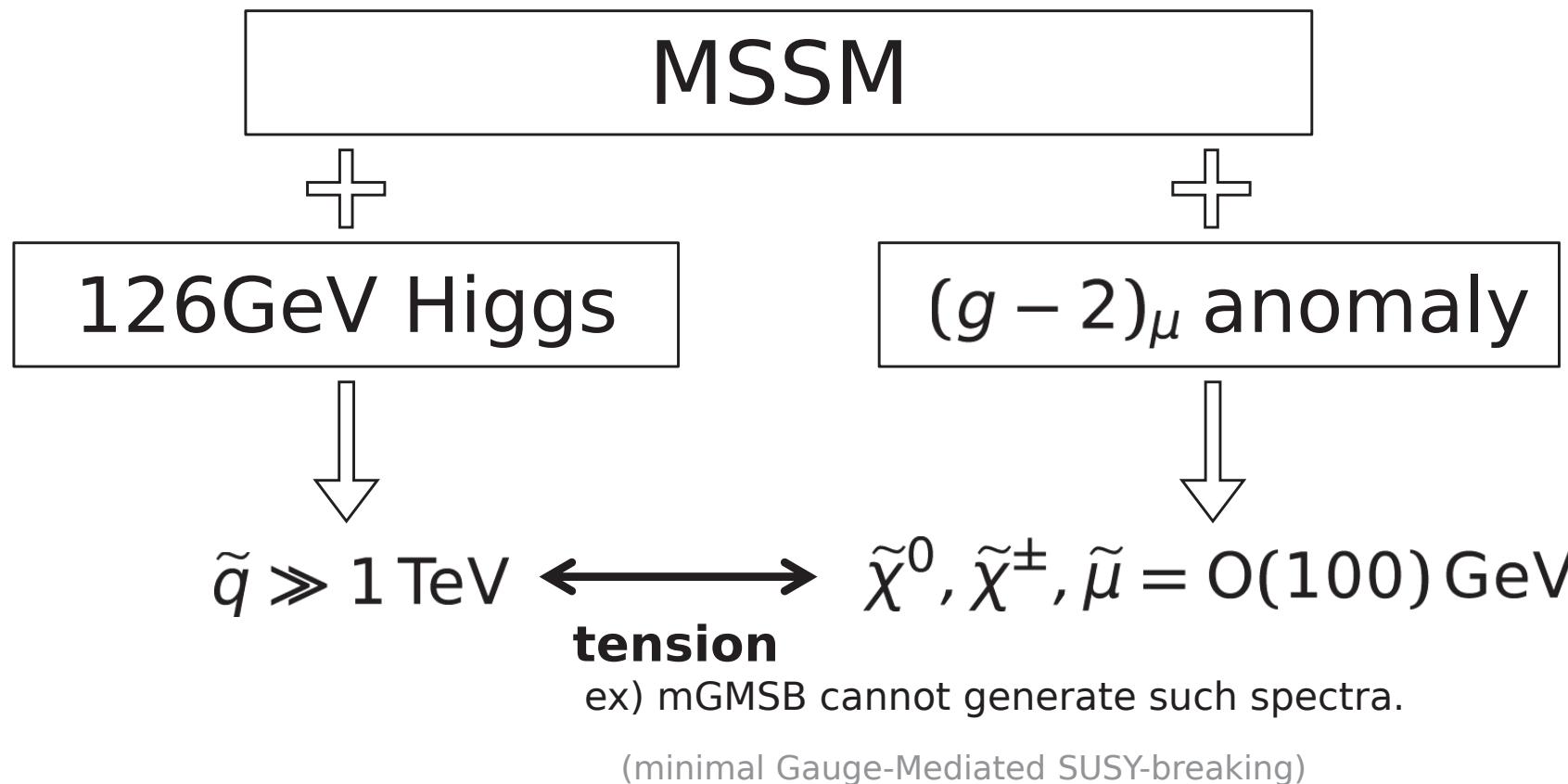
◉ Topic 1.

(Minimal SUSY Standard Model)



① Topic 2.

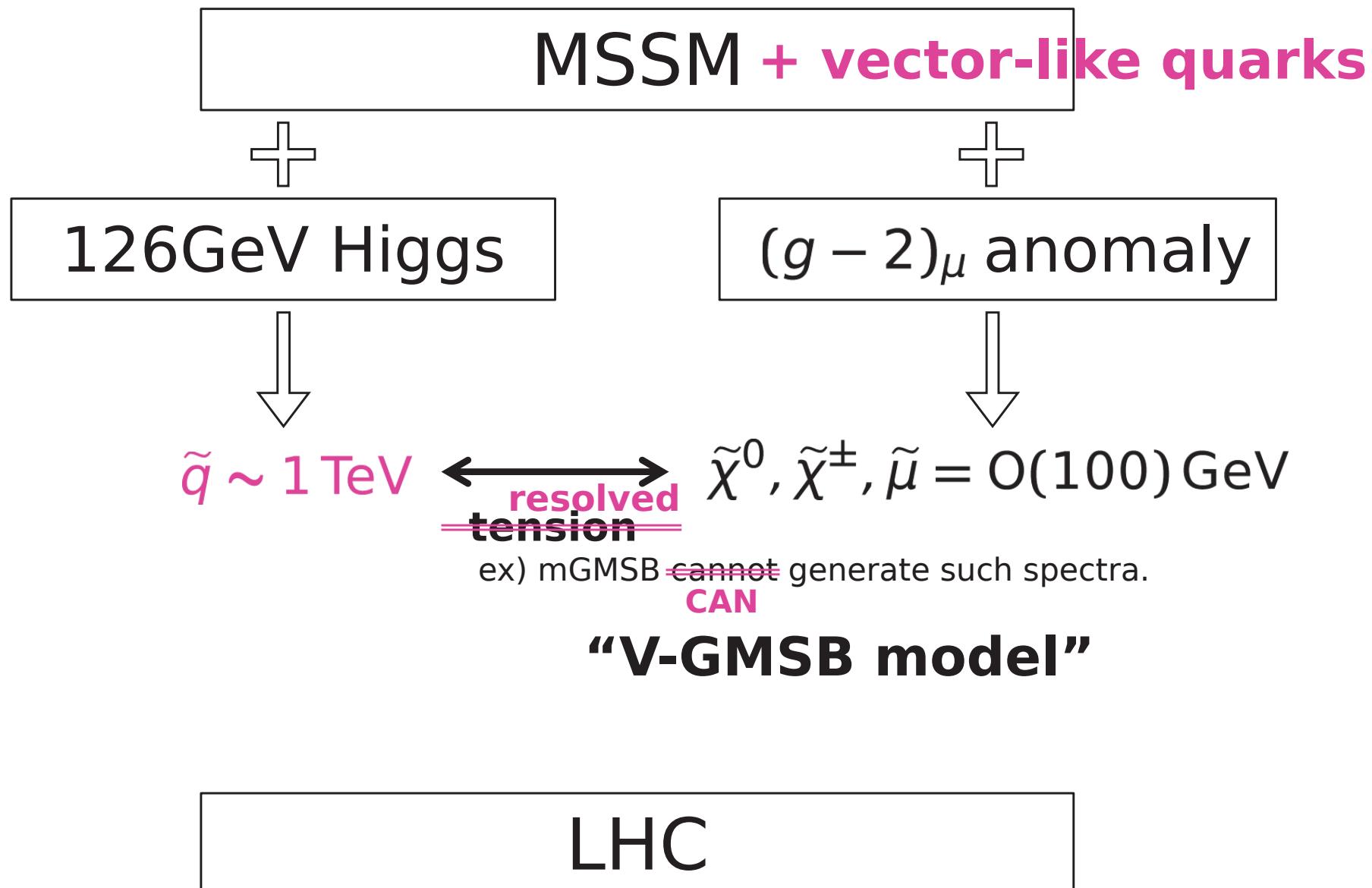
(Minimal SUSY Standard Model)



LHC

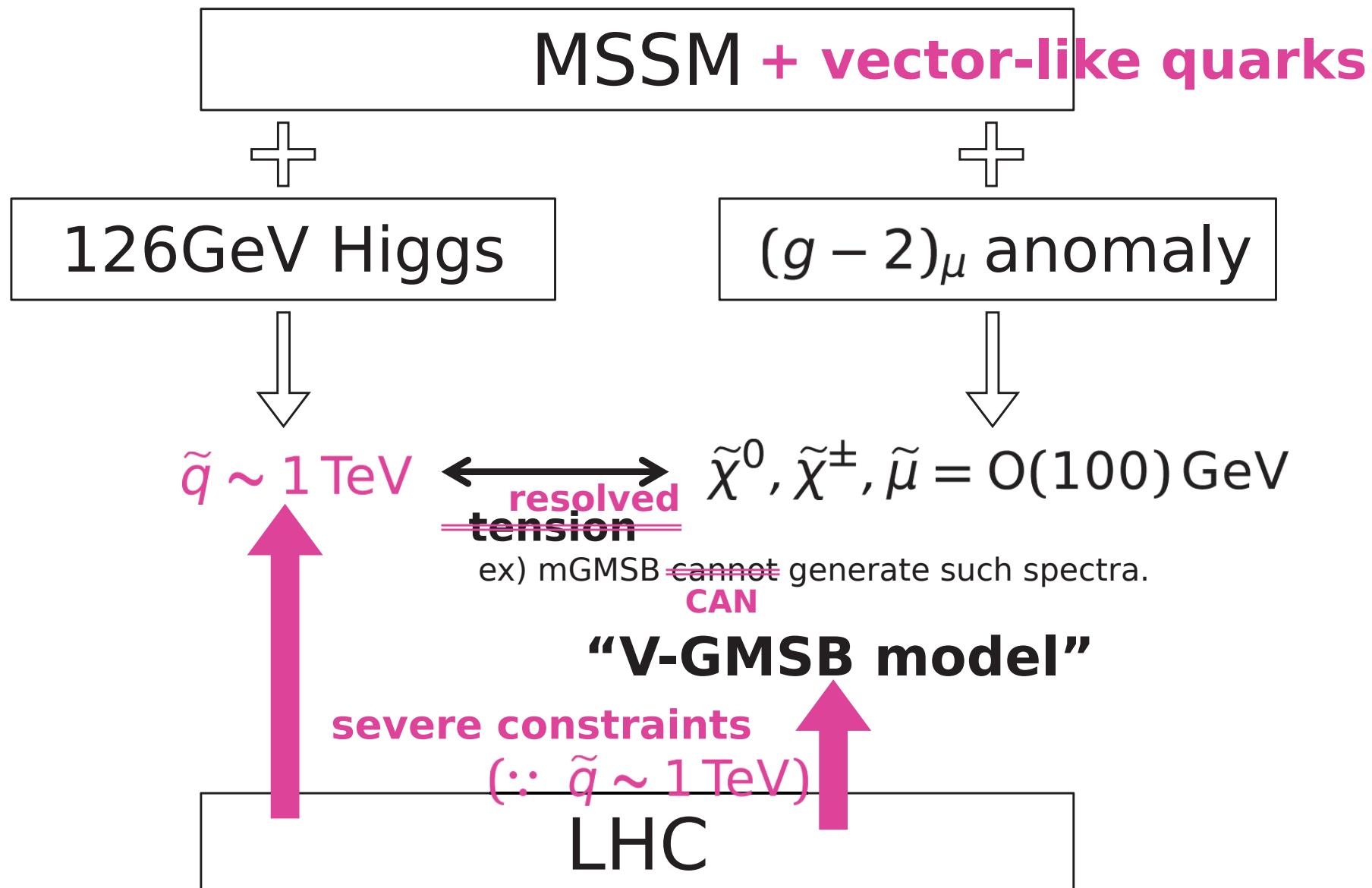
① Topic 2.

(Minimal SUSY Standard Model)

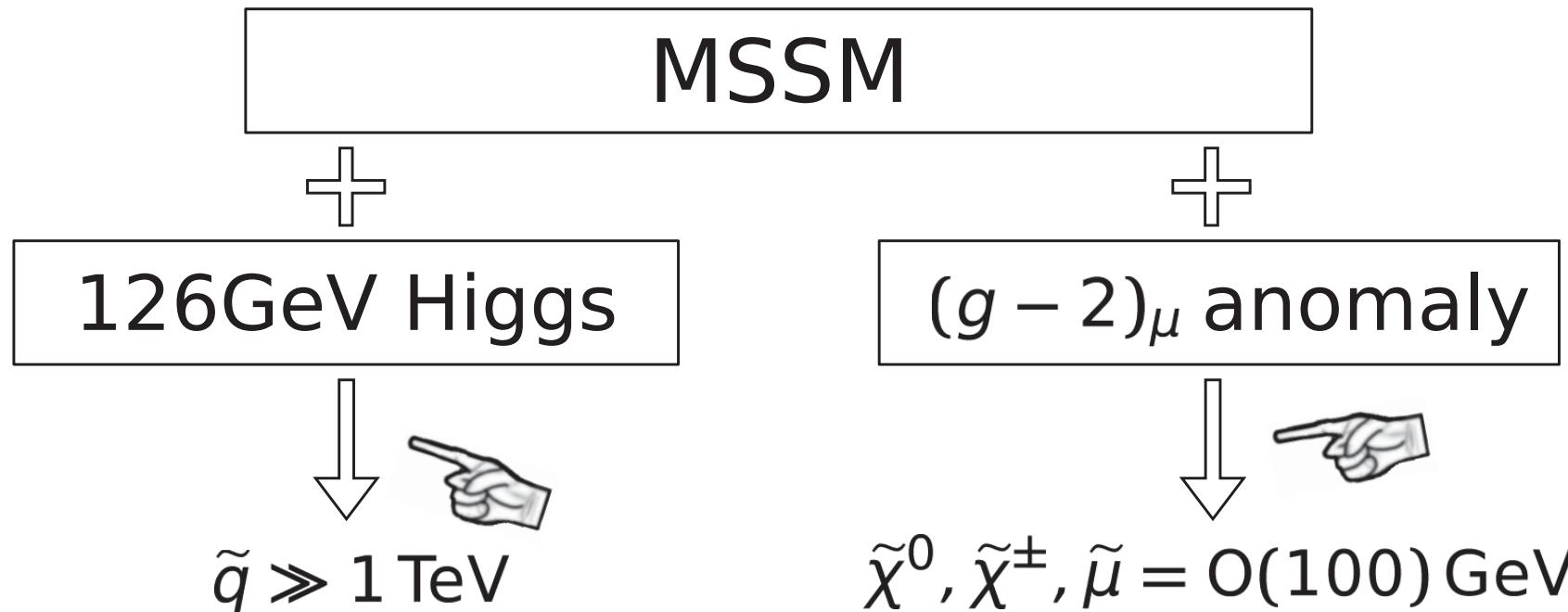


① Topic 2.

(Minimal SUSY Standard Model)



1. Foundation



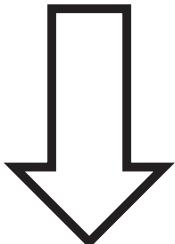
2. Topic 1) $\tilde{\chi}^0, \tilde{\chi}^\pm, \tilde{\mu}$ direct-search

3. Topic 2) V-GMSB model

[(MSSM + vector-like quarks) + GMSB]

Standard Model Now Completed!

- Problems
 - Hierarchy Problem, muon $g - 2$ anomaly, ...
- Anxiety towards ultimate theory



Supersymmetry (SUSY)

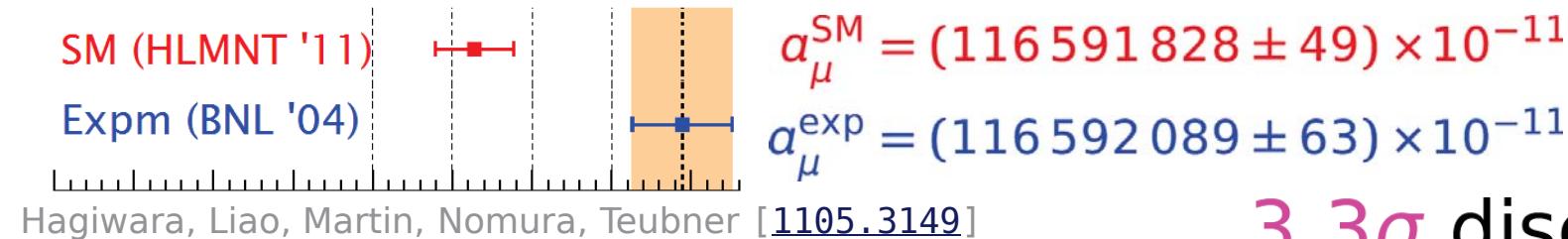
MSSM (Minimal SUSY Standard Model)

- hierarchy : solved. (or relaxed.)
- $(g - 2)_\mu$ anomaly : explained.
- gauge coupling unification : improved.

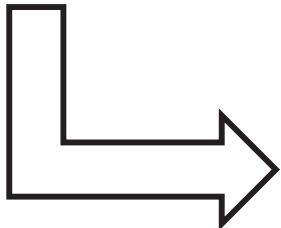
Muon $g-2$ Problem

$(g-2)_\mu$ anomaly

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



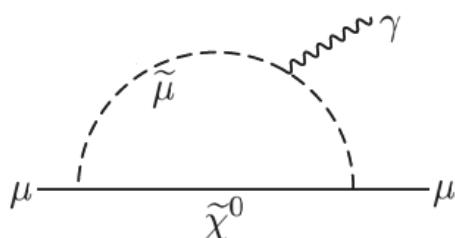
3.3σ discrepancy



can be explained with **MSSM**

if μ -term > 0 , $\tan \beta \gtrsim 10$,

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

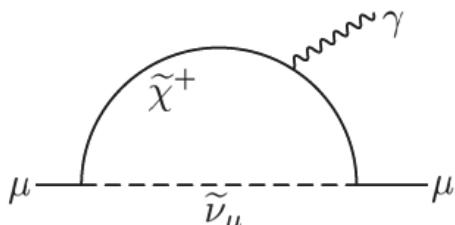


$$\Delta a_\mu (\tilde{\chi}^0, \tilde{\mu}) \approx \frac{g_Y^2}{(4\pi)^2} \frac{m_\mu^2}{m_{\text{soft}}^2} \text{sgn}(\mu) \tan \beta + \dots,$$

Lopez, Nanopoulos, Wang [[ph/9308336](#)]

Chattopadhyay, Nath [[ph/9507386](#)]

Moroi [[ph/9512396](#)]



$$\Delta a_\mu (\tilde{\chi}^\pm, \tilde{\nu}) \approx \frac{g_2^2}{(4\pi)^2} \frac{m_\mu^2}{m_{\text{soft}}^2} \text{sgn}(\mu) \tan \beta.$$

$W \ni \mu H_u H_d$ (Higgsino mass term), $\tan \beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$,

m_{soft} : SUSY-particle mass-scale, g_i : Gauge couplings.

tree
one-loop level (top-stop)

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

where $\alpha := A_t/m_{\tilde{t}}$.
(stop mixing parameter)

heavier $m_h \iff$

- \tilde{t} should be *heavy*
and/or
- stop mixing parameter α at sweet spot ($\sim \pm \sqrt{6}$).

tree
one-loop level (top-stop)

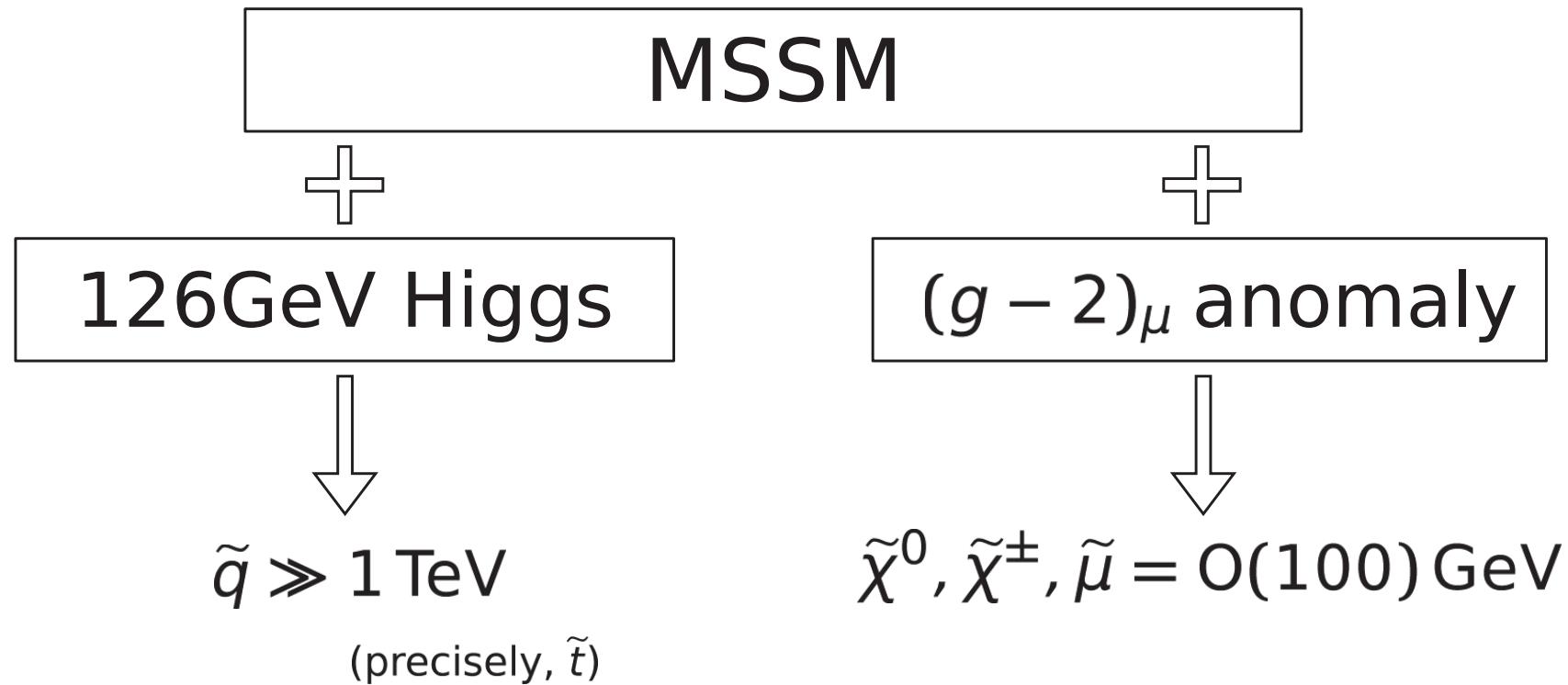
$$m_h^2 \approx m_Z^2 + \frac{3g_W^2 m_t^4}{8\pi^2 m_W^2} \left[\ln \frac{m_{\tilde{t}}^2}{m_t^2} - \frac{(\alpha^2 - 6)^2}{12} + 3 \right]$$

where $\alpha := A_t/m_{\tilde{t}}$.
(stop mixing parameter)

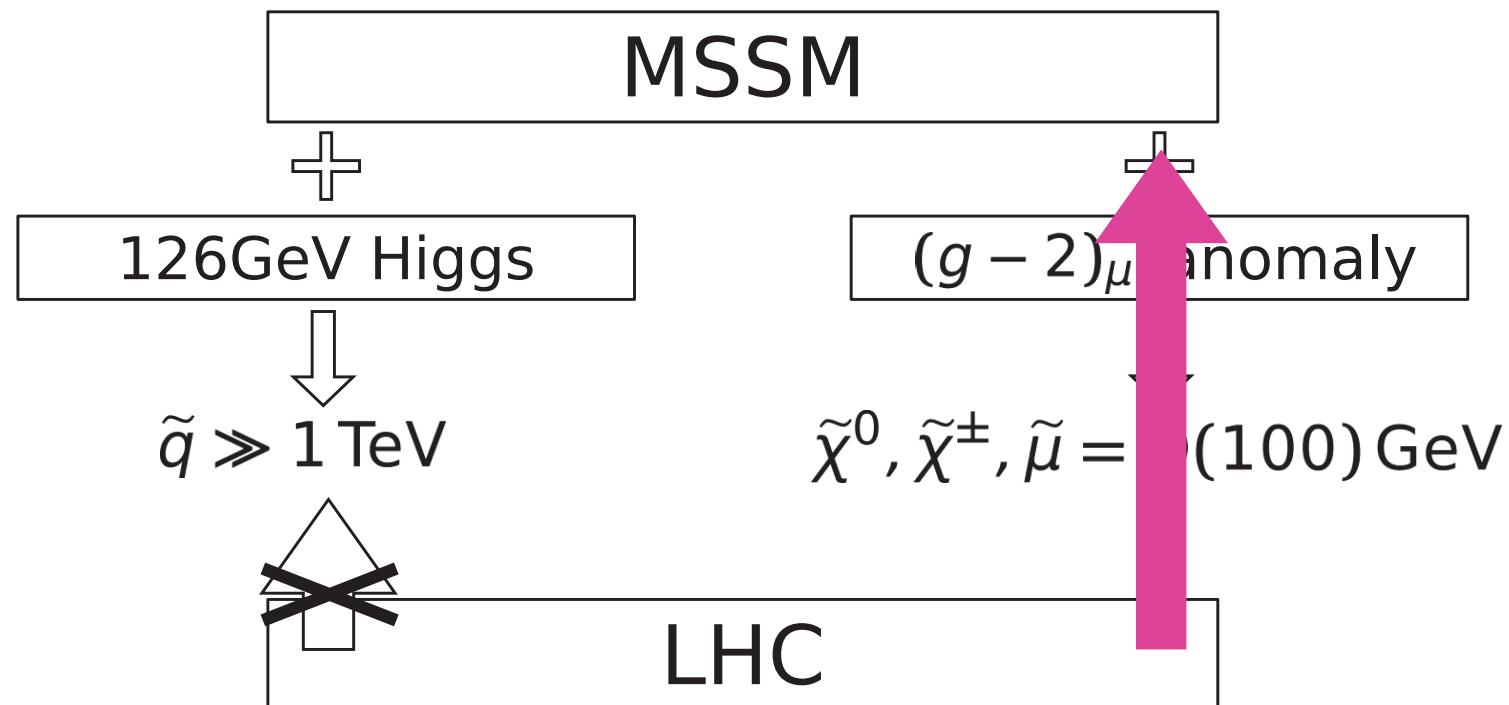
heavier $m_h \iff m_{\tilde{t}} \sim \begin{cases} 1\text{-}2\,\text{TeV} & (\alpha \sim \pm\sqrt{6}) \\ 0(10)\,\text{TeV} & (\alpha \sim 0) \end{cases}$

Ibe, Yanagida [[1112.2462](#)]
Draper, Meade, Reece, Shih [[1112.3068](#)]

- \tilde{t} should be *heavy*
and/or
- stop mixing parameter α at sweet spot ($\sim \pm\sqrt{6}$).



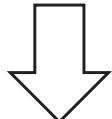
Topic 1 : SUSY search respecting $(g - 2)_\mu$



◎Where's SUSY?

- $m_h = 126 \text{ GeV} \Rightarrow m_{\tilde{t}} = 0(1-10) \text{ TeV} ?$
- Nothing@LHC $\Rightarrow m(\tilde{q}, \tilde{g}) \gtrsim 1 \text{ TeV}.$

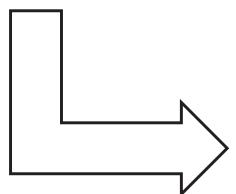
Colored = Heavy !?



Non-colored Search!!!

Many params : $\mu, \tan\beta, m_A; M_1, M_2, m_L^2, m_{\bar{E}}^2, \dots$

Various targets : $\tilde{e}, \tilde{\mu}, \tilde{\tau}, \widetilde{W}^\pm, \dots$



Use $(g - 2)_\mu$ as a guide.

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

- squarks & stau ($\tilde{t}, \tilde{\nu}_\tau$): **HEAVY**

↑ (to simplify LHC analyses)

- sleptons & $\tilde{\chi}^0, \tilde{\chi}^\pm \sim O(100) \text{ GeV}$

➤ sleptons: $(\tilde{e}, \tilde{\nu}_e) = (\tilde{\mu}, \tilde{\nu}_\mu) \ll (\tilde{t}, \tilde{\nu}_\tau)$

➤ gauginos: $M_1 : M_2 : M_3 = 1 : 2 : 6.$
(approximate GUT relation)

- A -terms = 0
- $\tan \beta = 40$
- $m_A = 1500 \text{ GeV}$ ($B_s \rightarrow \mu\mu$ constr. satisfied.)
- $m_h = 126 \text{ GeV}$ is assumed. ($\because \tilde{q}$ are decoupled.)
- R -parity conserved.

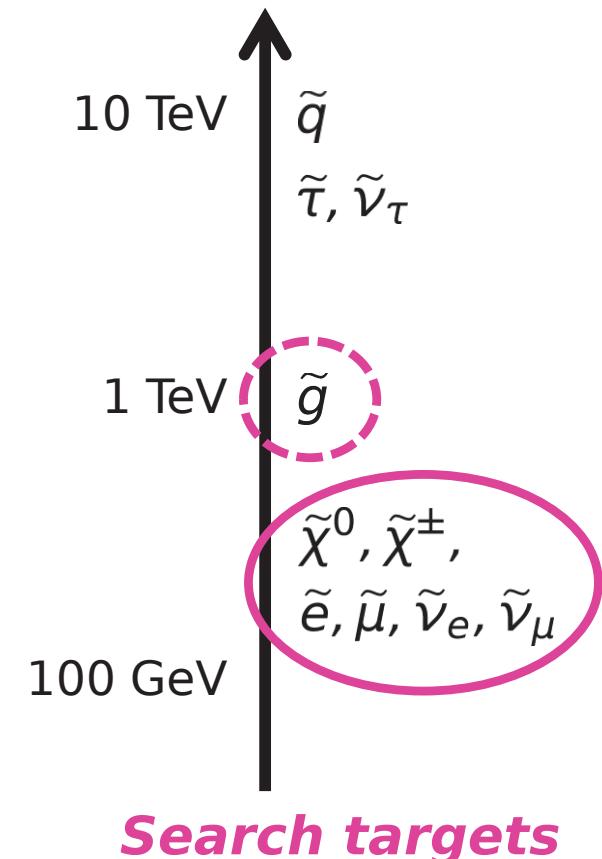
Rest Params: $(m_L^2, m_{\tilde{E}}^2)$: slepton soft-masses

(M_2, μ) : gaugino/Higgsino mass

All params are
input @ TeV-scale.
(PMSSM)

↓

MODEL INDEPENDENT!!



Rest Params: $(m_L^2, m_{\tilde{E}}^2)$: slepton soft-masses
 (M_2, μ) : gaugino/Higgsino mass

Two extreme cases

◎ $\tilde{\mu}_R$ -decoupled case
 $(m_{\tilde{E}}^2 = (3 \text{ TeV})^2)$

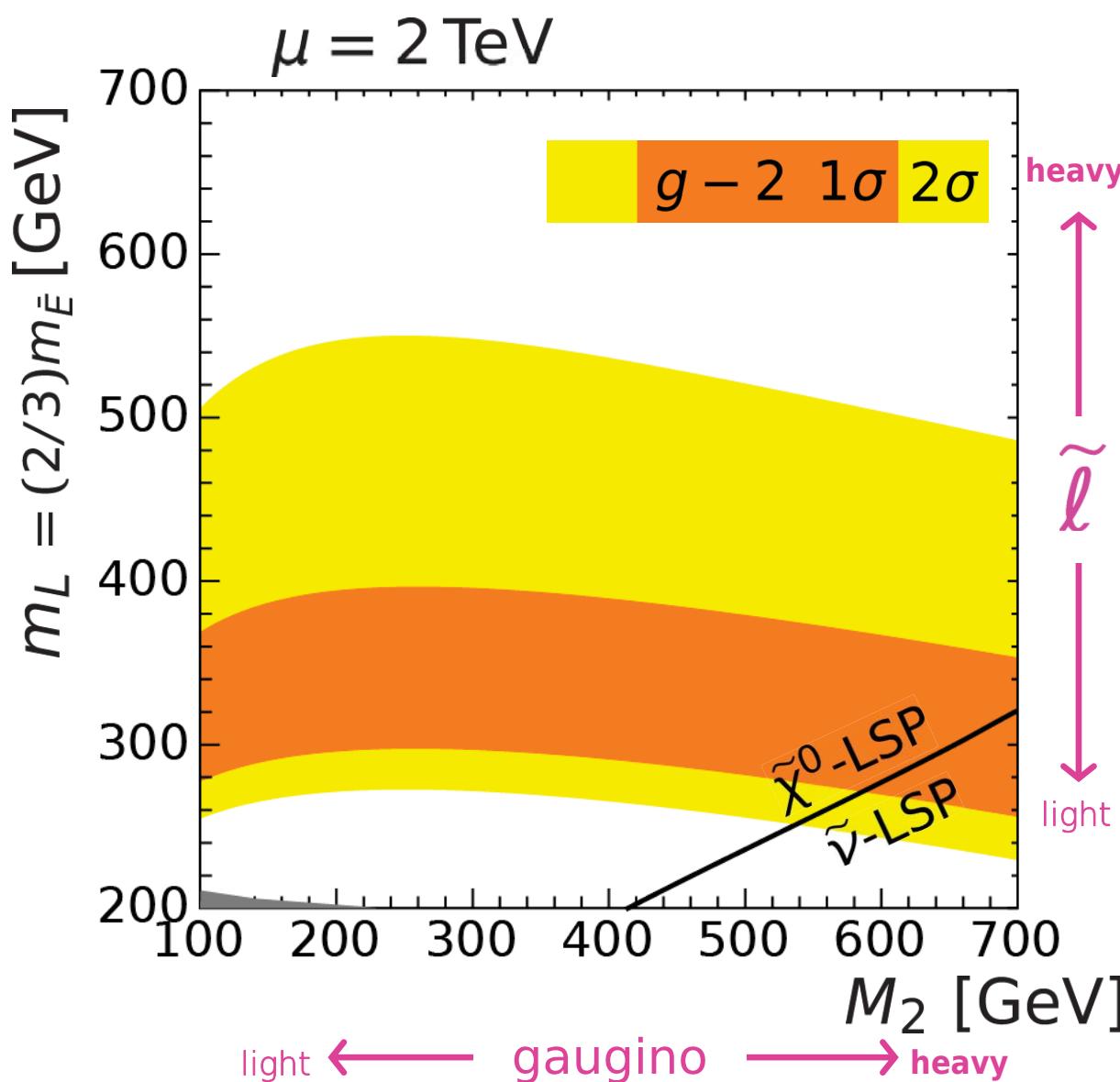
◎ \tilde{h} -decoupled case
 $(\mu = 2 \text{ TeV})$



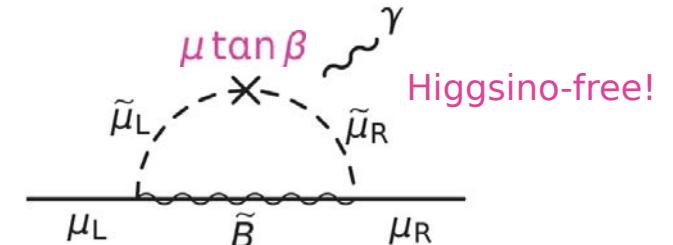
- Current Limit
- Future Prospects

Result: $g-2$ v.s. LHC current status

An extreme case: $\mu = 2 \text{ TeV}$, $m_L^2 : m_{\tilde{E}}^2 = 1 : (1.5)^2$



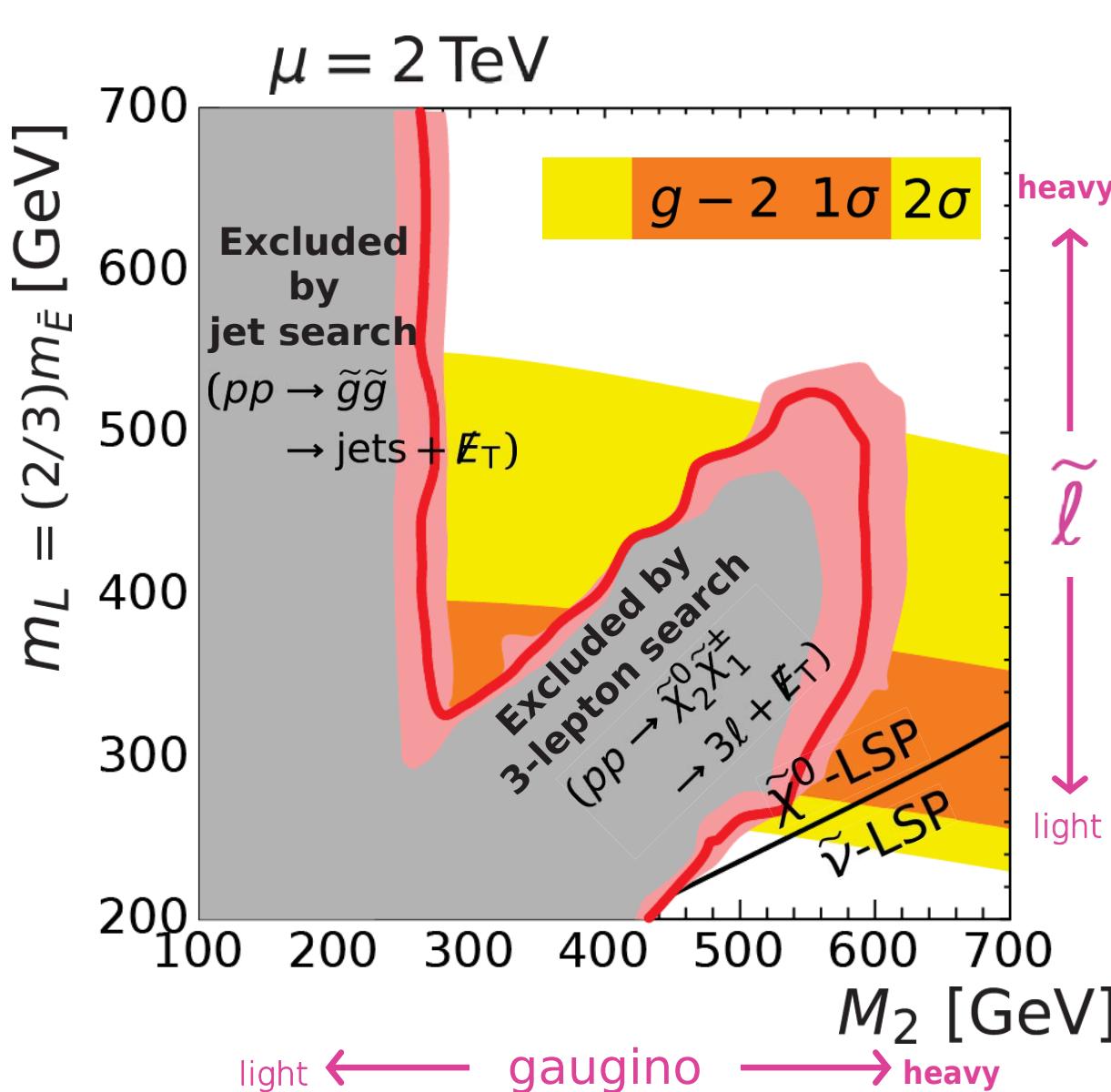
- $(g - 2)_\mu$ dominant source:



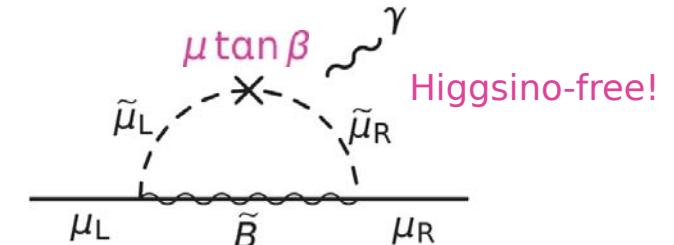
- Parameters:
 - $M_1 : M_2 : M_3 = 1 : 2 : 6$
 - $\mu = 2 \text{ TeV}$
 - $m_L^2 : m_{\tilde{E}}^2 = 1 : (1.5)^2$
 - $(\tan \beta, m_A) = (40, 1.5 \text{ TeV})$
- Soft-params set @ 7 TeV ($= m_{\tilde{t}}$).
- R -parity conserved.
- LSP is long-lived.
- squark/stau decoupled.
- slepton 1st-gen = 2nd-gen.
- A -terms = 0.

Result: $g-2$ v.s. LHC current status

An extreme case: $\mu = 2 \text{ TeV}$, $m_L^2 : m_{\tilde{E}}^2 = 1 : (1.5)^2$

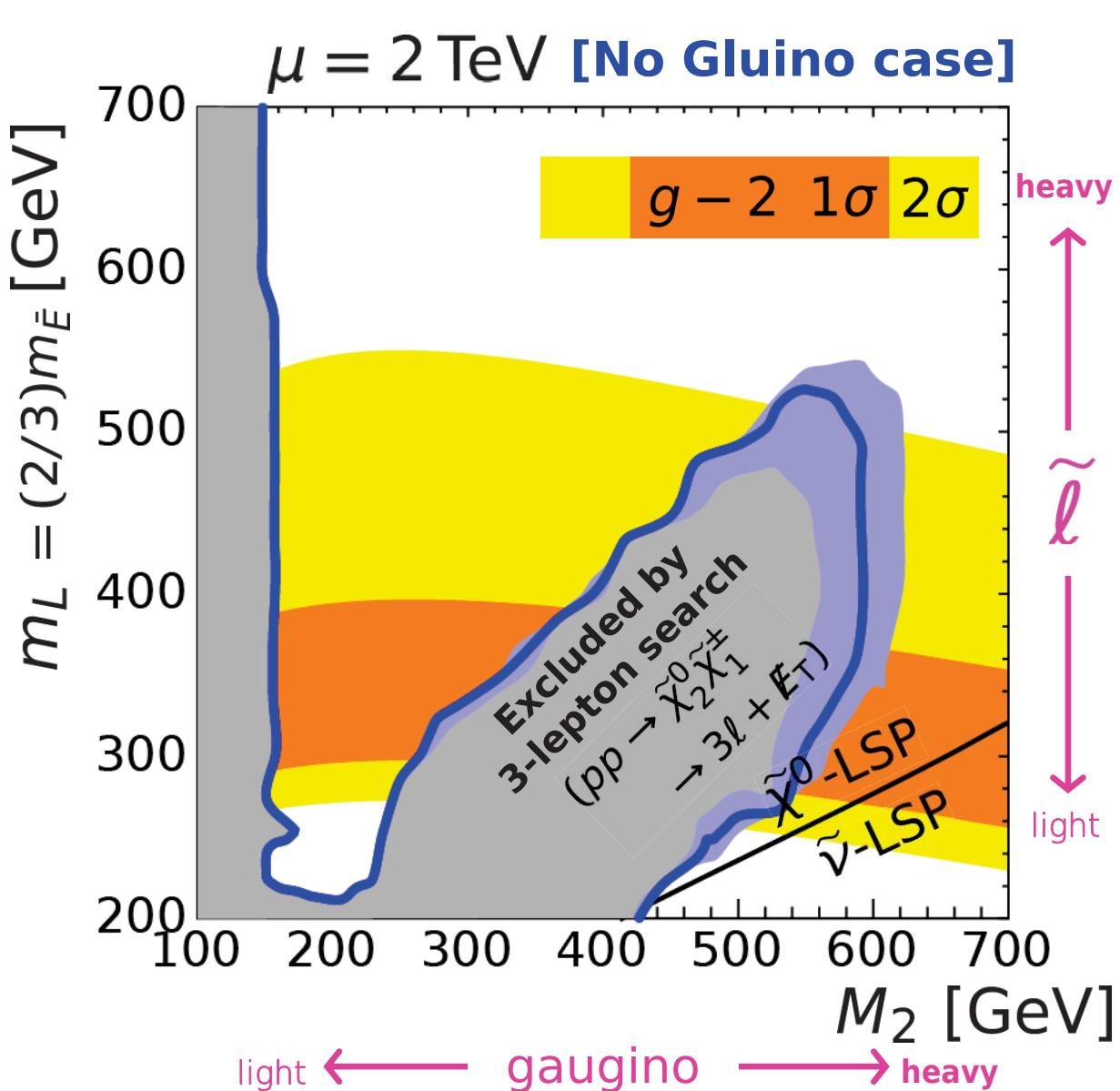


- $(g - 2)_\mu$ dominant source:

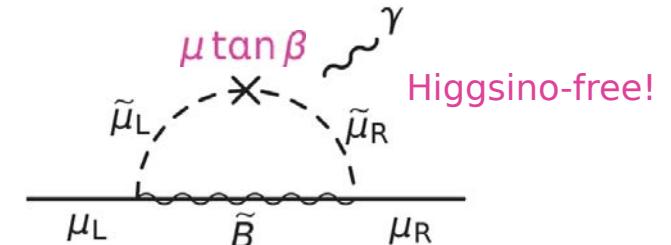


- Parameters:
 - $M_1 : M_2 : M_3 = 1 : 2 : 6$
 - $\mu = 2 \text{ TeV}$
 - $m_L^2 : m_{\tilde{E}}^2 = 1 : (1.5)^2$
 - $(\tan \beta, m_A) = (40, 1.5 \text{ TeV})$
- Soft-params set @ 7 TeV ($= m_{\tilde{t}}$).
- R -parity conserved.
- LSP is long-lived.
- squark/stau decoupled.
- slepton 1st-gen = 2nd-gen.
- A -terms = 0.

An extreme case: $\mu = 2 \text{ TeV}$, $m_L^2 : m_{\tilde{E}}^2 = 1 : (1.5)^2$



- $(g - 2)_\mu$ dominant source:

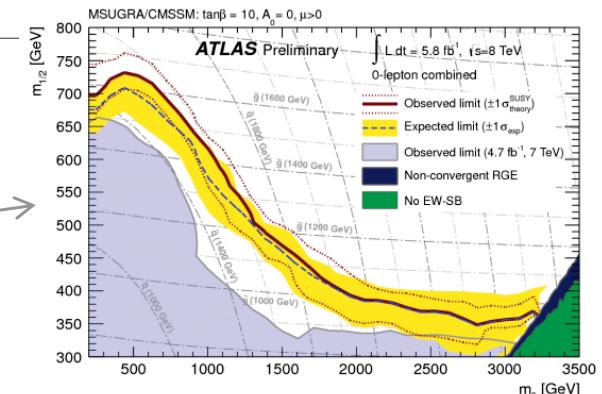


- Parameters:
 - $M_1 : M_2 : M_3 = 1 : 2 : 3$
 - $\mu = 2 \text{ TeV}$
 - $m_L^2 : m_{\tilde{E}}^2 = 1 : (1.5)^2$
 - $(\tan \beta, m_A) = (40, 1.5 \text{ TeV})$
- Soft-params set @ 7 TeV ($= m_t$).
- R -parity conserved.
- LSP is long-lived.
- squark/stau decoupled.
- slepton 1st-gen = 2nd-gen.
- A -terms = 0.

jet search ($pp \rightarrow \tilde{g}\tilde{g} \rightarrow \text{jets} + \cancel{E}_T$)

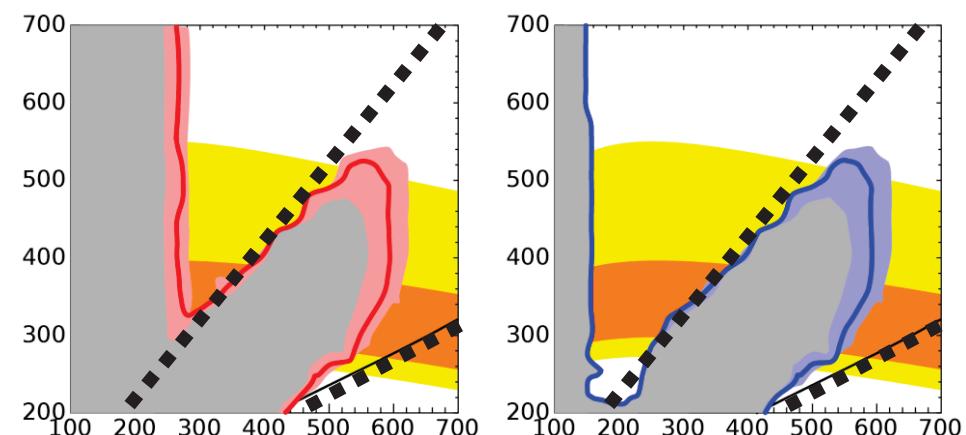
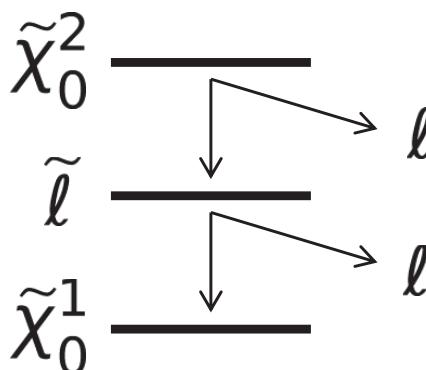
- ATLAS 8TeV 5.8fb^{-1} [[ATLAS-CONF-2012-109](#)]
- 2-6 hard jets + no lepton + \cancel{E}_T
- Original bound : $\tilde{g} \gtrsim 950\text{ GeV}$ (CMSSM, $\tilde{q} \gg \tilde{g}$)

$$\implies M_2 \gtrsim 300\text{ GeV} \text{ in our model}$$



3-lepton search ($pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow 3\ell + \cancel{E}_T$)

- ATLAS 8TeV 13fb^{-1} [[ATLAS-CONF-2012-154 \(obsolete\)](#)]
- Exact 3 leptons + \cancel{E}_T + vetoing SM-like signal
 (no b -jets, no lepton pairs near M_Z , etc...)
- Degenerated regions
 are not excluded.
 (near the dotted lines)



Rest Params: $(m_L^2, m_{\tilde{E}}^2)$: slepton soft-masses
 (M_2, μ) : gaugino/Higgsino mass

Two extreme cases

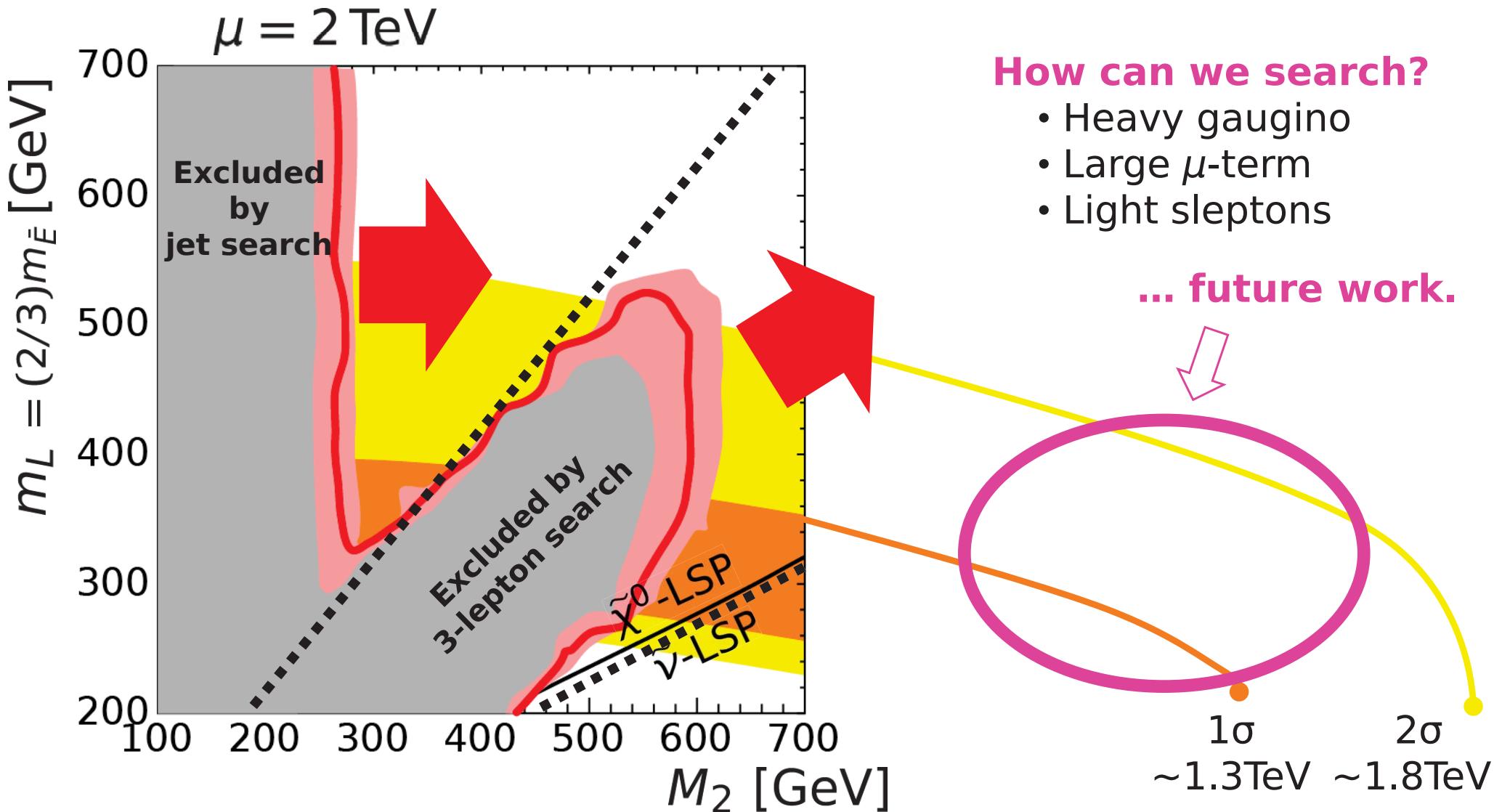
◎ $\tilde{\mu}_R$ -decoupled case
 $(m_{\tilde{E}}^2 = (3 \text{ TeV})^2)$

◎ \tilde{h} -decoupled case
 $(\mu = 2 \text{ TeV})$



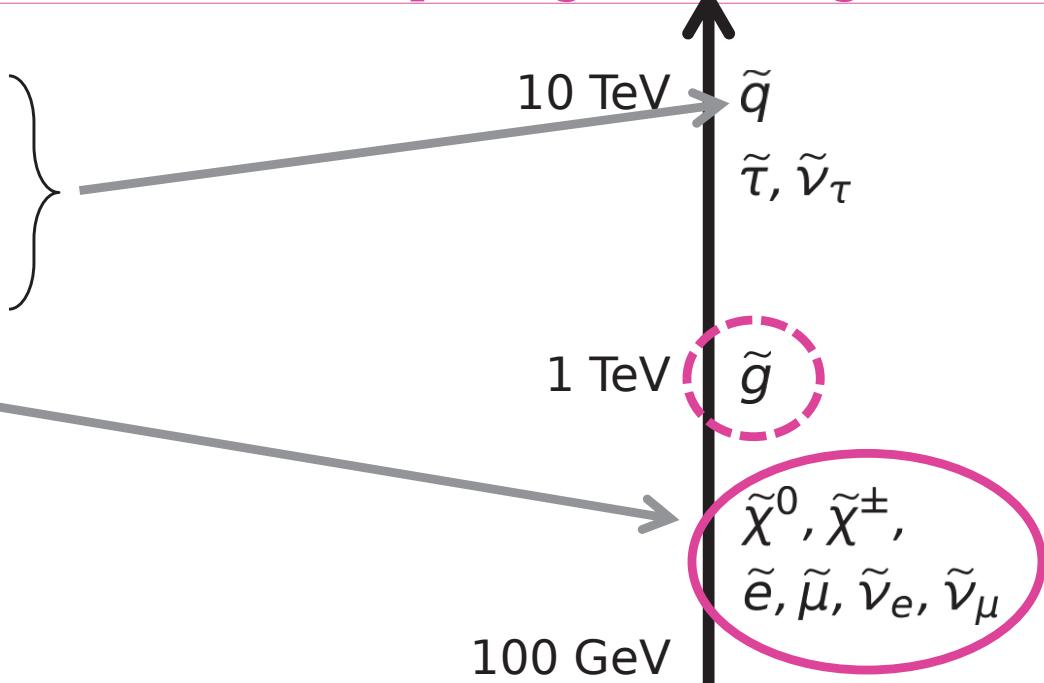
- Current Limit
- Future Prospects

An extreme case: $\mu = 2 \text{ TeV}$, $m_L^2 : m_{\tilde{E}}^2 = 1 : (1.5)^2$



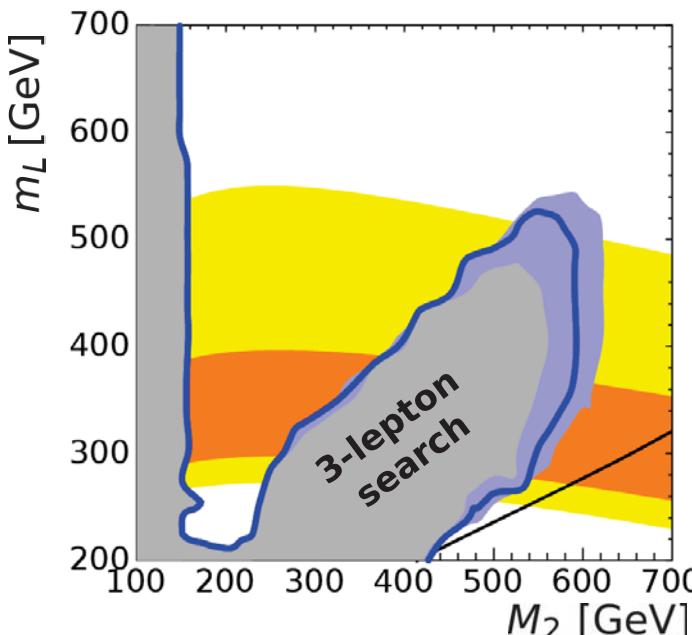
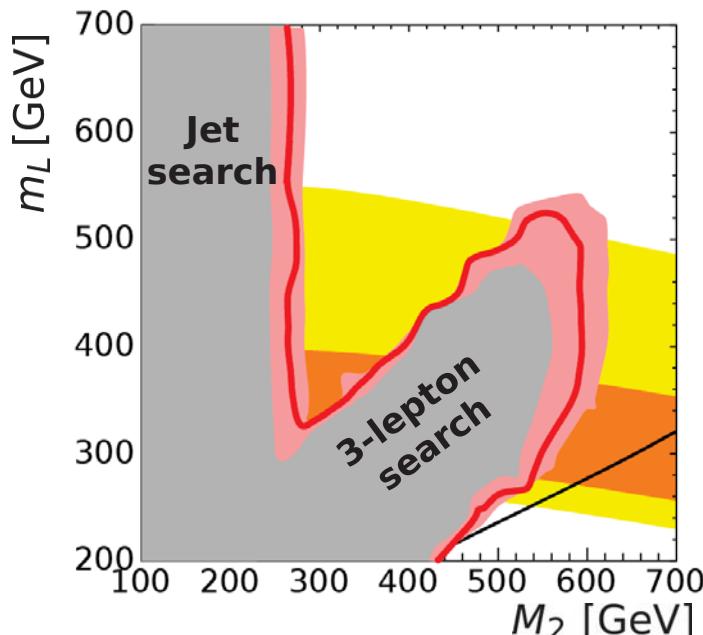
Summary of Topic 1 : Non-colored SUSY search (respecting the muon g-2)

- 126 GeV Higgs
- SUSY Not Found yet
- $(g - 2)_\mu$ anomaly



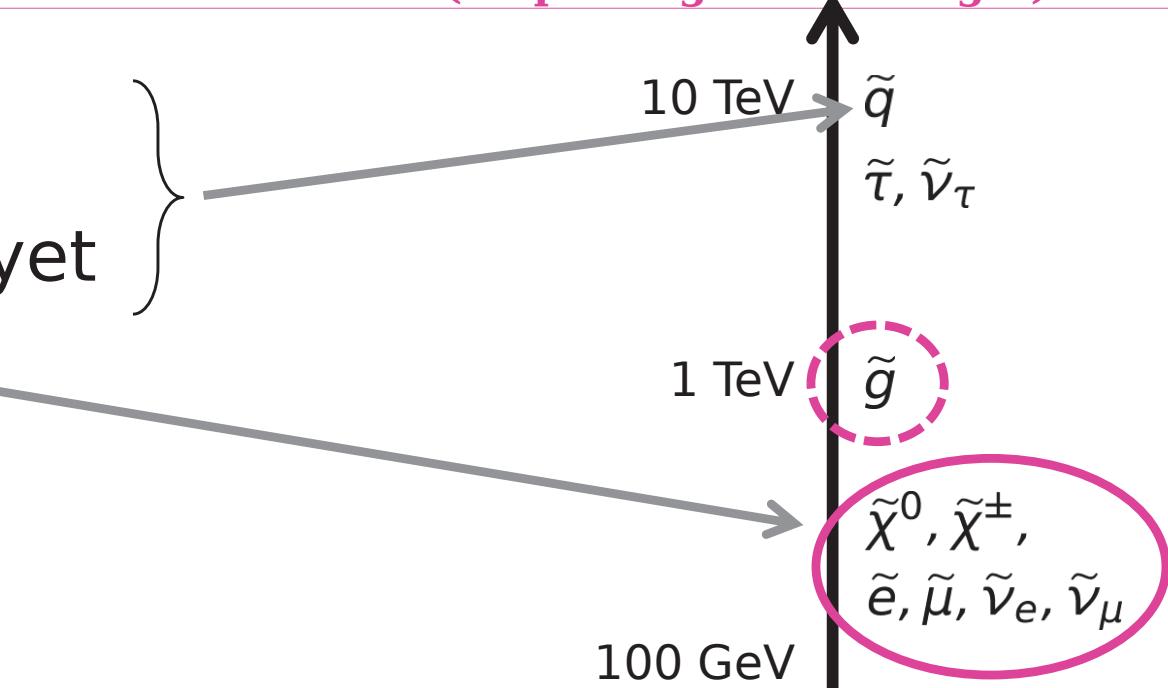
An extreme case: $\mu = 2 \text{ TeV}$, $m_L^2 : m_{\tilde{E}}^2 = 1 : (1.5)^2$

Jet: [ATLAS-CONF-2012-109](#)
3L: [ATLAS-CONF-2012-154](#)

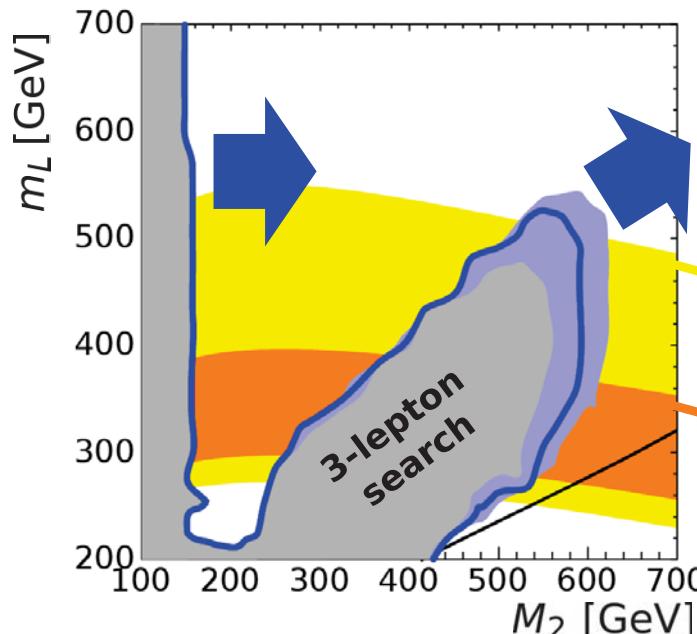
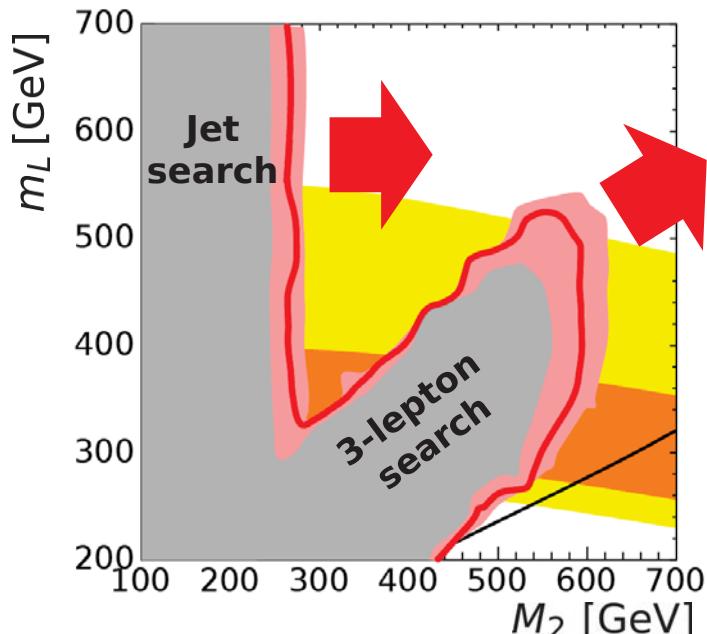


Summary of Topic 1 : Non-colored SUSY search (respecting the muon g-2)

- 126 GeV Higgs
- SUSY Not Found yet
- $(g - 2)_\mu$ anomaly



An extreme case: $\mu = 2 \text{ TeV}$, $m_L^2 : m_{\tilde{E}}^2 = 1 : (1.5)^2$

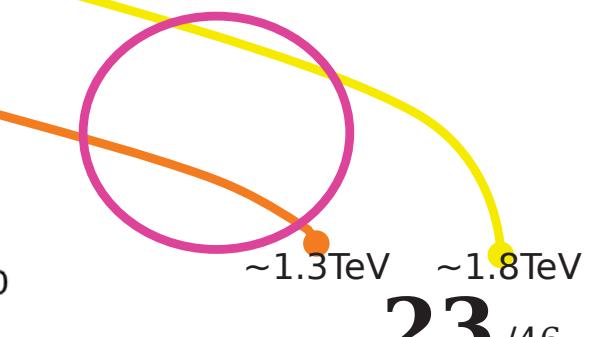


Jet: [ATLAS-CONF-2012-109](#)
3L: [ATLAS-CONF-2012-154](#)

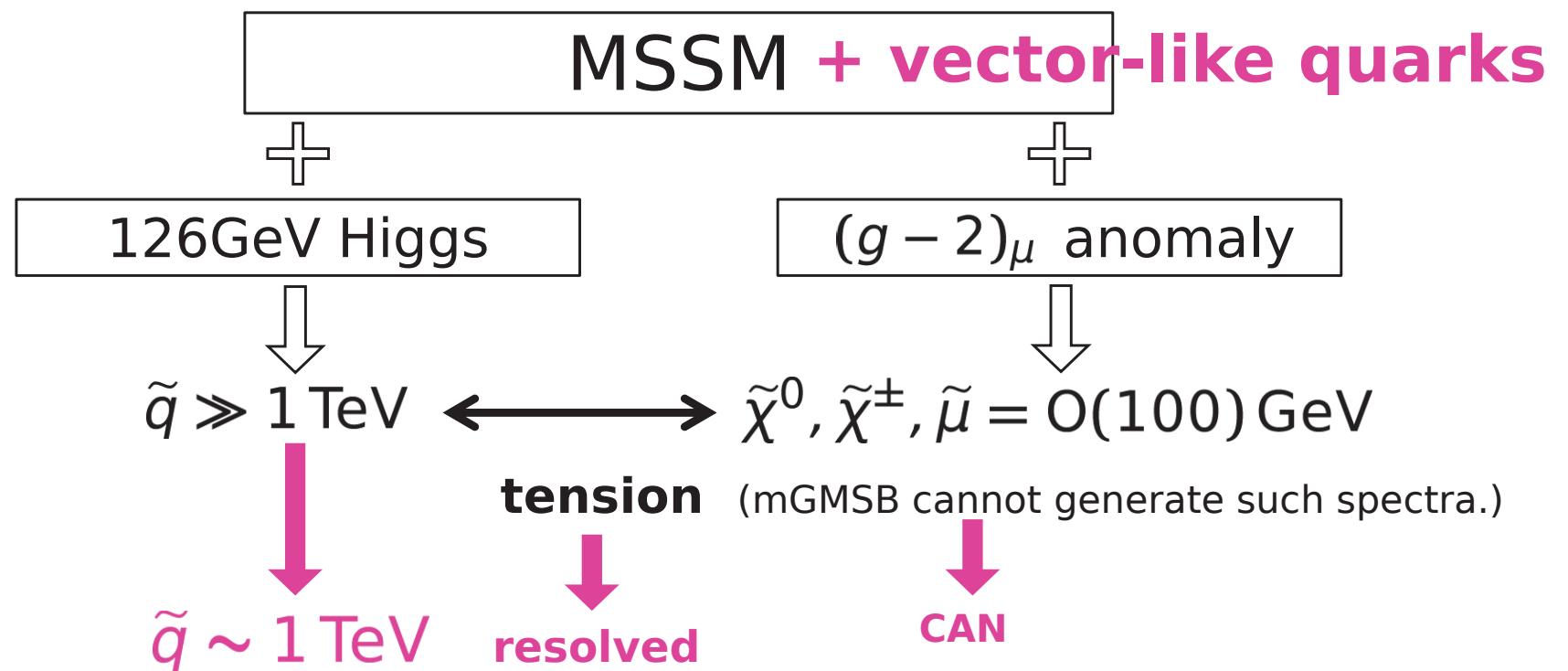
How can we search?

- Heavy gaugino
- Large μ -term
- Light sleptons

... future work.

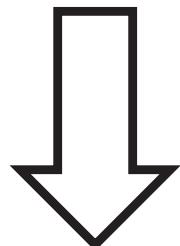


Topic 2 : V-GMSB



MSSM + GMSB (or mSUGRA)

$\implies (g - 2)_\mu \text{ with } m_{H^\pm} = 126 \text{ GeV}$



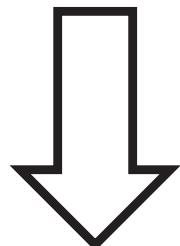
MSSM + more complicated ~~SUSY~~

or

Extended model + GMSB/mSUGRA

MSSM + GMSB (or mSUGRA)

$\Rightarrow (g - 2)_\mu$ with $m_{H^\pm} = 126 \text{ GeV}$



MSSM + more complicated ~~SUSY~~

or

V-MSSM

+ GMSB/mSUGRA

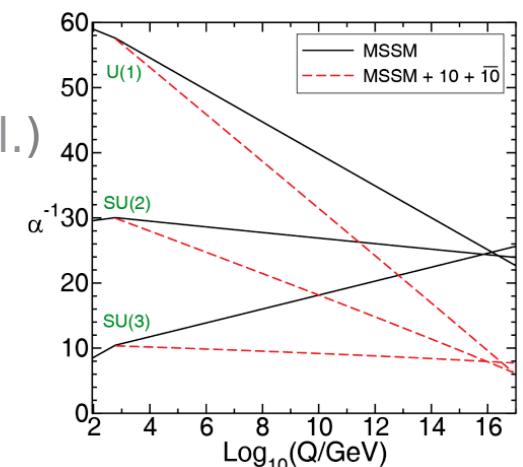
- ◎ V-MSSM = MSSM + $(\mathbf{10} + \overline{\mathbf{10}})$, i.e. $\begin{cases} \mathbf{10} = (Q', \bar{U}', \bar{E}') \\ \overline{\mathbf{10}} = (\bar{Q}', U', E') \end{cases}$
extra Vector-like matters

$$W_{\text{extra}} = Y' Q' H_u \bar{U}' + Y'' \bar{Q}' H_d U' \quad (\text{cf. } W_{\text{MSSM}} \ni Y_t Q H_u \bar{U})$$

$$+ M_V Q' \bar{Q}' + M_V U' \bar{U}' + M_V E' \bar{E}'$$

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

- Vector-like \Rightarrow No gauge anomaly.
- Mixings : necessary (to avoid stable particles)
but must be tiny. (to avoid large flav-viol.)
- Y' : IR fixed to $\sim 1.05 \Rightarrow m_h$ well increased.
- Y'' : reduces $m_h \Rightarrow$ assumed small.



Martin [0910.2732]

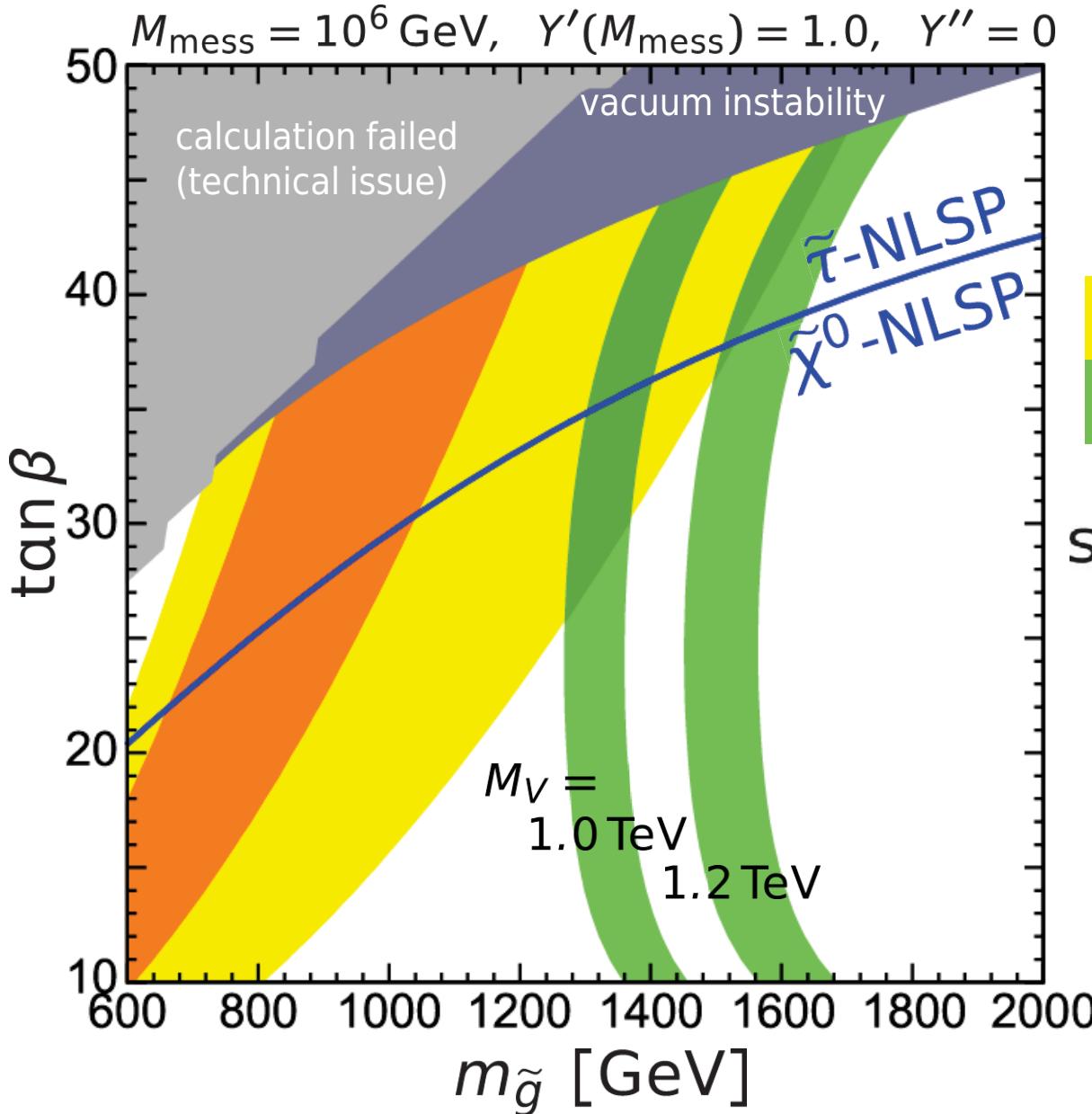
RESULT

in this talk

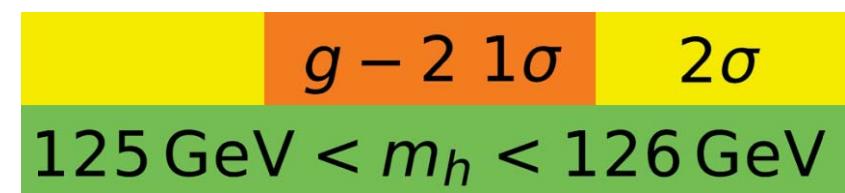
with {

- GMSB framework
- mSUGRA framework
→ See [[1112.5653](#)]

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



||
1
+
 $\Delta(g-2) > 0$ (IR fixed)
||
1.0



simultaneous realization:

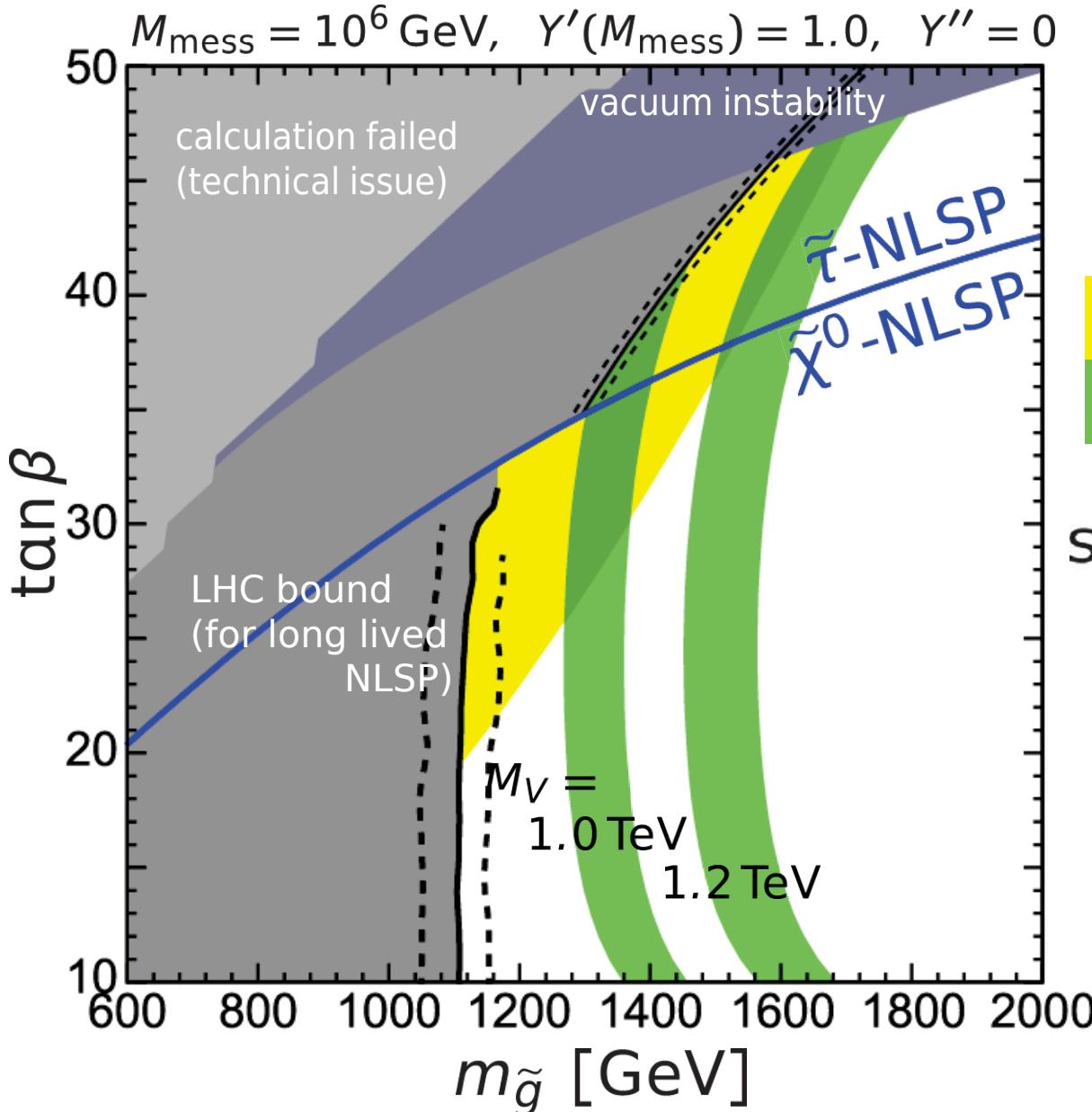
$M_V \lesssim 1.2 \text{ TeV}$,

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

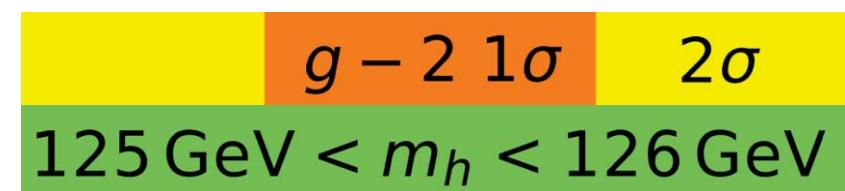
$\tan \beta \sim \mathcal{O}(10)$

→ **LHC LIMIT!?**

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



||
1
+
 $\Delta(g-2) > 0$ (IR fixed)
||
1.0



simultaneous realization:

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

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

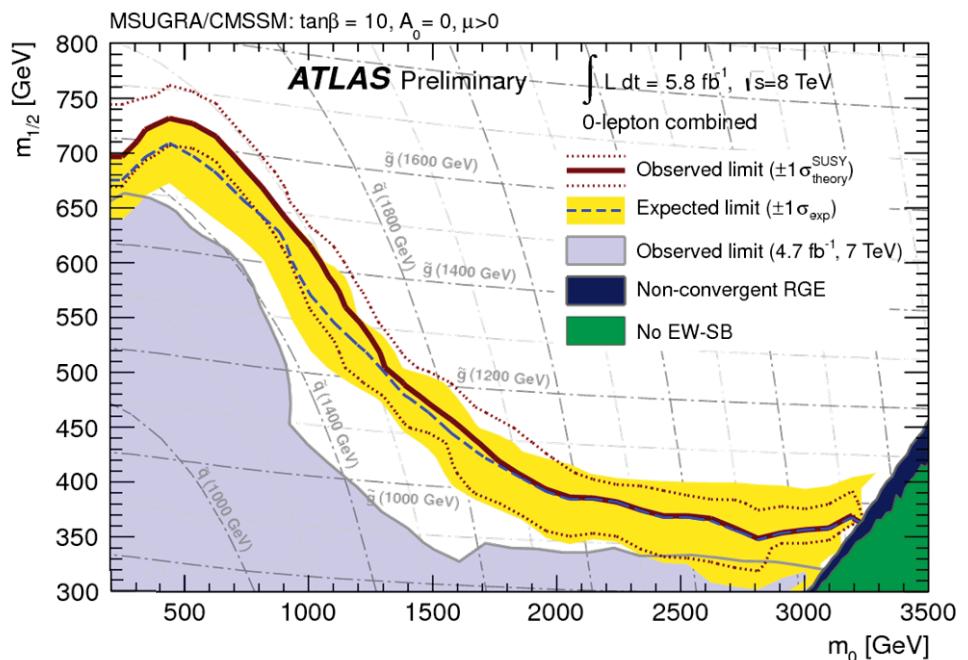
$\tan \beta \sim \mathcal{O}(10)$

→ **LHC LIMIT!?**

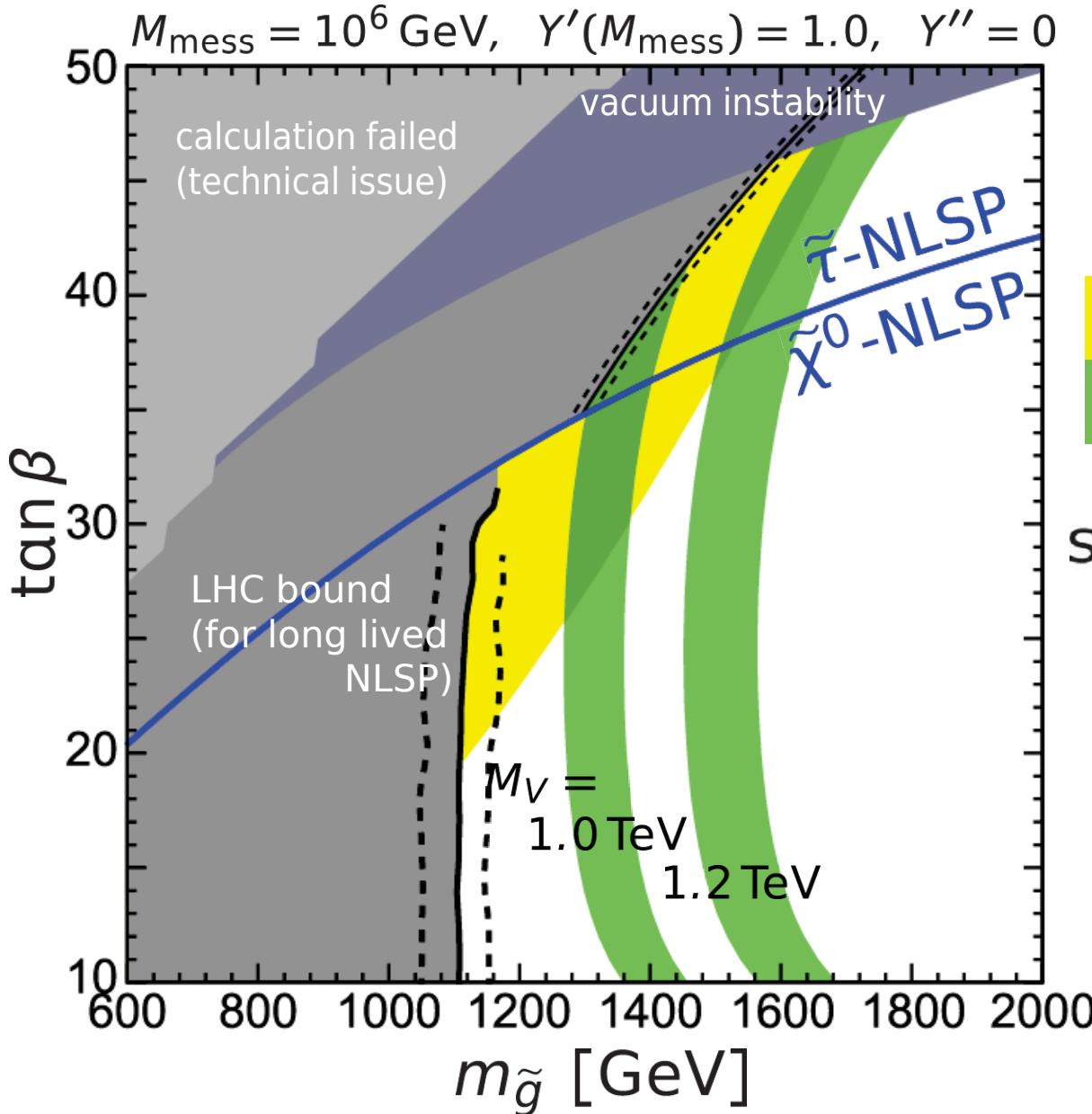
NLSP	Long-lived NLSP	NLSP prompt decay
$\tilde{\chi}_1^0$	jet + E_T ($\tilde{\chi}_1^0 \tilde{\chi}_1^0$) (same as mSUGRA)	jet + E_T and $2\gamma + E_T$ (from $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$)
$\tilde{\tau}_1$	Long-lived stau	multi-tau

Our analysis

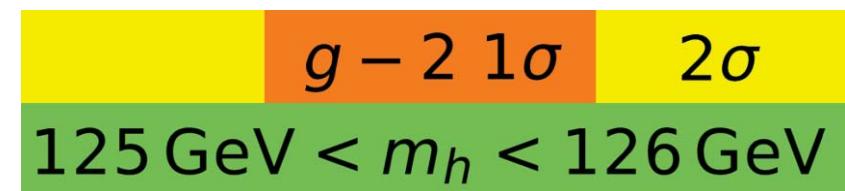
- Neutralino NLSP
→ ATLAS 8 TeV- 5.8 fb^{-1}
(2-6 jets + E_T)
[ATL-CONF-2012-109]
- Stau NLSP
→ CMS 7 TeV- 5.0 fb^{-1}
(assuming $pp \rightarrow \tilde{\tau}_1 \tilde{\tau}_1^*$)
 $\rightsquigarrow m_{\tilde{\tau}_1} > 223 \text{ GeV}$ [1205.0272]



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



||
1
+
 $\Delta(g-2) > 0$ (IR fixed)
1.0



simultaneous realization:

$M_V \lesssim 1.2 \text{ TeV},$
 $m_{\tilde{g}} \lesssim 1.6 \text{ TeV},$
 $\tan \beta \sim \mathcal{O}(10)$

Appendix

LHC-constraints from
extra-quark search.

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

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

➤ Mass

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

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

& (t'_1, t'_2, b', τ')

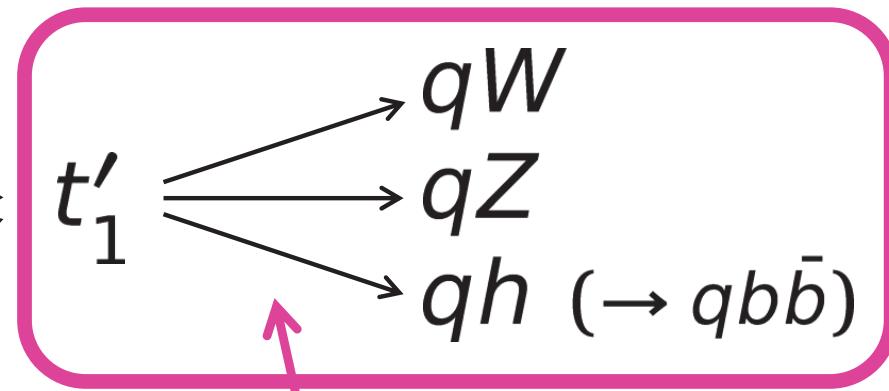
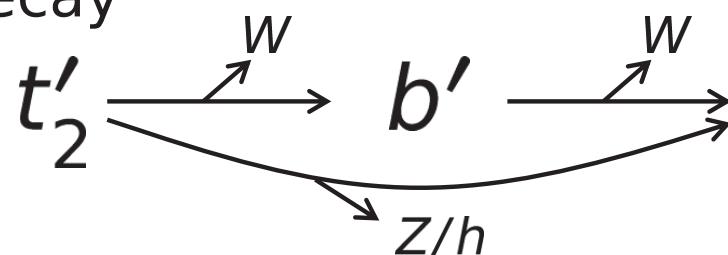
$$W_{\text{extra}} = Y' Q' H_u \bar{U}' + M_V Q' \bar{Q}' + M_V U' \bar{U}' + M_V E' \bar{E}'$$

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

➤ Production

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

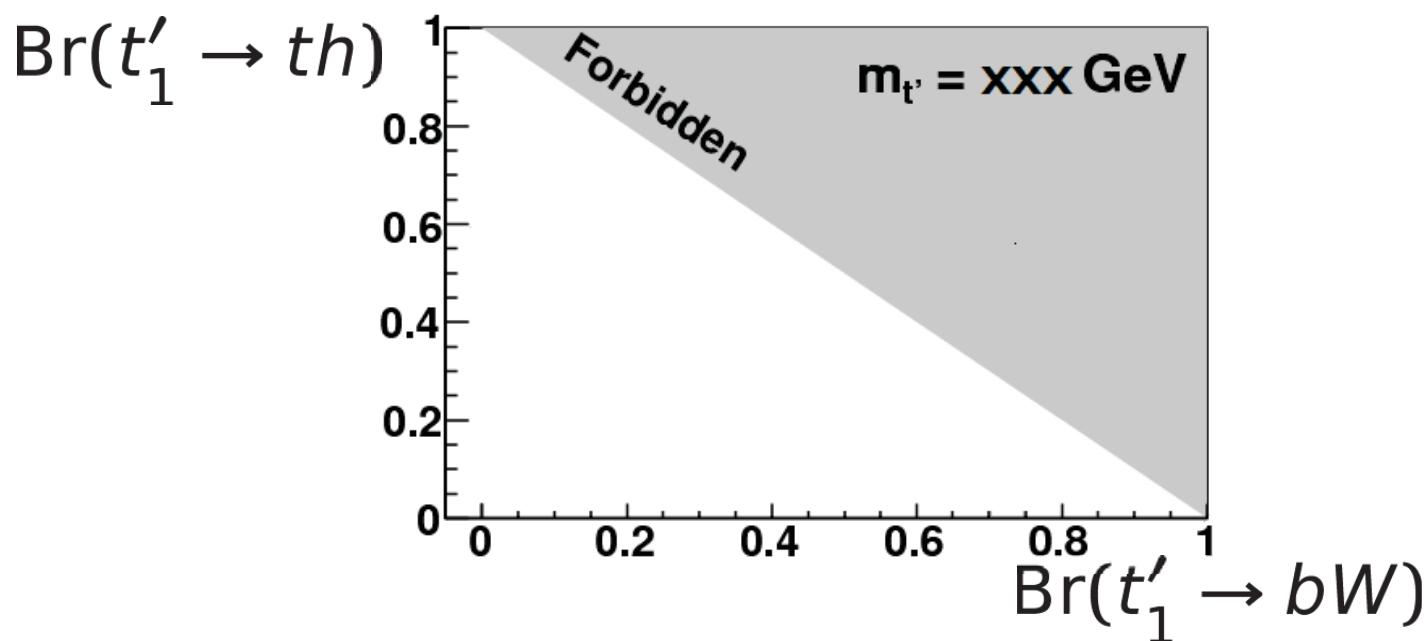
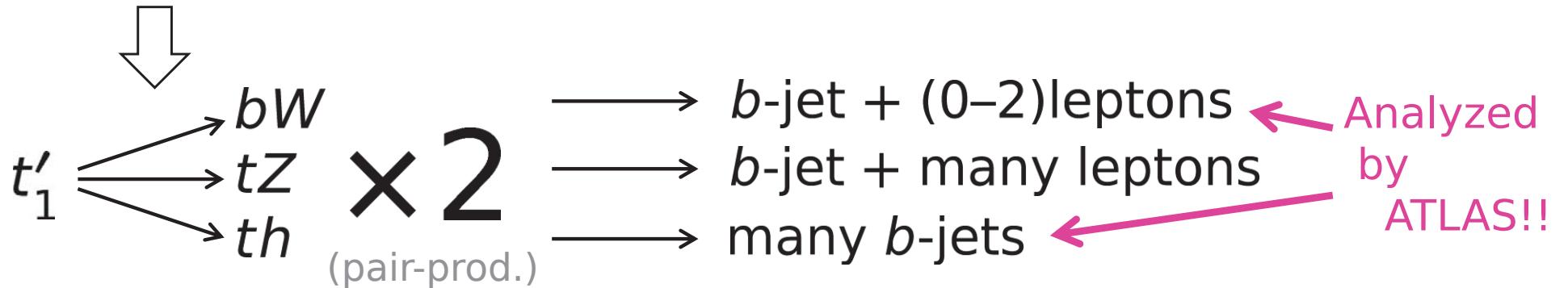
➤ Decay



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

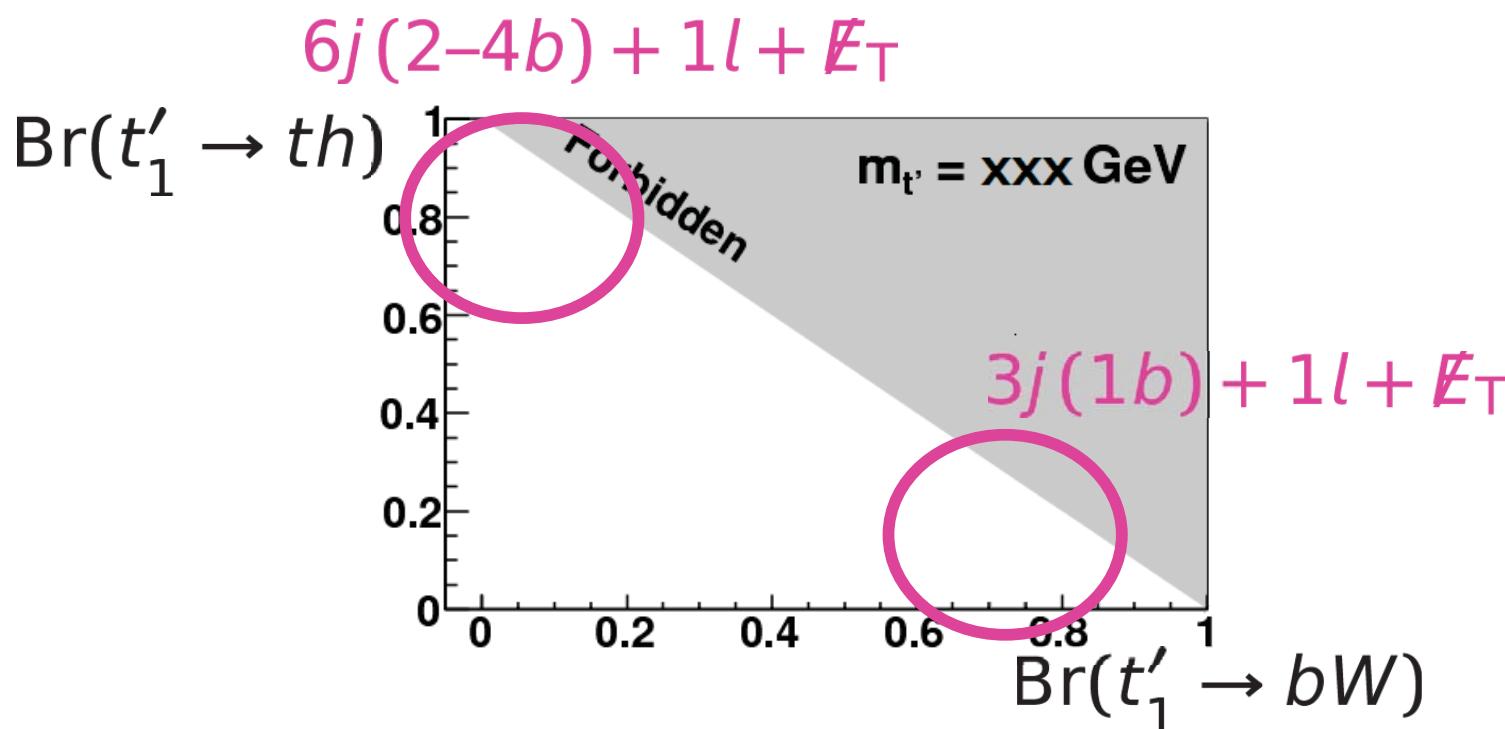
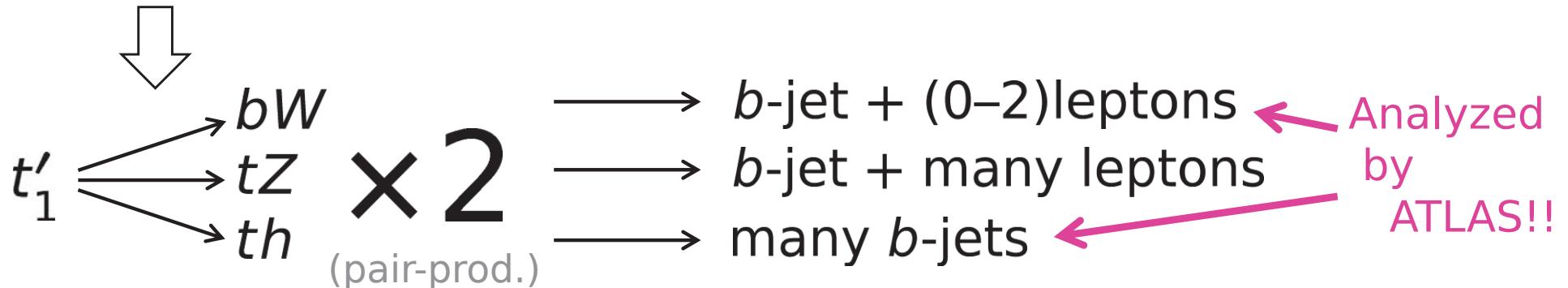
$$W_{\text{mix}} = \epsilon_i Q_i H_u U' + \epsilon'_i Q' H_u \bar{U}_i + \epsilon''_i Q' H_d \bar{D}_i + \epsilon^L_i L_i H_d \bar{E}'$$

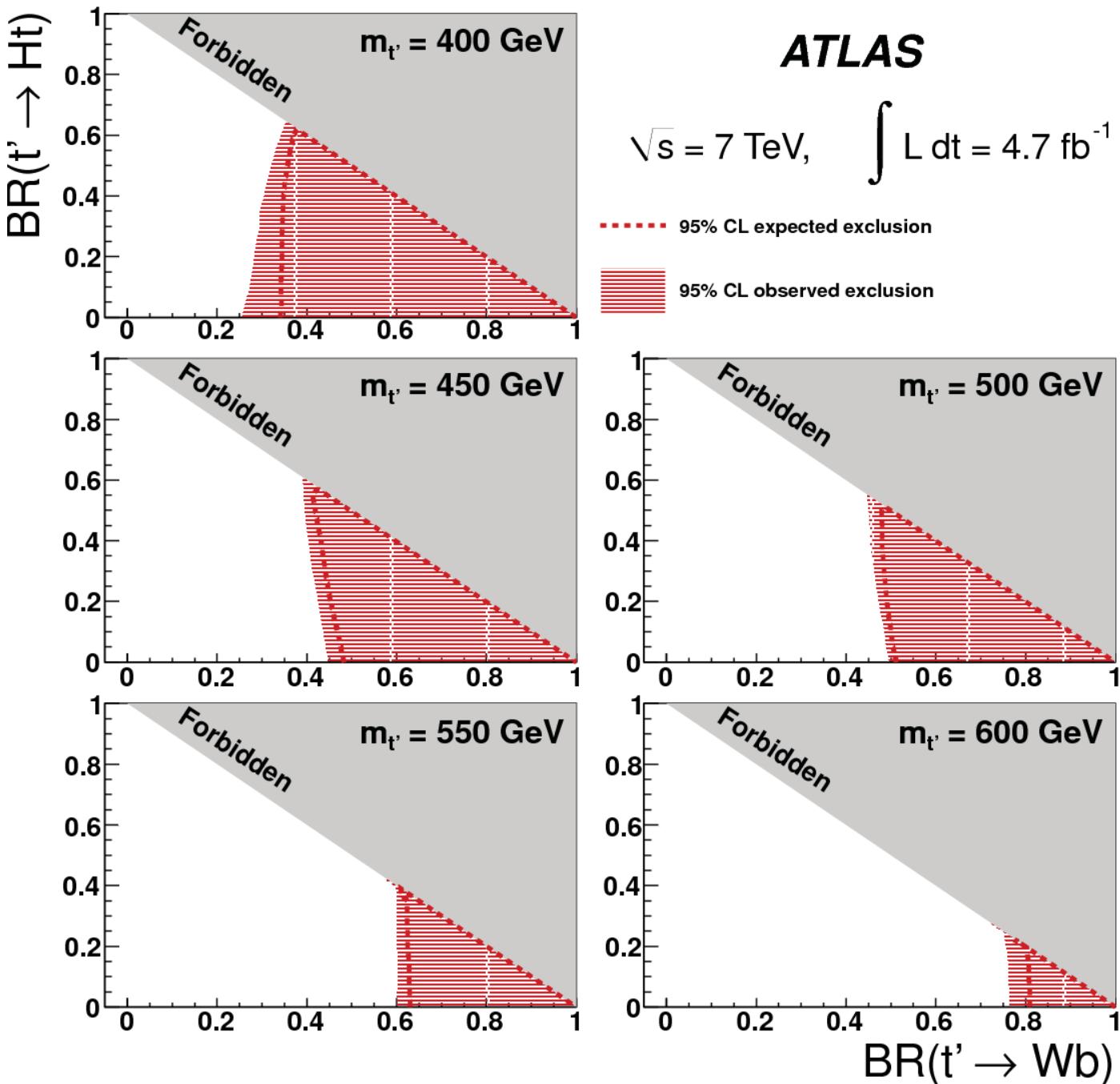
- Assumption: mixing with **3-gen.** only. ($\epsilon_1 = \epsilon_2 = 0$) etc.

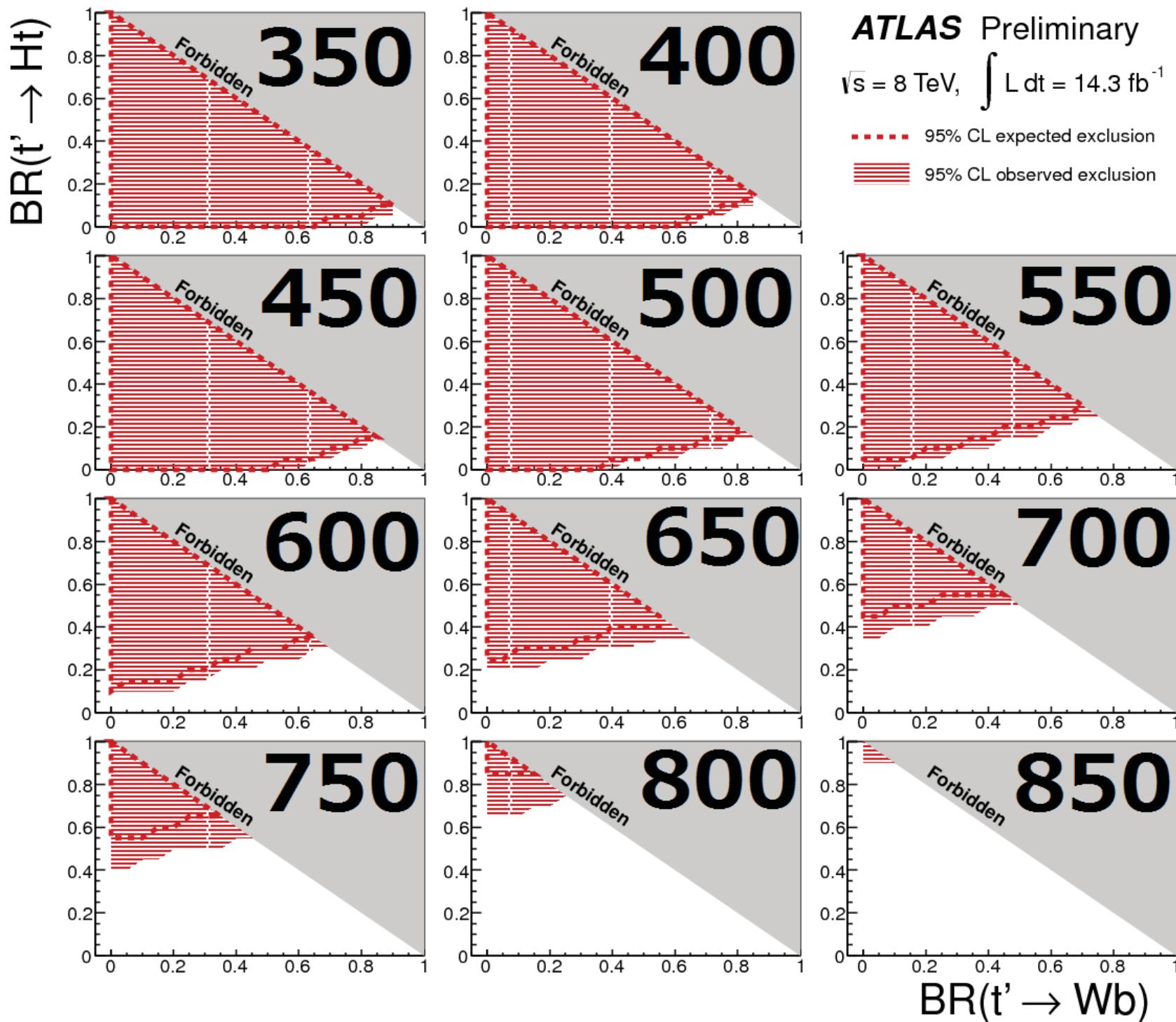


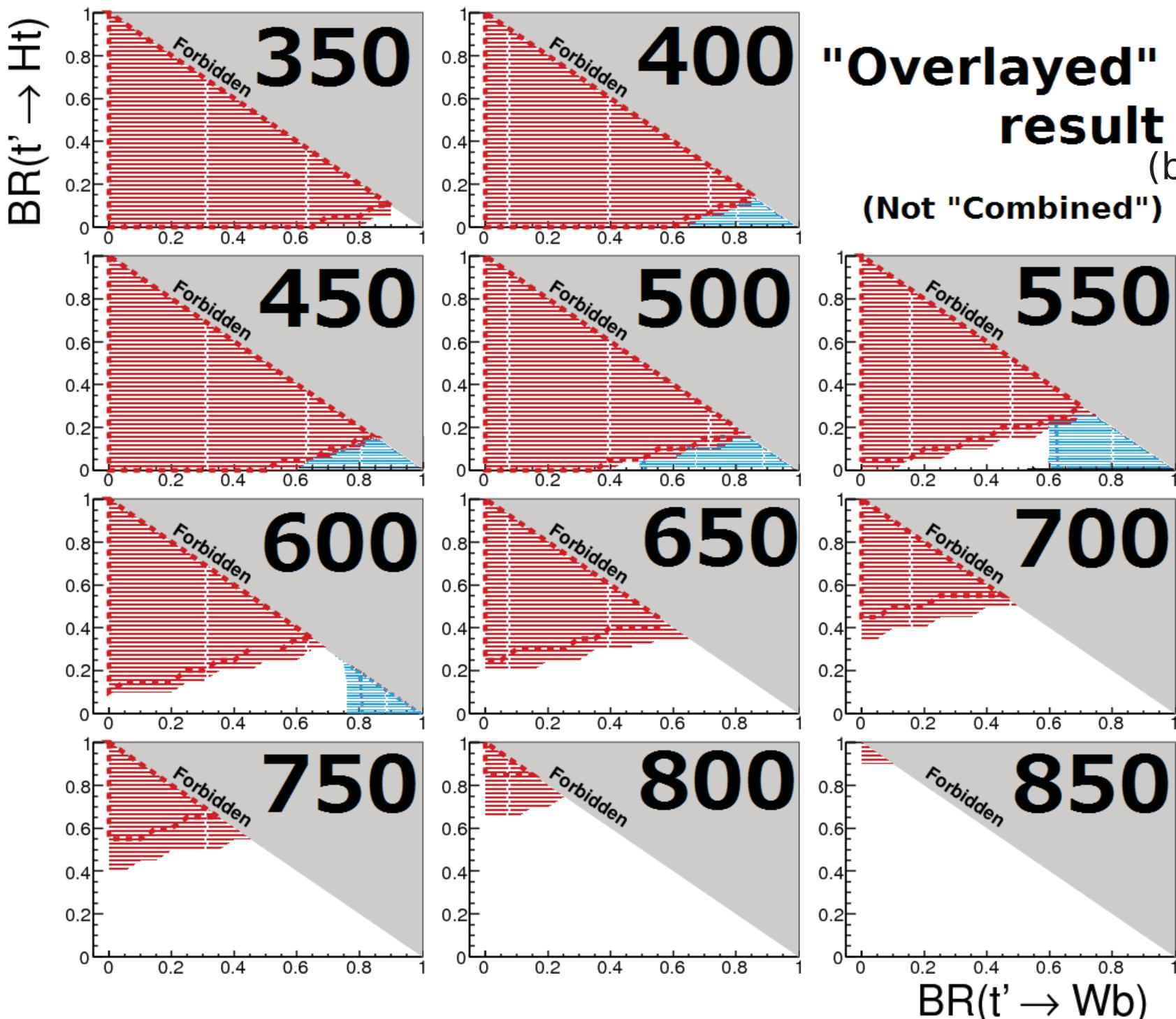
$$W_{\text{mix}} = \epsilon_i Q_i H_u U' + \epsilon'_i Q' H_u \bar{U}_i + \epsilon''_i Q' H_d \bar{D}_i + \epsilon^L_i L_i H_d \bar{E}'$$

- Assumption: mixing with **3-gen.** only. ($\epsilon_1 = \epsilon_2 = 0$) etc.



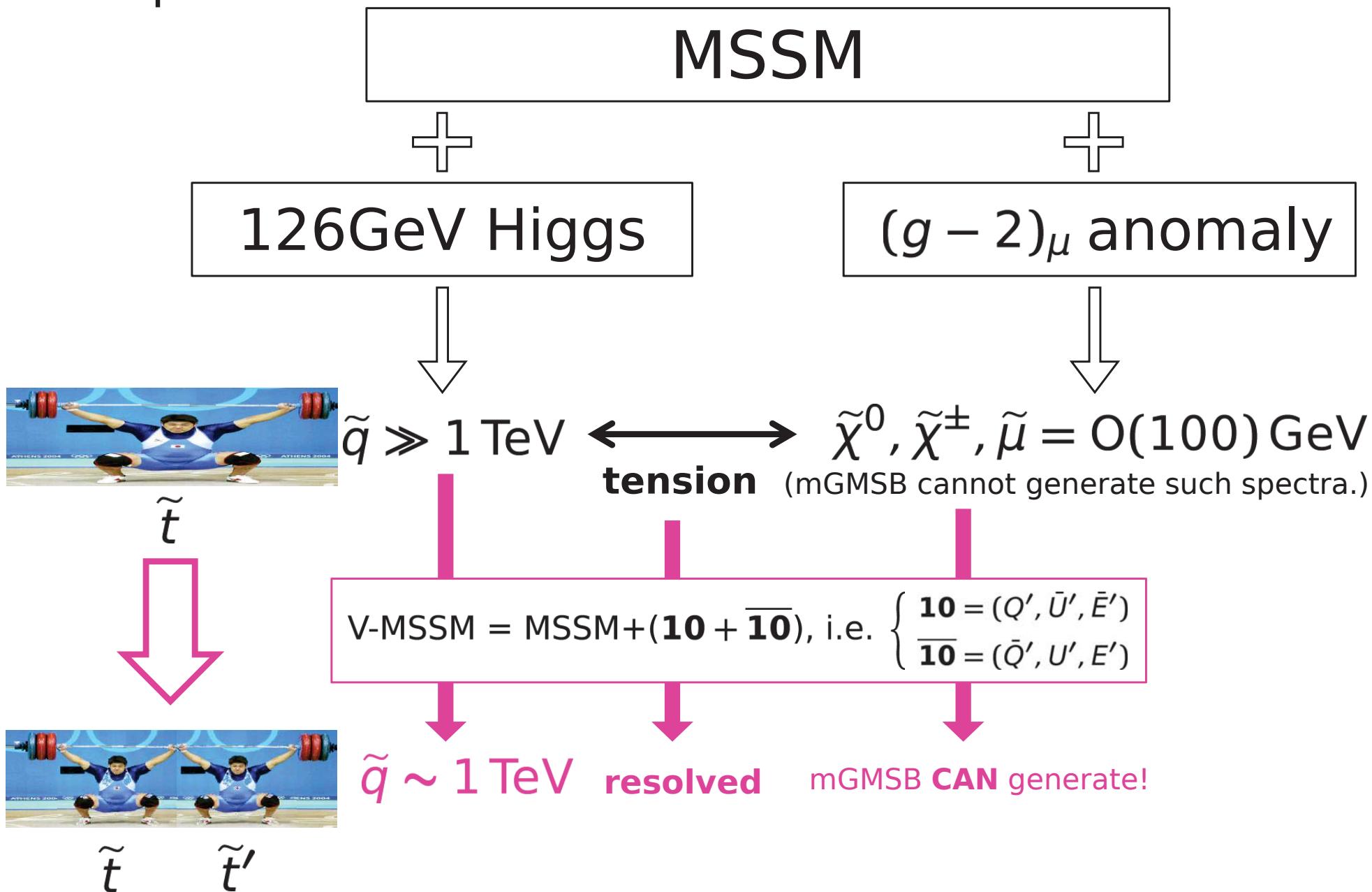




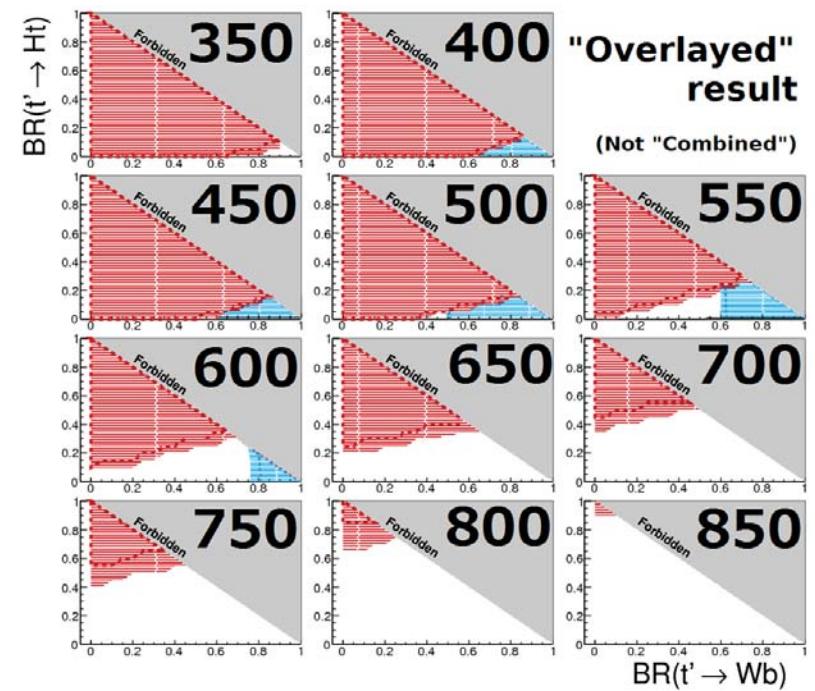
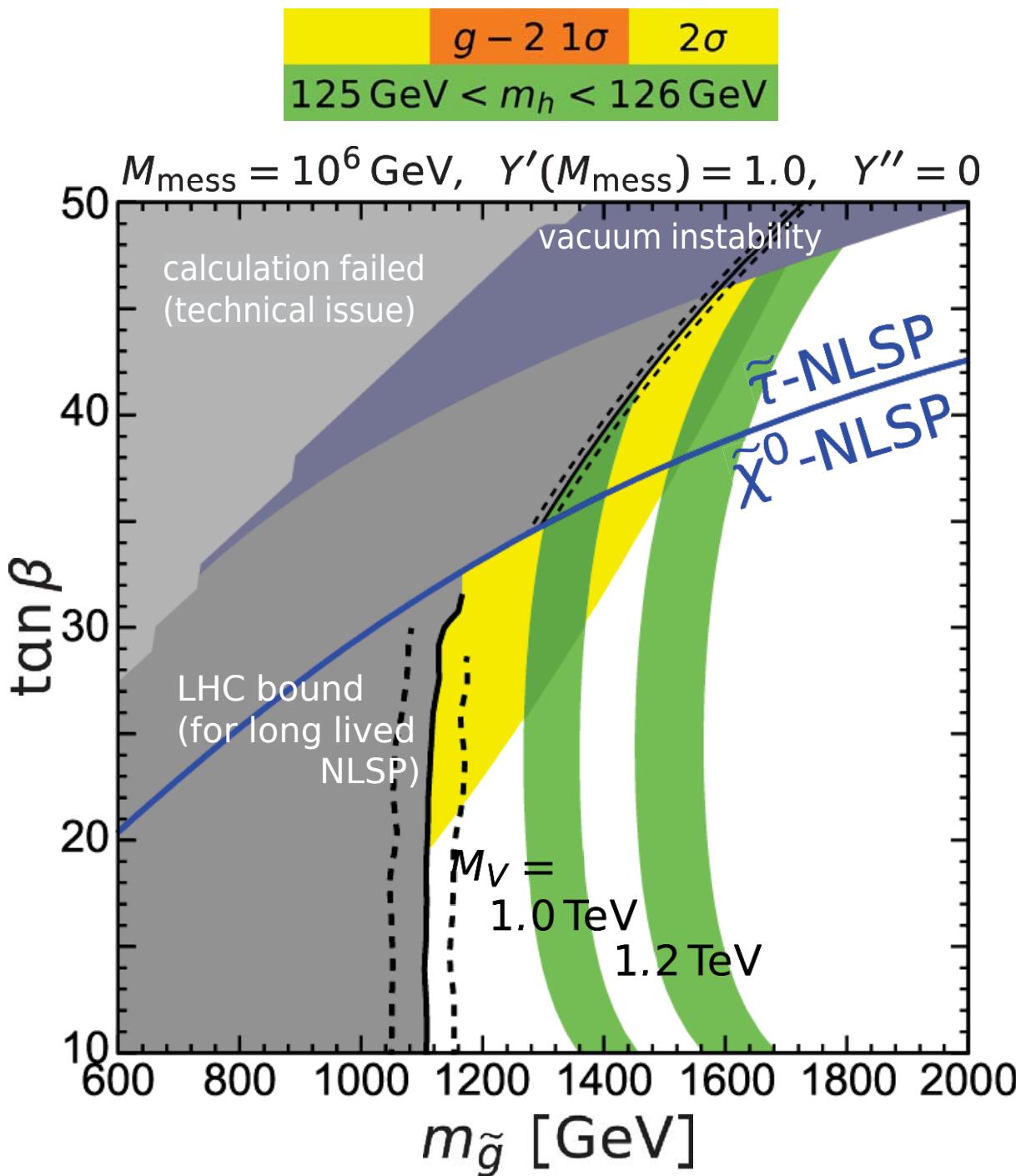


"Overlaid" result
(by myself)
(Not "Combined")

○ Topic 2.



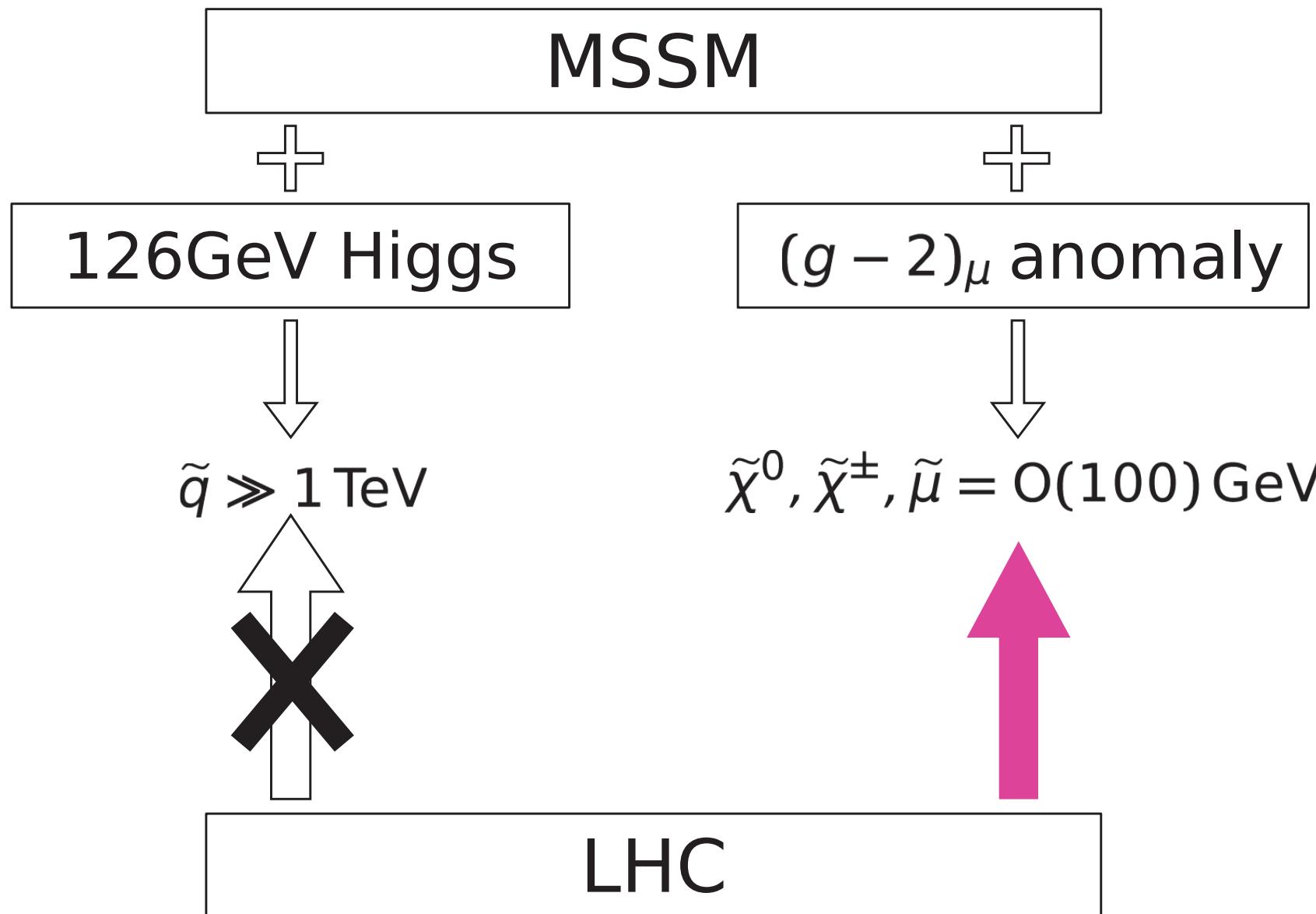
VMSSM + GMSB explains muon g-2 anomaly under 126GeV Higgs



Summary?

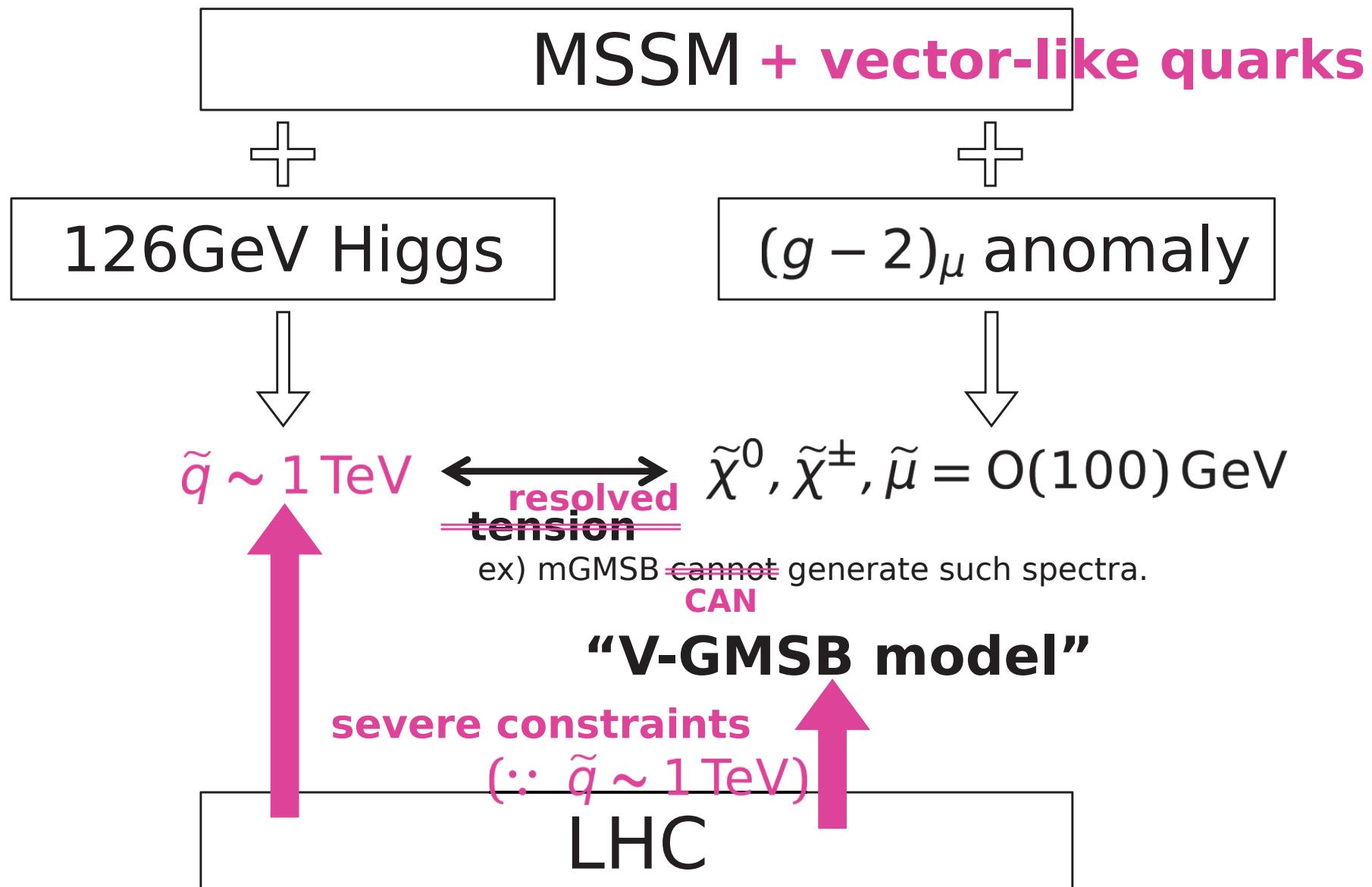
◉ Topic 1.

(Minimal SUSY Standard Model)



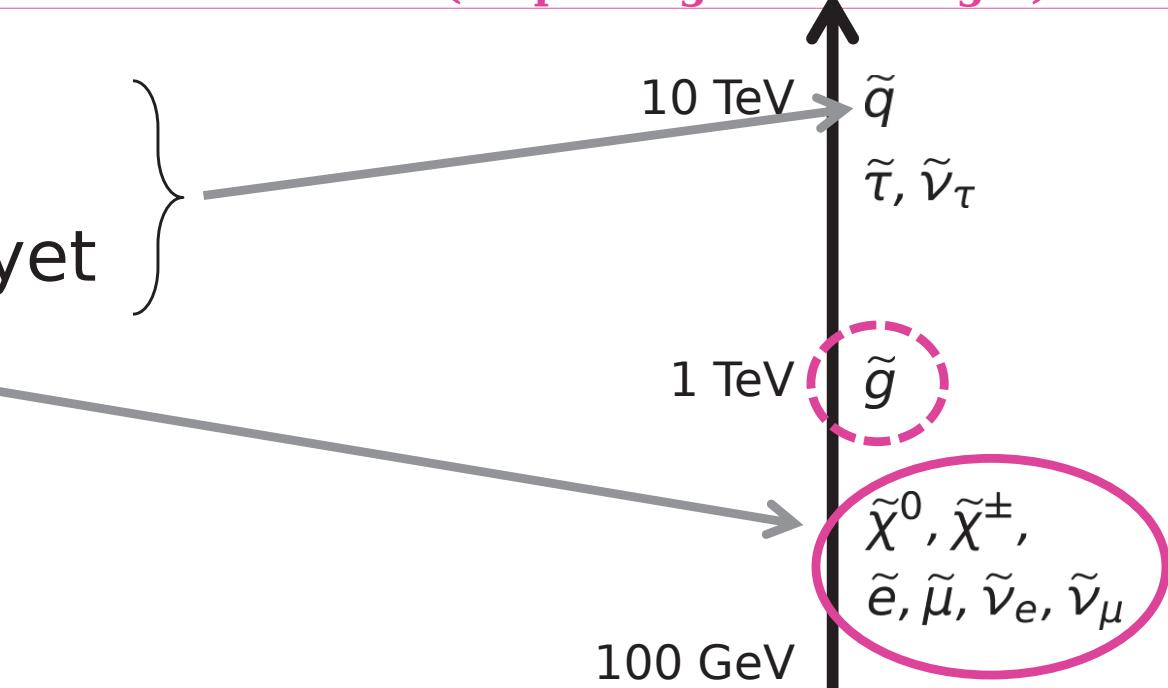
① Topic 2.

(Minimal SUSY Standard Model)

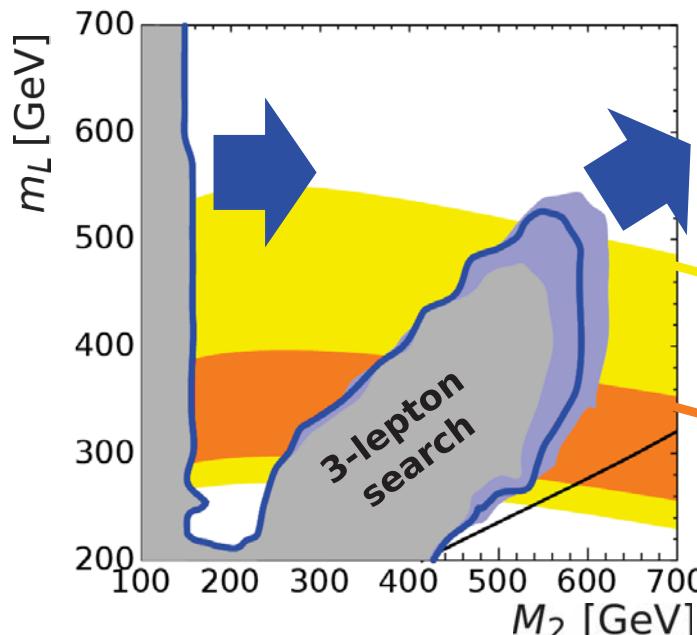
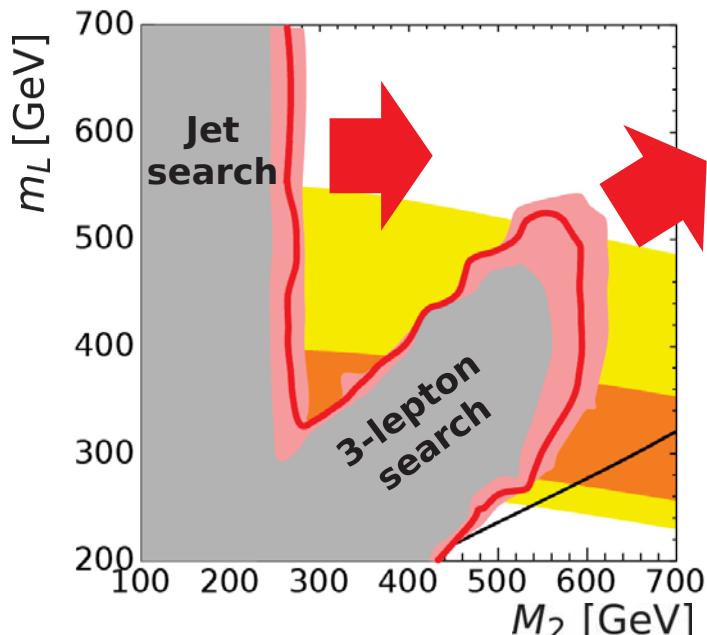


Summary of Topic 1 : Non-colored SUSY search (respecting the muon g-2)

- 126 GeV Higgs
- SUSY Not Found yet
- $(g - 2)_\mu$ anomaly



An extreme case: $\mu = 2 \text{ TeV}$, $m_L^2 : m_{\tilde{E}}^2 = 1 : (1.5)^2$

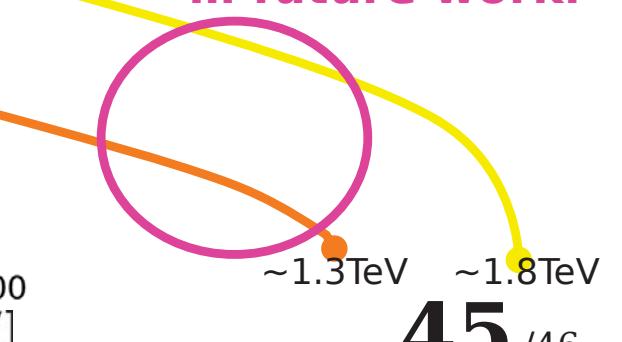


Jet: [ATLAS-CONF-2012-109](#)
3L: [ATLAS-CONF-2012-154](#)

How can we search?

- Heavy gaugino
- Large μ -term
- Light sleptons

... future work.



VMSSM + GMSB explains muon g-2 anomaly under 126GeV Higgs

