Natural Supersymmetry at the LHC

JHEP12(2010)019

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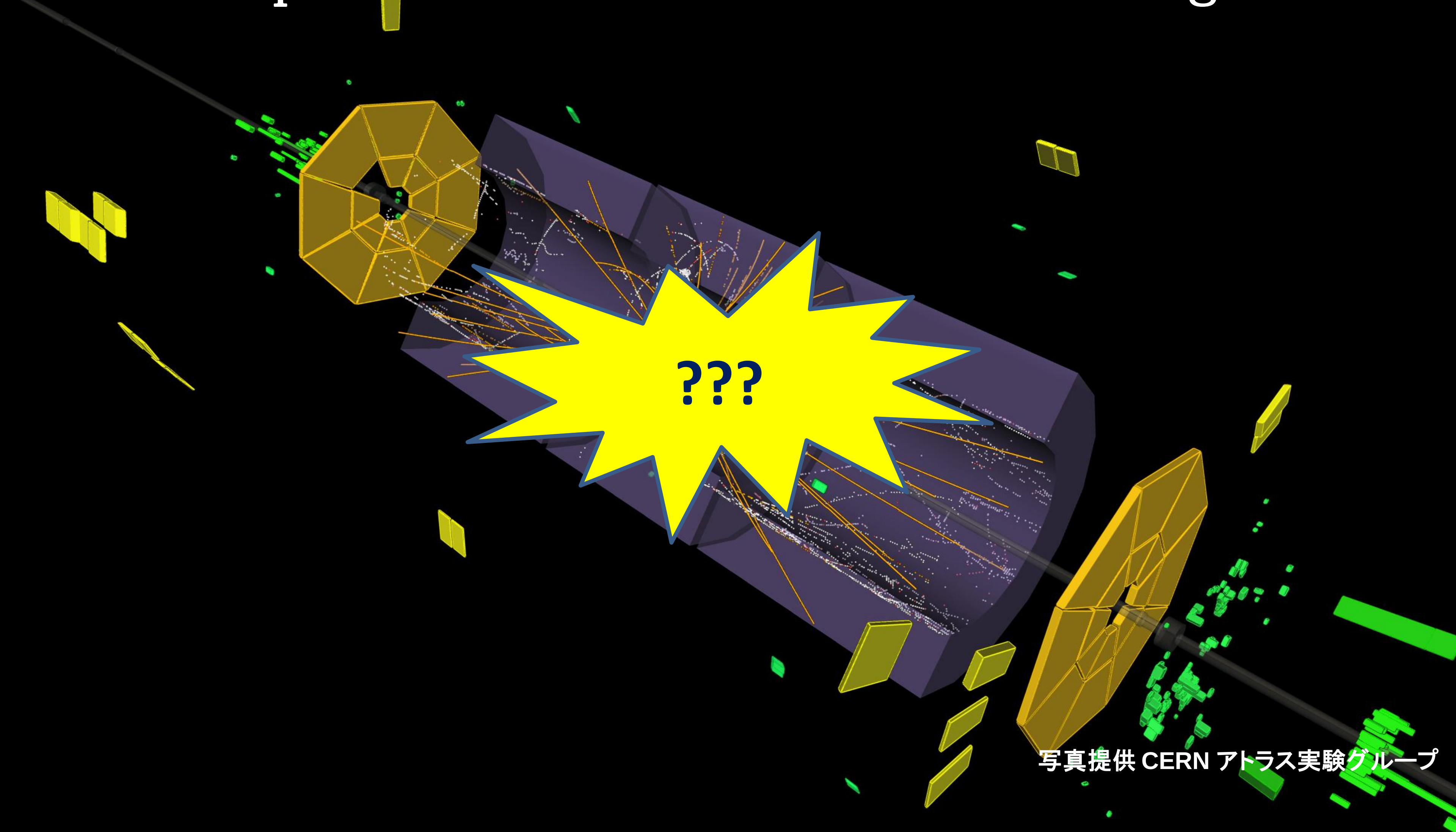
LHC experiments have started taking data.

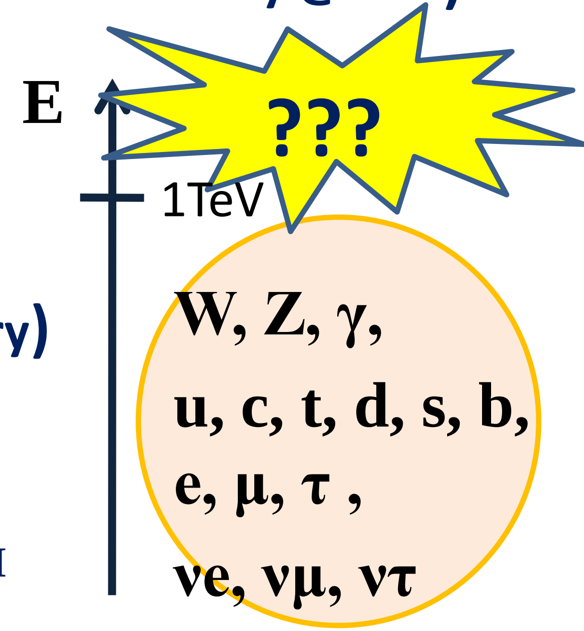


写真提供 CERN アトラス実験グループ

What will appear at the LHC?

Introduction

(What is the basis for expecting the discovery @ LHC)



What we know

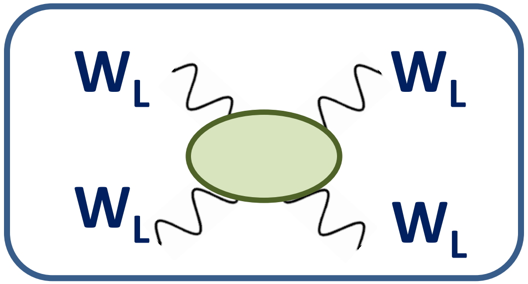
Non-linear σ model (low energy effective theory)

Global : $SU(2)_L \times SU(2)_R \to SU(2)_C$

Gauge : $SU(2)_L \times U(1)_Y \quad \to U(1)_{EM}$

The limit of validity exists;

Unitarity violation ($\gtrsim$ 1 TeV)

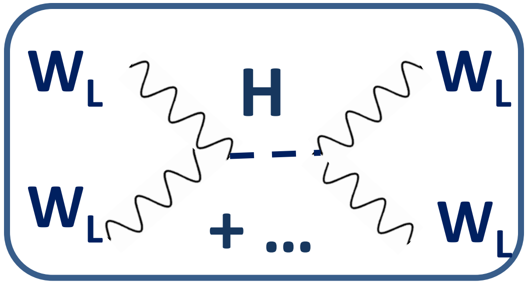


⇨ **@ $\lesssim$ TeV scale, an important discovery exists!**

Is it Higgs boson?

Introduction

- **Higgs boson is the last undiscovered particle in the SM (Standard Model) of particle physics.**
- **Higgs will restore the unitarity of $W_L W_L$ scatt.**



Introduction

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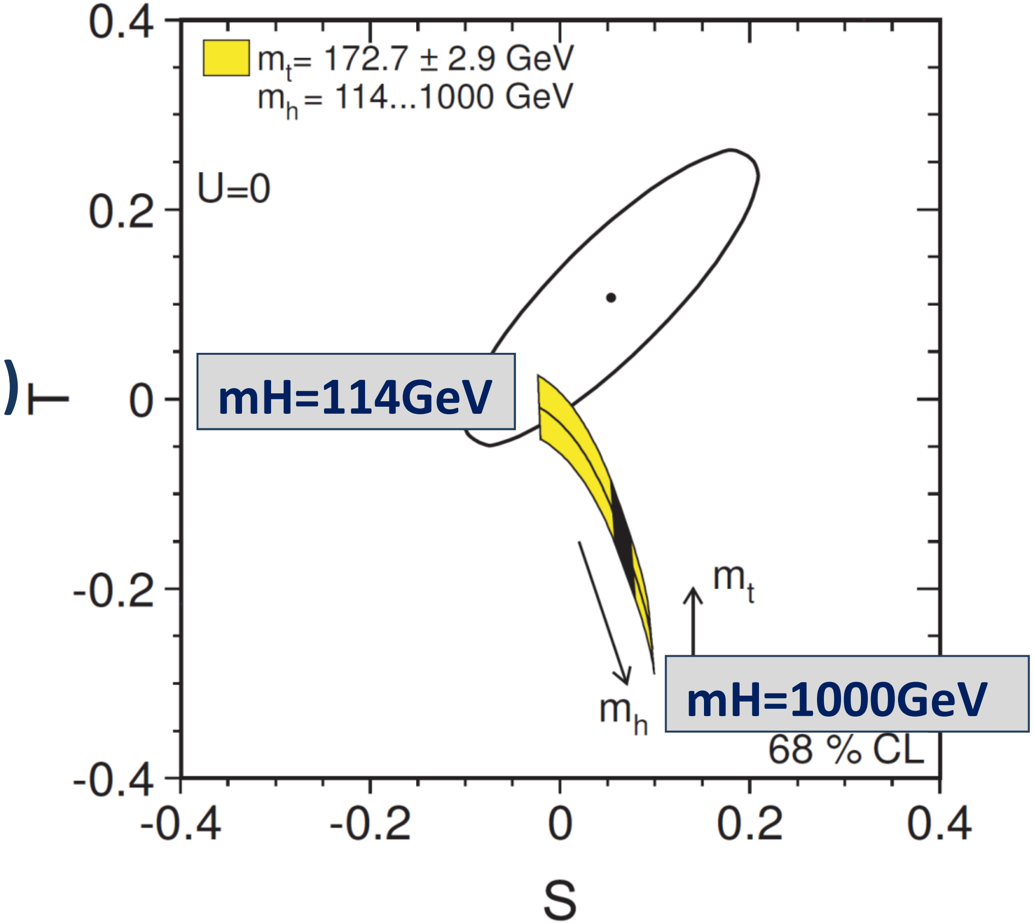
- **EWPMs (Electroweak Precision measurements) are consistent with light Higgs boson.**



http://lepewwg.web.cern.ch/LEPEWWG/plots/summer2005/s05_stu_contours.eps

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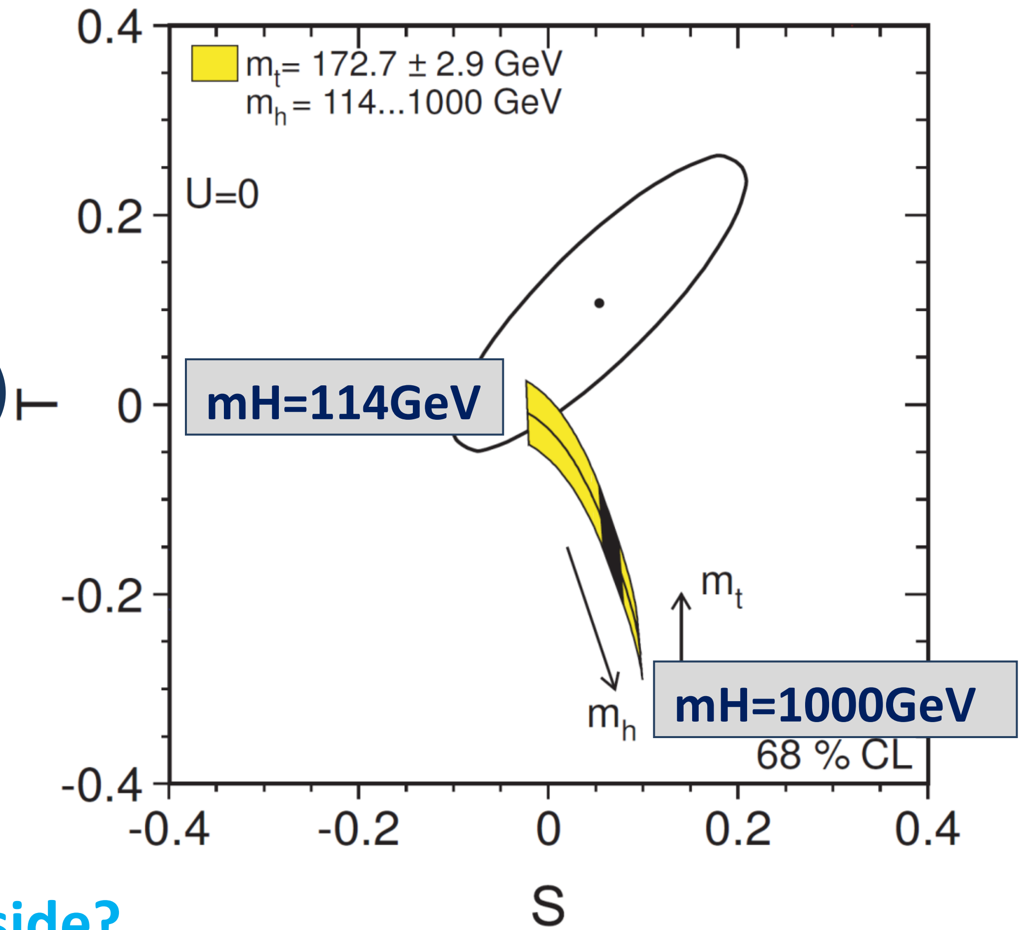
- SM (light Higgs) is good for data.



What about it for theoretical side?

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Introduction

What about it for theoretical side?

In the SM, there is the hierarchy problem.

- The Higgs Potential $V = m^2 |h|^2 + (\lambda/4) |h|^4$

($v^2 = -2\, m^2/\lambda$,
$m_h{}^2 = \lambda v^2$)

- The Higgs mass $m_h{}^2 / 2 = -\, m^2$

Introduction

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$\downarrow$ ($v^2 = -2 m^2/\lambda$, $m_h^2 = \lambda v^2$)

- The Higgs mass $m_h^2 / 2 = - m^2 + \delta m_h^2$

Quantum correction $\delta m_h^2 \sim (y_t^2/16\pi^2) \Lambda^2$
$\sim (y_t^2/16\pi^2) M_{Pl}^2$

hierarchy problem

$$m_h^2 / 2 \Longleftrightarrow (y_t^2/16\pi^2) M_{Pl}^2$$

Introduction

- Supersymmetry (SUSY) is one of the solution to the hierarchy problem.

⇨ Λ^2 terms are canceled!

There are only logarithmic terms.

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light Higgs!

Higgs Potential **gauge coupling！**

$$V = m_1^2|H_1^0|^2 + m_2^2|H_2^0|^2 + (m_3^2 H_1^0 H_2^0 + \mathrm{h.c.}) + \underline{\frac{g^2 + g'^2}{8}}(|H_1^0|^2 - |H_2^0|^2)^2$$

in MSSM (Minimal Supersymmetric Standard Model)
the lightest Higgs boson mass, m_h, can be as large as 130 GeV.

Y. Okada, M. Yamaguchi and T. Yanagida, Prog. Theor. Phys. 85, 1 (1991); J. R. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. B 257, 83 (1991); H. E. Haber and R. Hempfling, Phys. Rev. Lett. 66, 1815 (1991).

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light Higgs + R-parity

→ consistent with EWPM !

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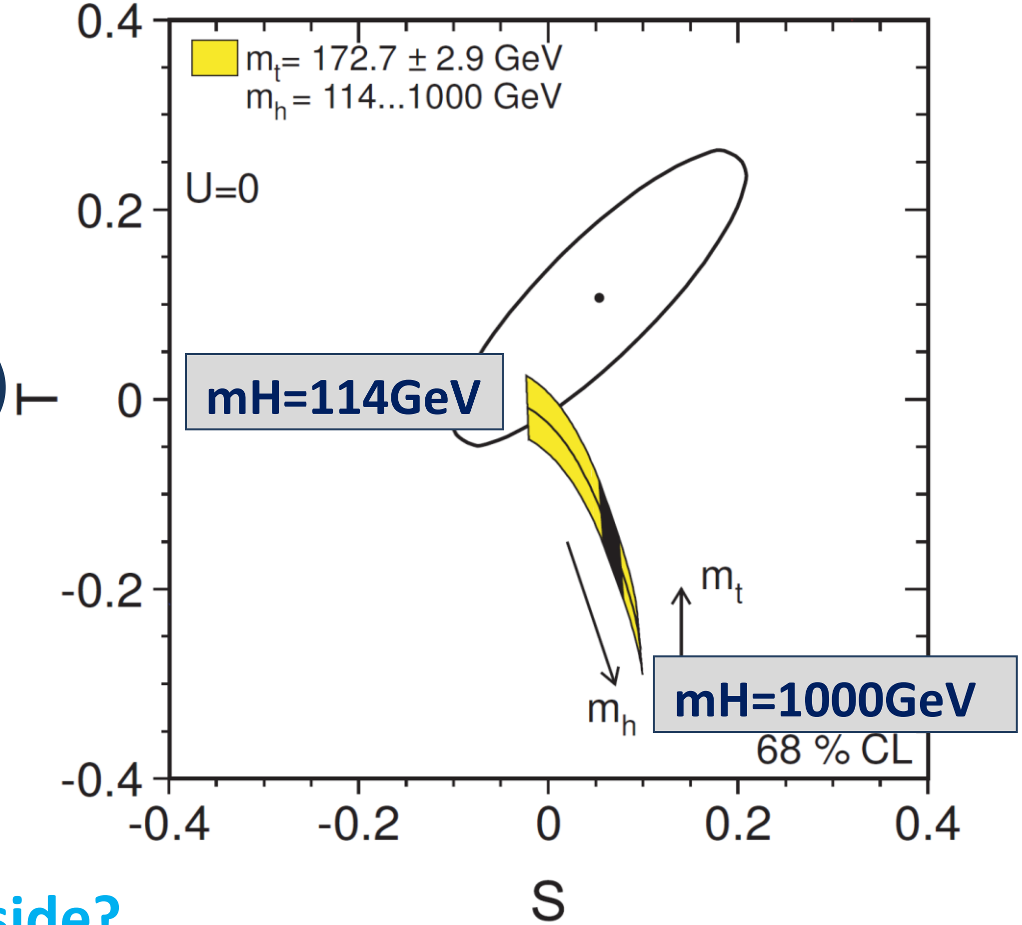

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→ consistent with EWPM !

Sounds like a good idea

Introduction

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⇨ **Λ^2 terms are canceled!**

There are only logarithmic terms.

Fine-tuning disappear ?

Introduction

- Supersymmetry (SUSY) is one of the solution to the hierarchy problem.

⇨ Λ^2 terms are canceled!
There are only logarithmic terms.

Fine-tuning disappear ?

No.

⇨ We should give more consideration to fine-tuning problem in SUSY
if we take the naturalness seriously.

Naturalness in SUSY model

What kind of a SUSY signal
with "Naturalness" will appear

Naturalness

How far is the fine-tuning?

1%?, 0.01% ? 10%?

In the SM with cutoff scale Λ~ 10TeV,

(← the scenario is also good for data and theory.)

$$m_h^2 / 2 \Longleftrightarrow \cancel{(y_t^2/16\pi^2)\, M_{Pl}^2}$$

$$(100\ \text{GeV})^2 / 2 \Longleftrightarrow (y_t^2/16\pi^2)\, (10\text{TeV})^2$$

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$$(100\ \mathrm{GeV})^2 / 2 \;\Big/\; (y_t^2/16\pi^2)\,(10\mathrm{TeV})^2 \;\lesssim 1\%$$

- If we allow ~ 1 % tuning, we don’t need to consider low scale SUSY for Naturalness.

- If we consider the low scale SUSY for Naturalness, ≧10 % tuning is favor.

⇨ In this talk, < 10 % tuning is called fine-tuning.

Naturalness

$$V = m^2 |h|^2 + (\lambda/4) |h|^4$$

$$-2 m^2 = m_h^2 \leqq (130\ \text{GeV})\hat{}2$$

$$m^2 = \mu^2 + (m_{Hu}^2)_{tree} + (m_{Hu}^2)_{rad}$$

if each contribution is much larger than Higgs mass,

fine-tuning is required.

Naturalness

$$V = m^2 |h|^2 + (\lambda/4) |h|^4$$

$$- 2 m^2 = m_h^2 \leqq (130\ \mathrm{GeV})^2$$

$$m^2 = \mu^2 + (m_{Hu}^2)_{tree} + (m_{Hu}^2)_{rad}$$

- For μ term,

Requiring $\Delta^{-1} = m_h^2/2\mu^2$ > 10 %,

⇨ $|\mu| \lesssim 290\ \mathrm{GeV}$

Naturalness

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- For m_{Hu} term,

$$m_{H_u}^2|_{\rm rad} \simeq -\frac{3y_t^2}{8\pi^2}(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2)\ln\left(\frac{M_{\rm mess}}{m_{\tilde{t}}}\right)$$

Because the small logarithm is favor,

we assume $M_{\rm mess} \sim 10 \text{ TeV}$

Naturalness

$$V = m^2 |h|^2 + (\lambda/4) |h|^4$$

$$-2 m^2 = m_h^2 \leqq (130 \text{ GeV})^2$$

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$$m_{\tilde{t}} \equiv (m_{\tilde{q}_3} m_{\tilde{u}_3})^{1/2}$$

Requiring $\Delta^{-1} \equiv m_h^2/2m_{H_u}^2|_{\rm rad}$ **> 10 %,**

$$500 \text{ GeV} \lesssim m_{\tilde{t}} \lesssim 500 \text{ GeV} \quad \text{for } |A_t| \sim m_{\tilde{t}}$$

$$250 \text{ GeV} \lesssim m_{\tilde{t}} \lesssim 360 \text{ GeV} \quad \text{for } |A_t| \sim 2m_{\tilde{t}}$$

...

From experiments, mh > 114.4GeV (lower bound)

From naturalness (upper bound)

- **From μ term,** ($\Delta^{-1} = m_h^2/2\mu^2$ and require $\Delta^{-1} > 10\%$)

$$|\mu| \lesssim 290 \text{ GeV}$$ ➡ **Light Higgsino**

- **From m_{Hu} term** ($\Delta^{-1} \equiv m_h^2/2m_{H_u}^2|_{\rm rad}$) **& Higgs mass bound**

$$500 \text{ GeV} \lesssim m_{\tilde{t}} \lesssim 500 \text{ GeV} \quad \text{for } |A_t| \sim m_{\tilde{t}}$$

$$250 \text{ GeV} \lesssim m_{\tilde{t}} \lesssim 360 \text{ GeV} \quad \text{for } |A_t| \sim 2m_{\tilde{t}}$$

$$m_{\tilde{t}_1} \lesssim 400 \text{ GeV} \quad (|A_t| \sim m_{\tilde{t}})$$

$$m_{\tilde{t}_1} \lesssim 200 \text{ GeV} \quad (|A_t| \sim 2m_{\tilde{t}})$$

➡ **Light stop**

By assuming a small logarithm ($M_{\rm mess} \sim 10$ TeV)

➡ **Massless gravitino**

➡ **Stop/Higgsino/gravitino system!**

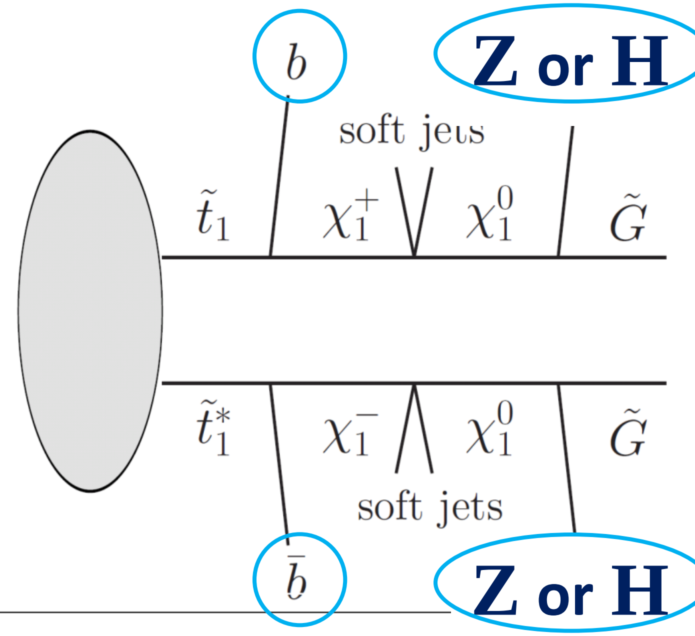
(Stop/Higgsino/gravitino)

Measurement of Natural SUSY signals at the LHC

(Stop/Higgsino/gravitino)

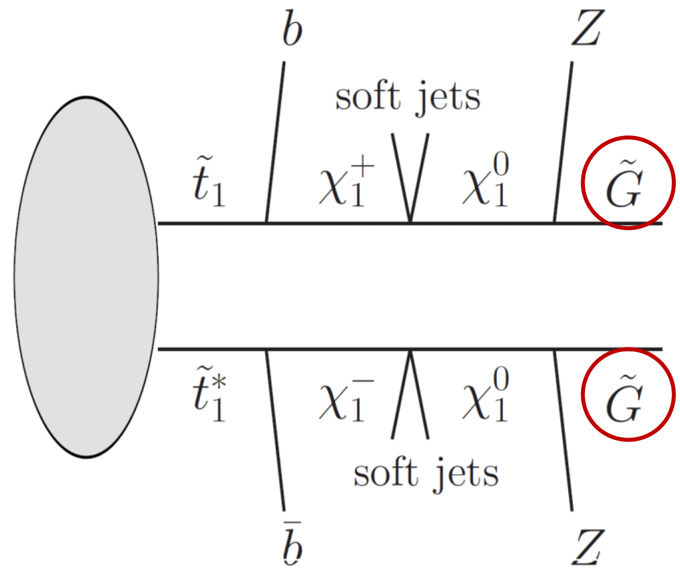
SUSY event topology

$$\sigma_{\tilde{t}_1 \tilde{t}_1} = 18 \text{ pb}$$



particle	mass [GeV]	branching ratio
χ_1^0	193.8	$\mathrm{Br}(\chi_1^0 \to \tilde{G}Z) = 0.80$, $\mathrm{Br}(\chi_1^0 \to \tilde{G}h) = 0.20$
χ_2^0	202.8	$\mathrm{Br}(\chi_2^0 \to \chi_1^0 q\bar{q}) = 0.40$, $\mathrm{Br}(\chi_2^0 \to \chi_1^0 \nu\bar{\nu}) = 0.19$, $\mathrm{Br}(\chi_2^0 \to \chi_1^\pm q\bar{q}) = 0.13, \cdots$
χ_1^+	197.3	$\mathrm{Br}(\chi_1^+ \to \chi_1^0 q\bar{q}) = 0.67$, $\mathrm{Br}(\chi_1^+ \to \chi_1^0 l^+\nu) = 0.33$
$\tilde{t}_1$	230.6	$\mathrm{Br}(\tilde{t}_1 \to \chi_1^+ b)$=1.0
$\tilde{t}_2$	559.4	$\mathrm{Br}(\tilde{t}_2 \to Z\tilde{t}_1) = 0.38$, $\mathrm{Br}(\tilde{t}_2 \to W^+\tilde{b}_1) = 0.20$, $\mathrm{Br}(\tilde{t}_2 \to \chi_1^0 t) = 0.16$, $\mathrm{Br}(\tilde{t}_2 \to \chi_1^+ b) = 0.16, \cdots$
$\tilde{b}_1$	404.1	$\mathrm{Br}(\tilde{b}_1 \to W^-\tilde{t}_1) = 0.73$, $\mathrm{Br}(\tilde{b}_1 \to \chi_1^- t) = 0.24, \cdots$
h	119.6	$\mathrm{Br}(h \to b\bar{b}) = 0.82, \cdots$
$\tilde{G}$	~ 0	

(Stop/Higgsino/gravitino)



In the final state,

there are 2 missing particles(gravitino).

M_{T2} is a helpful variable:

The endpoint shows the parent particle mass

$$M_{T2} = \min_{\mathbf{k}_T + \mathbf{k}'_T = \not{p}_T} \left[\max \left\{ M_T(\mathbf{p}_T, \mathbf{k}_T), M_T(\mathbf{p}'_T, \mathbf{k}'_T) \right\} \right]$$

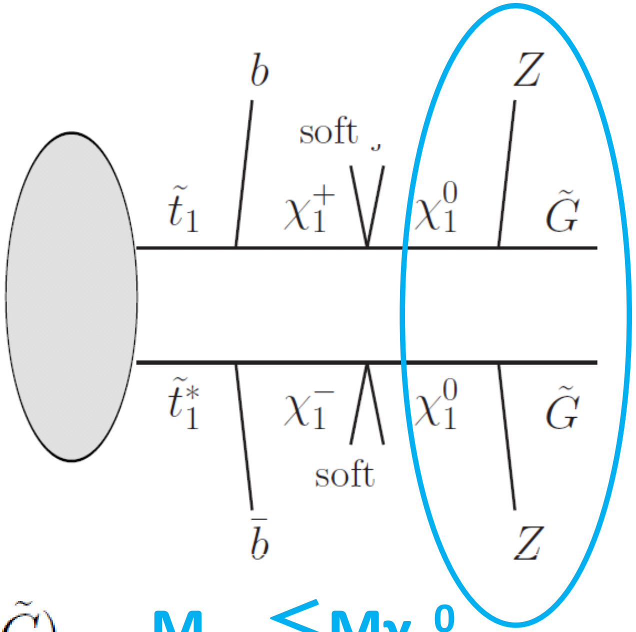
$$M_T^2(\mathbf{p}_T, \mathbf{k}_T) = m_{\text{visible}}^2 + m_X^2 + 2 \left(E_T^{\text{visible}} E_T^X - \mathbf{p}_T \cdot \mathbf{k}_T \right)$$

$$\leqq M_{\text{parent particle}}$$

Higgsino mass measurement

- χ_1^0 is mainly produced from stops which are produced in pair

  → there are a pair of χ_1^0 in each event



- M_{T2} variable for the system;

$$\chi_1^0\chi_1^0 \to (Z\tilde{G})(Z\tilde{G}) \to (l^+l^-\tilde{G})(l'^+l'^-\tilde{G})$$

$M_{T2} \leqq M\chi_1^0$

(to reduce ttbar)

- We assume massless gravitino

M_{T2} is a helpful variable.

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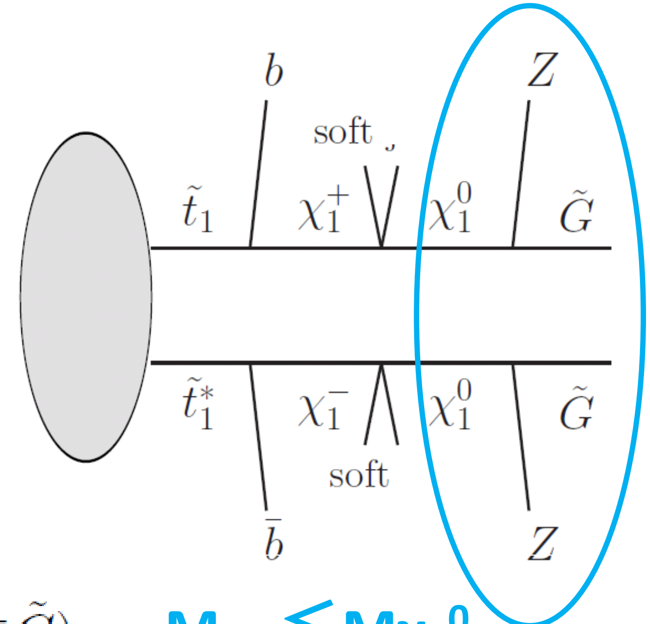

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$M_{T2} \leqq M\chi_1^0$

(to reduce ttbar)

- We assume massless gravitino

$$m_{\chi_1^0} = 198 \pm 2 \text{ GeV}$$
$$(193.8 \text{ GeV})$$

We require

- Z to be lepton pairs with same flavor and opposite charges. If all 4 leptons have the same flavor, we take the combination in which the difference of 2 reconstructed Z masses is smaller than the other combination.

- four leptons ($p_T > 10$ GeV)
- 85 GeV $< m_{l^+l^-} <$ 95 GeV
- $M_{\text{eff}} > 250$ GeV and $\not{p}_T > 50$ GeV

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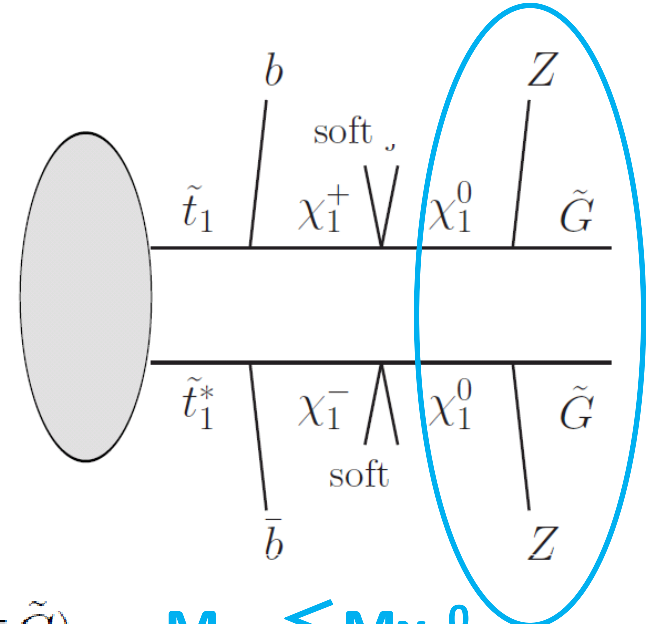

$+l^-\tilde{G})(l'^+l'^-\tilde{G})$

$M_{T2} \leqq M_{\chi_1^0}$

o

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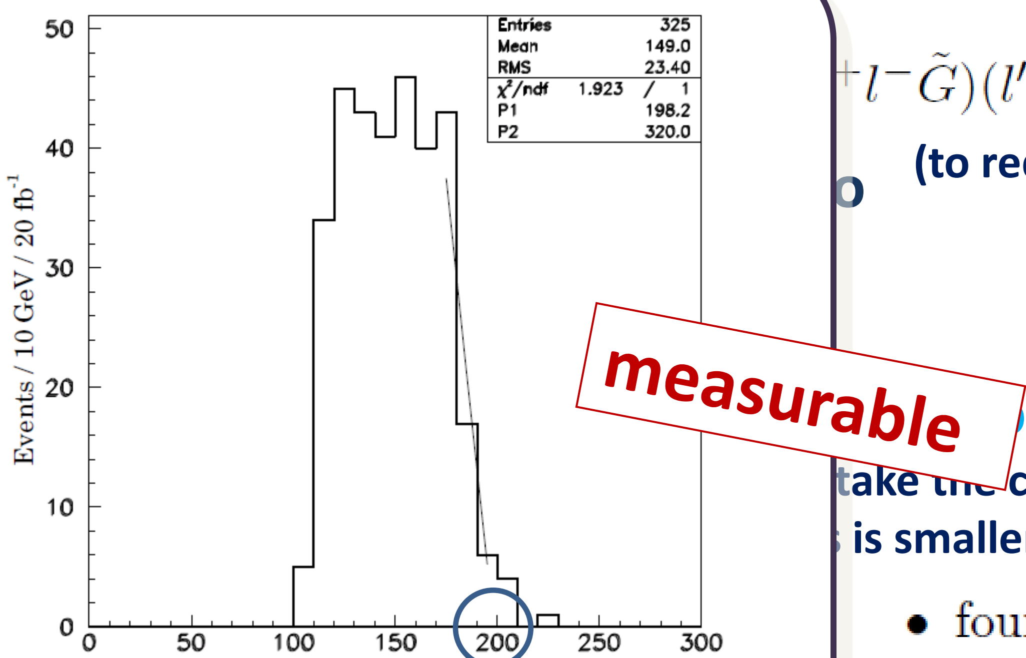

M_{T2} [GeV]

$\mathcal{L} = 20\,\text{fb}^{-1}$

r and opposite charges. If

take the combination in which the

is smaller than the other combination.

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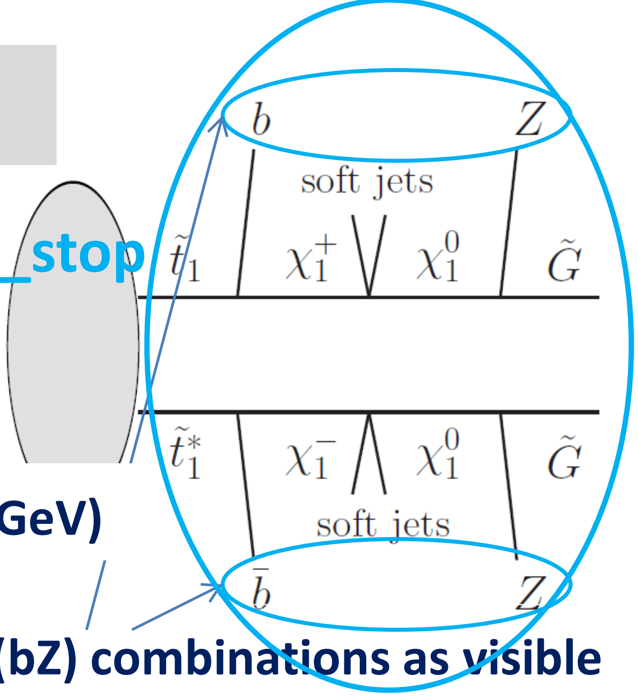
measurement of stop mass

Lighter stop mass measurement

- **Stop mass can be measured by $M_{T2} \leqq M\_stop$ using the M_{T2} distribution by including two hard jets.**



→ **we require $2 \leqq N_j \leqq 5$ hard jets (pT > 20 GeV)**

We use a pair of (bZ) combinations as visible particles in the definition of the M_{T2} variable.

- **Strategy to select a combination**

$$m_{j_1 Z_1} + m_{j_2 Z_2} = \min_{i \neq j}(m_{j_i Z_1} + m_{j_j Z_2})$$

- **At least either of j_1 or j_2 is b-tagged**

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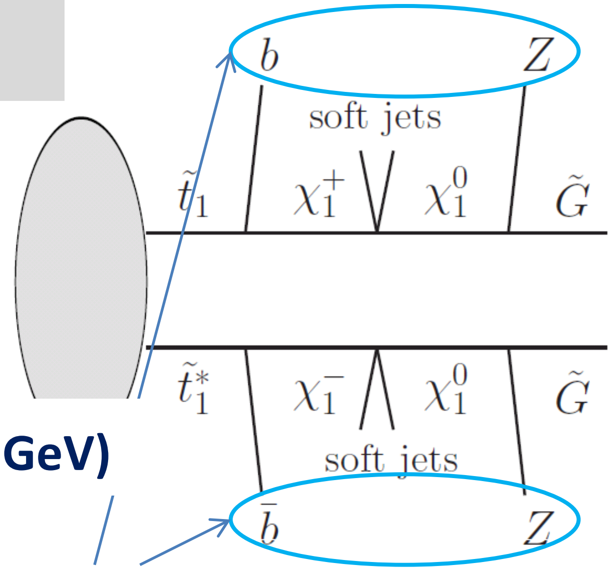

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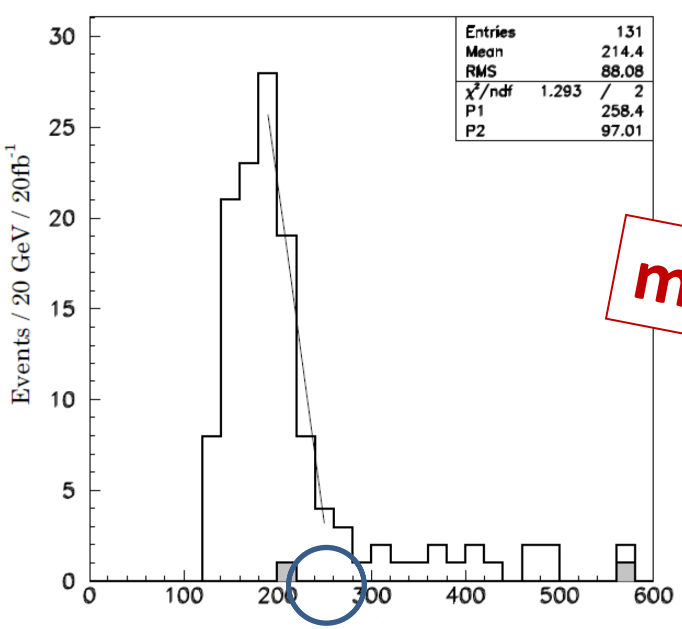


M_{T2} [GeV]

bination

$$m_{j_1 Z_1} + m_{j_2 Z_2} = \min_{i \neq j}(m_{j_i Z_1} + m_{j_j Z_2})$$

$$m_{\tilde{t}_1} = 258 \pm 6 \text{ GeV}$$

(230.6 GeV **)**

$$\mathcal{L} = 20\,\text{fb}^{-1}$$

measurement of Higgs mass

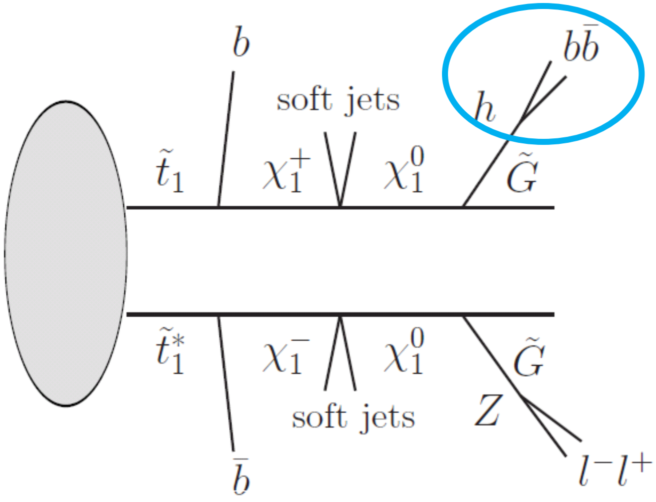
from SUSY cascade decay

Higgs mass measurement

In signal events, we treat

two leading p_T jets (j_1 and j_2) as the Higgs boson

lepton pair (l_1 and l_2) as the Z boson



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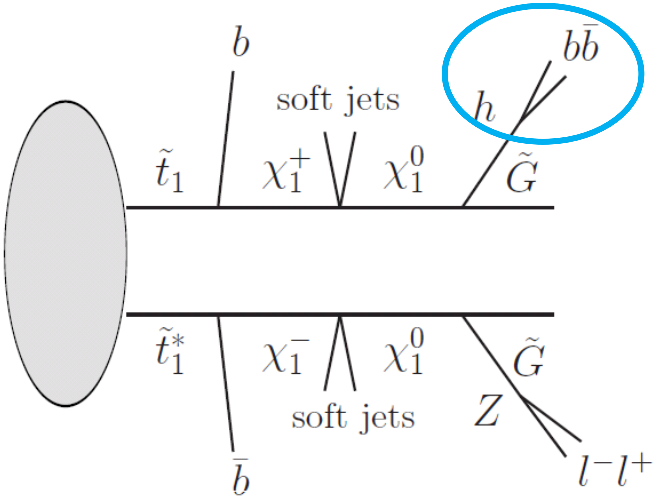
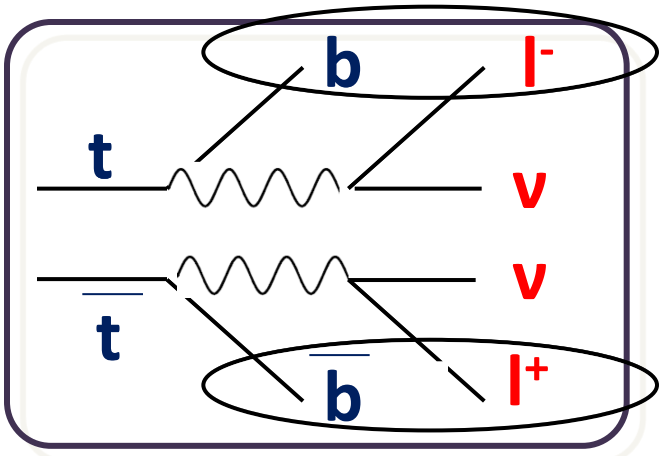


- **To reduce ttbar BG**

  (→ 2 b-jets, 2 leptons & MET),
  we use M_{T2} variable for CUT.

$$M_{T2}((j_1 l_1)(j_2 l_2)) > 180\text{GeV}$$

(ttbarBG < mt ～170 GeV)



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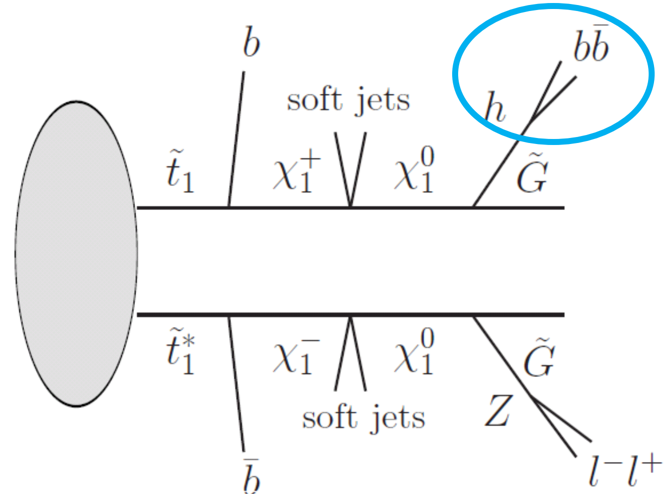

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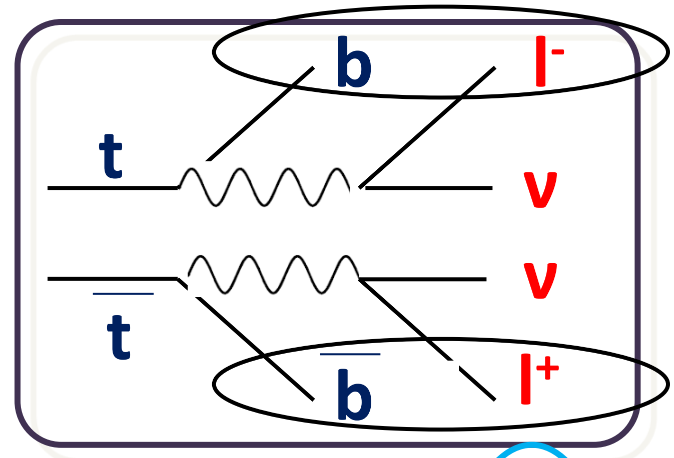
$$M_{T2}((j_1 l_1)(j_2 l_2)) > 180\text{GeV}$$

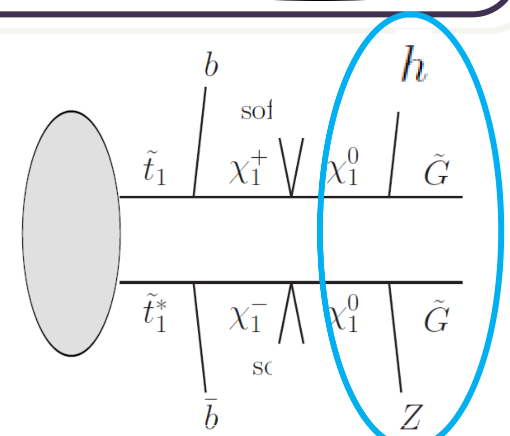
(ttbarBG < mt ∼170 GeV)



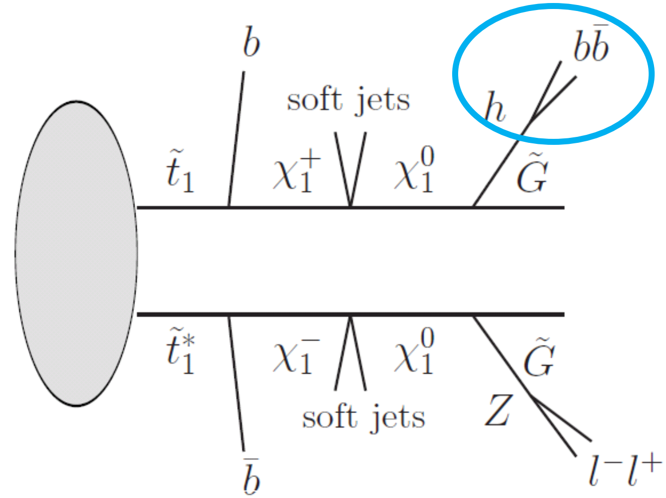
- **To reduce the combinatorial BG,**

$$M_{T2}((j_1 j_2)(l_1 l_2)) < 200 \text{ GeV}$$

(signal < $m\chi_1^0$ ∼195 GeV)



Higgs mass measurement



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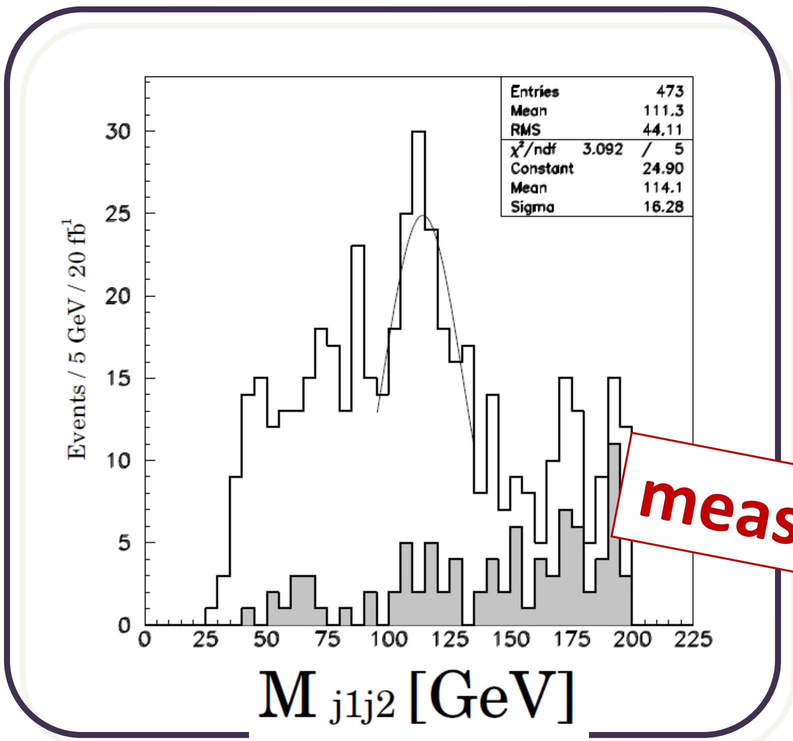
CUT

- a lepton pair with the same flavor and opposite charge with $p_T > 10$ GeV
- $85 \text{ GeV} < m_{l^+l^-} < 95 \text{ GeV}$,
- at least two hard jets with $p_T > 50$ GeV,
- at least three and less than five hard jets with $p_T > 30$ GeV,
- $M_{\text{eff}} > 250$ GeV,
- at least one of the two hardest jets is b-tagged.



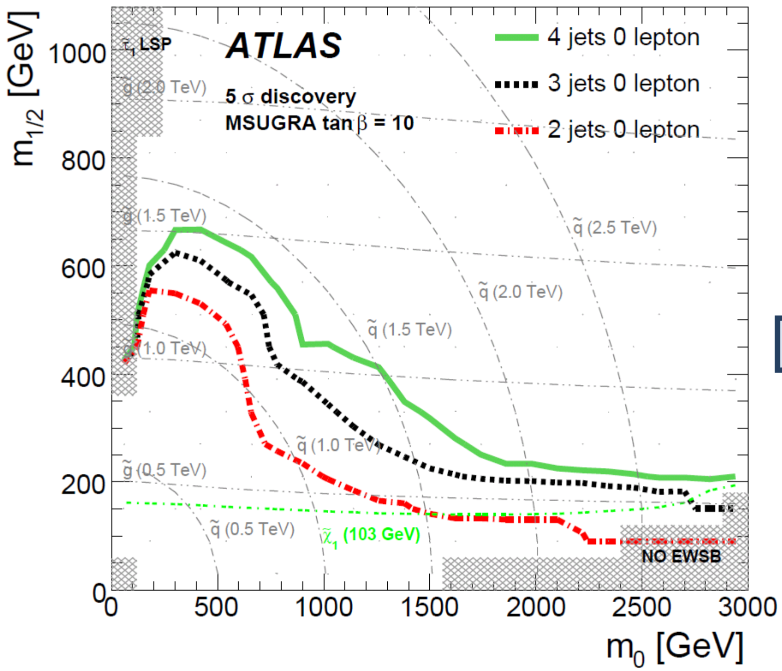
measurable

$$m_h = 114 \pm 16 \text{ GeV}$$

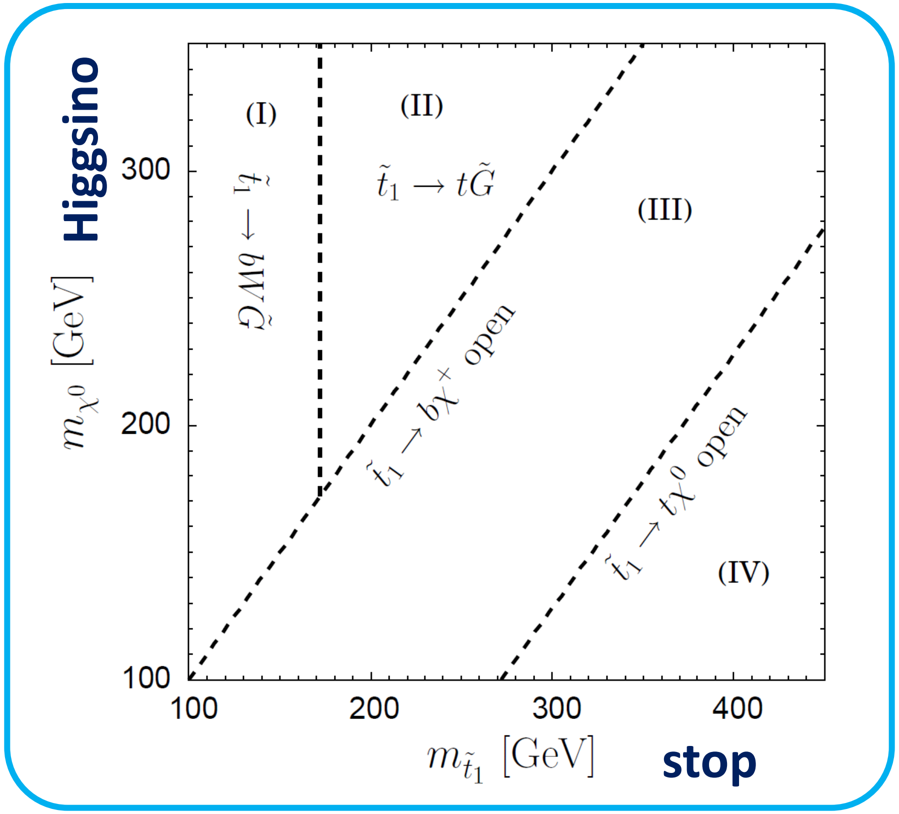
$$\mathcal{L} = 20\,\text{fb}^{-1}$$

Discovery of Natural SUSY signals at the LHC

SUSY Search



The ATLAS Collaboration 0901.0512



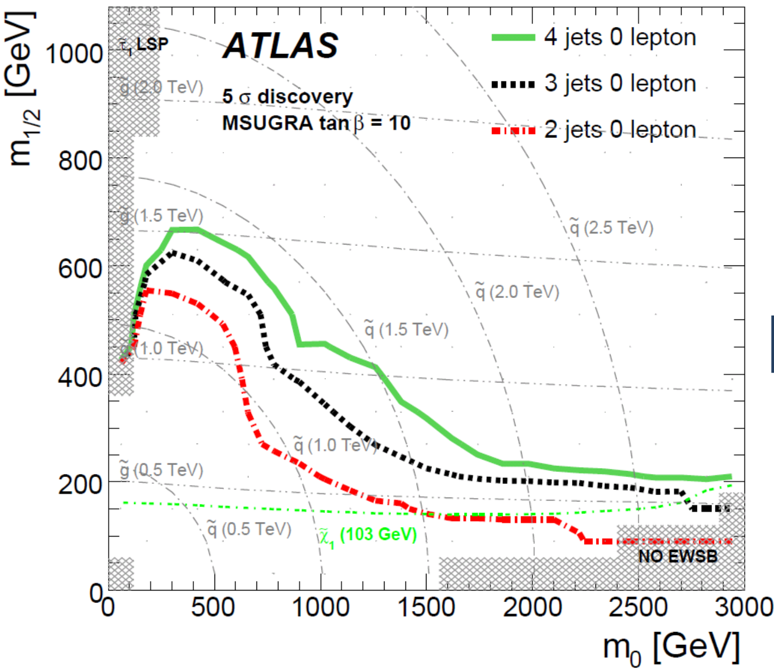
MA, H. D. Kim, R. Kitano, Y. Shimizu, 2010

msugra

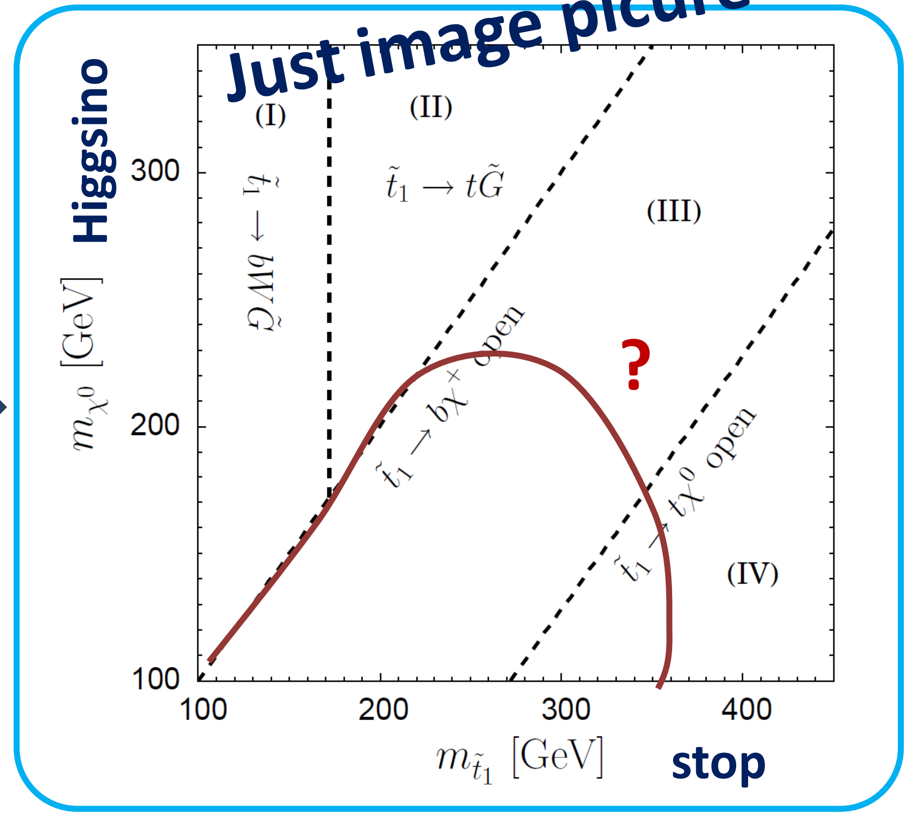
SUSY Search

Very preliminary.

Just image picure



The ATLAS Collaboration 0901.0512



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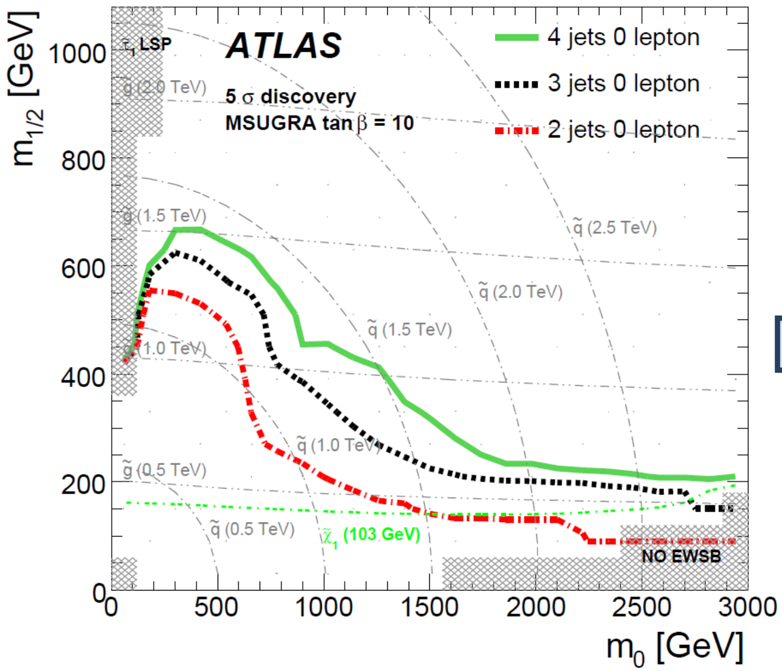

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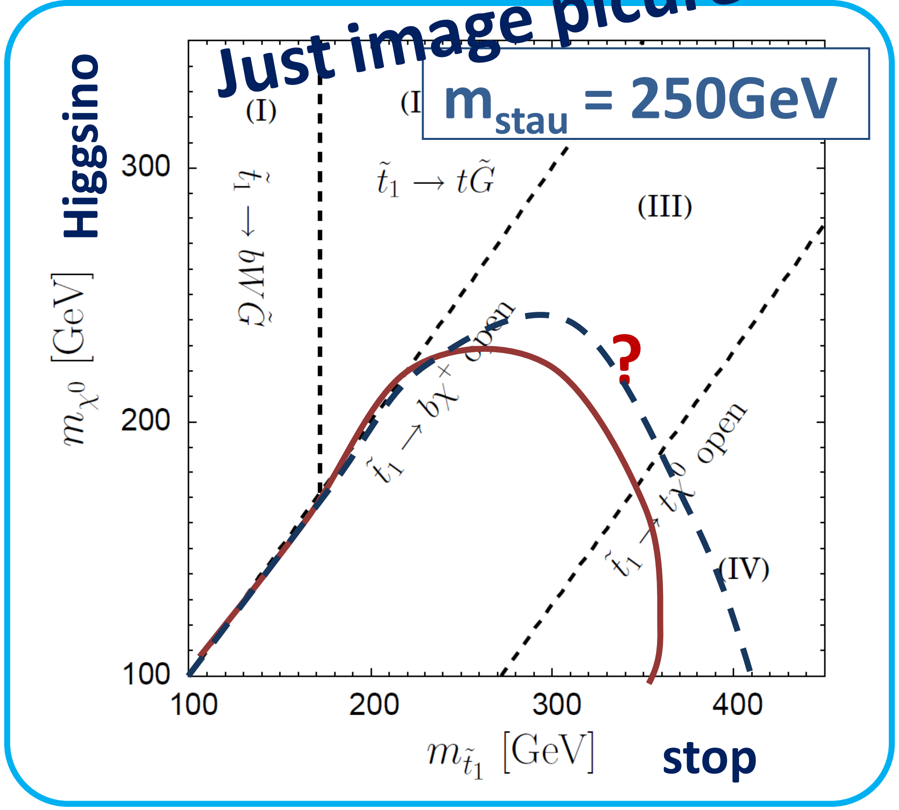

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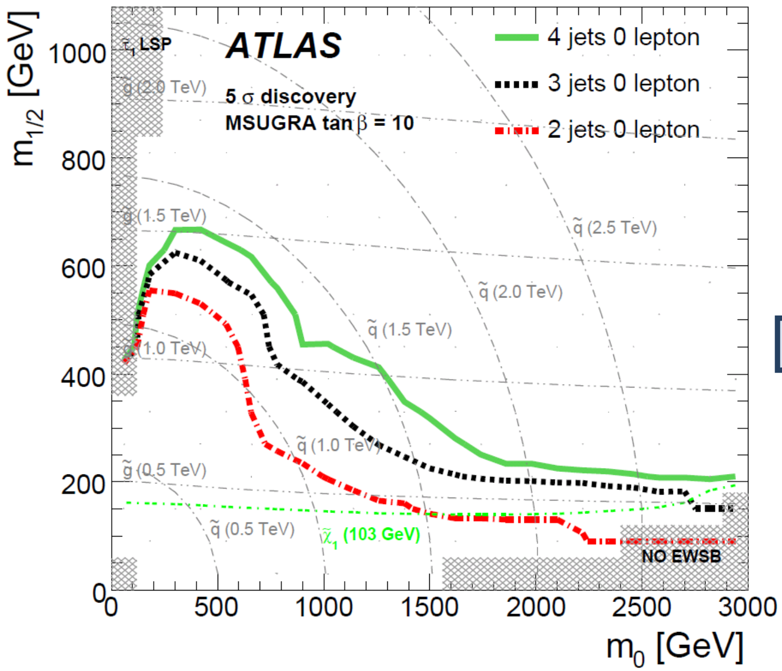

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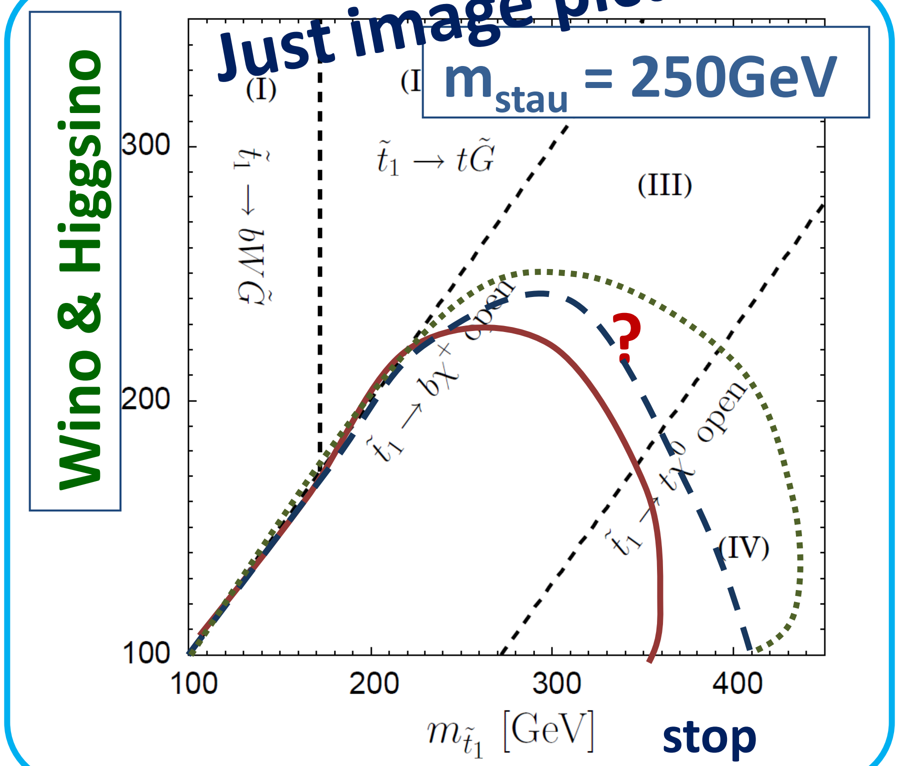
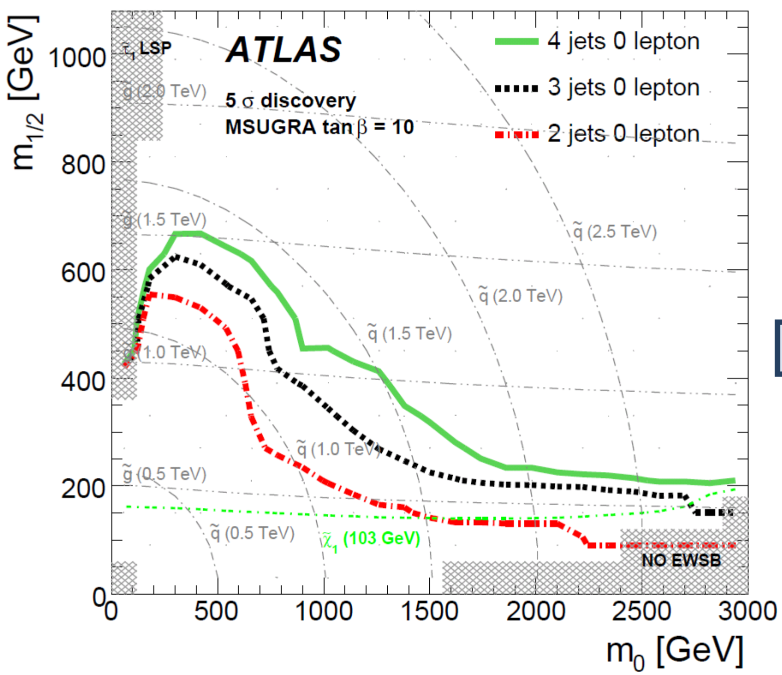


Now we are studying

SUSY Search



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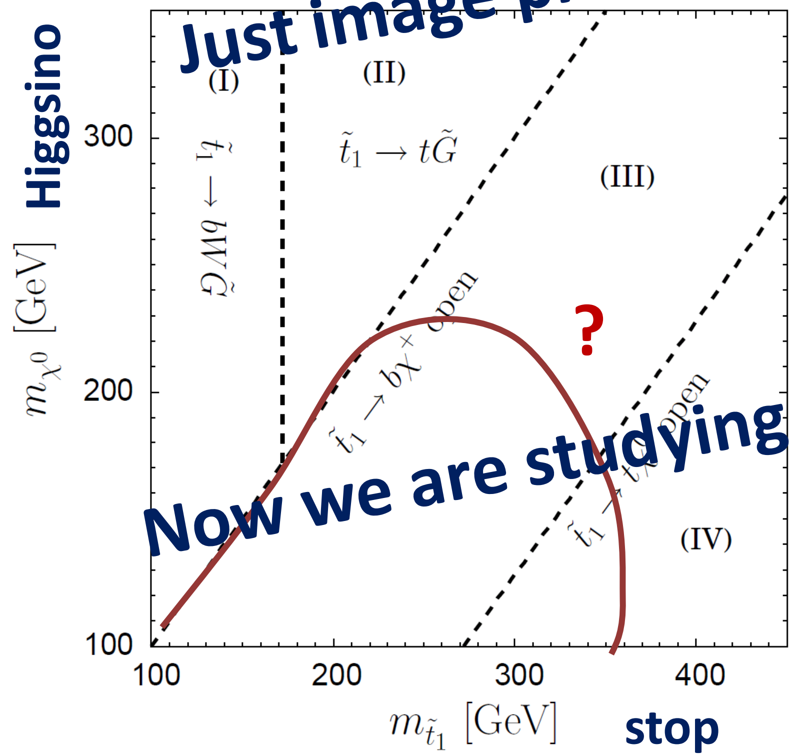


Now we are studying

- discovery potential of low scale SUSY
- fine tuning was a good guiding principle or not

SUSY Search

Sample point

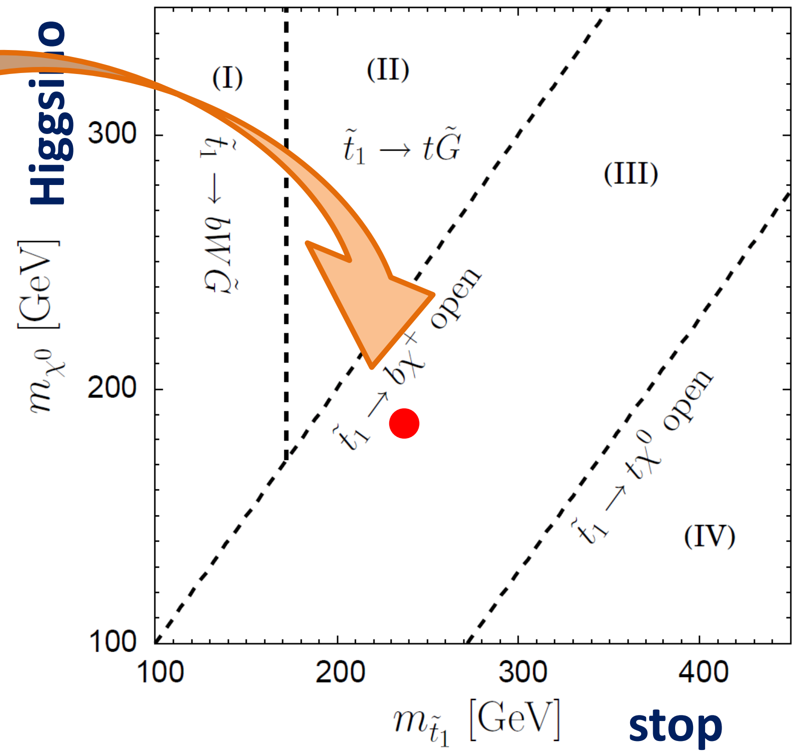
@ $\sqrt{s} = 7\ \mathrm{TeV}, 1\ \mathrm{fb}^{-1}$

1 b + l^+l^- (from Z) + MET

~ 10 events for 2 expected BG

(after cuts)

MA, H. D. Kim, R. Kitano, Y. Shimizu, 2010



discovery potential of low scale SUSY

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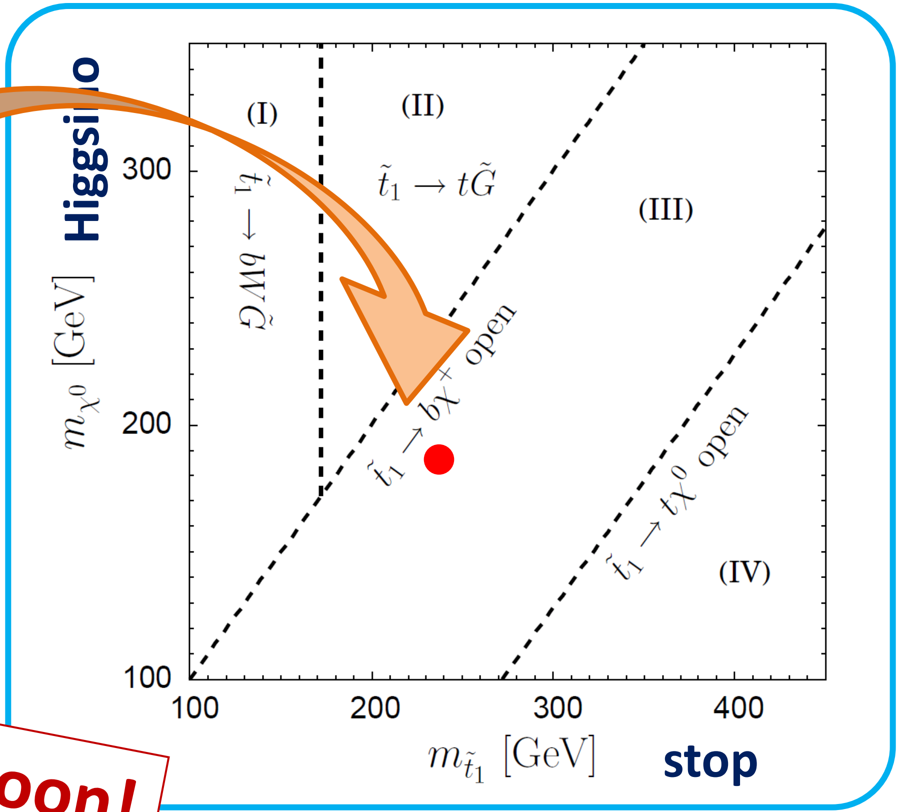

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(after cuts)

SUSY signal is coming soon!

discovery potential of low scale SUSY

fine tuning was a good guiding principle or not