A brief review of SUSY at the LHC

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Outline

1. Introduction
2. SUSY search at the LHC
3. 125 GeV Higgs in SUSY
4. Summary

DM Silver Jubilee Symposium, June 20, 2012

1. Introduction

SUSY is motivated by various issues

- It's a good solution for the hierarchy problem
- Gauge couplings are unified at the GUT scale
  (one of the most promising models for UV completion)
- Lightest superparticle (LSP) is dark matter (DM) candidate

And more in SUSY...
Leptogenesis for baryon asymmetry, inflation, muon g-2, strong CP problem, ...

SUSY has a potential to address many of the problems in standard model (SM)

To explain many of those issues, superparticle mass should be around TeV scale

Now the LHC is running to find the TeV-scale superparticles

However...

- No SUSY signal has been found so far
- 125 GeV SM-like Higgs signal is reported, which is fairly heavy compared to the prediction in minimal SUSY SM (MSSM)

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Today,

- Recent SUSY search at the LHC
- 125 GeV Higgs in SUSY

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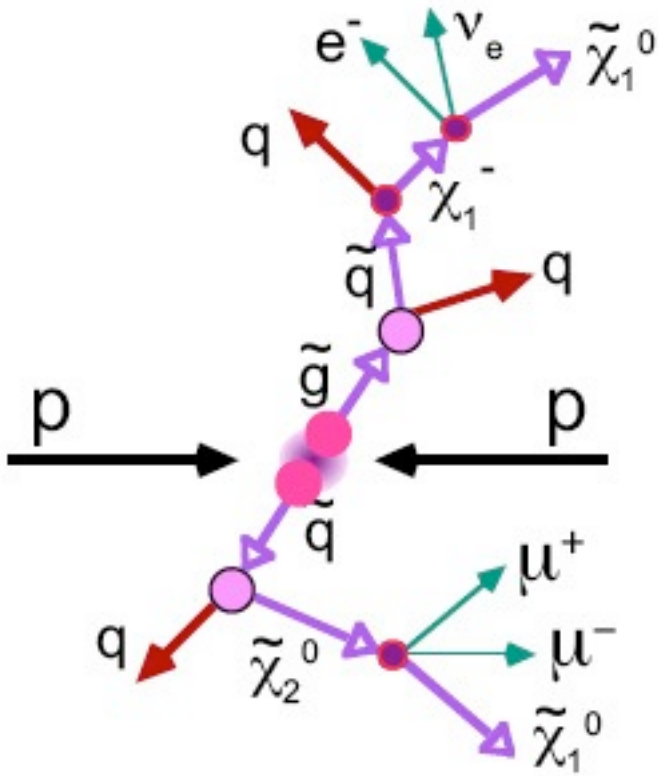
2. SUSY search at the LHC

- SUSY events are usually dominated by $\tilde{g}\tilde{g}, \tilde{g}\tilde{q}$ and $\tilde{q}\tilde{q}$ production

- LSP is usually assumed to be neutral and stable with R-parity, so it's observed as large missing transverse energy ($\not{E}_T$)



[CMS webpage]

So far no large $\not{E}_T$ has been observed

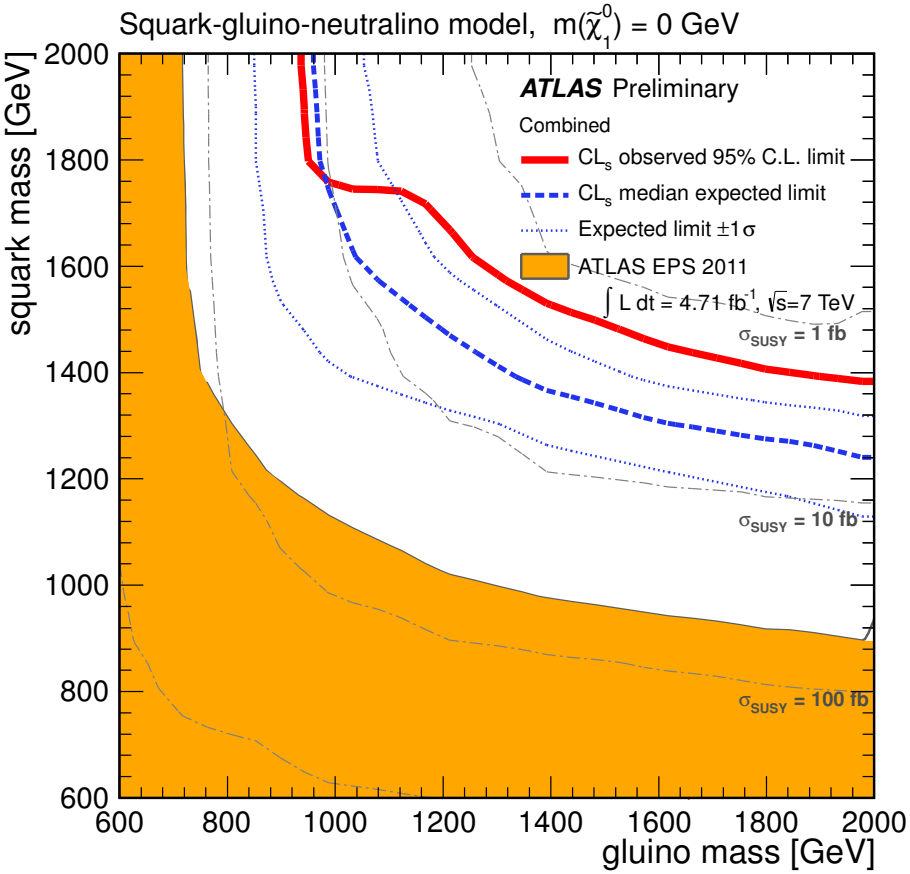
→ (i) Squark/gluino is too heavy to be produced yet, or

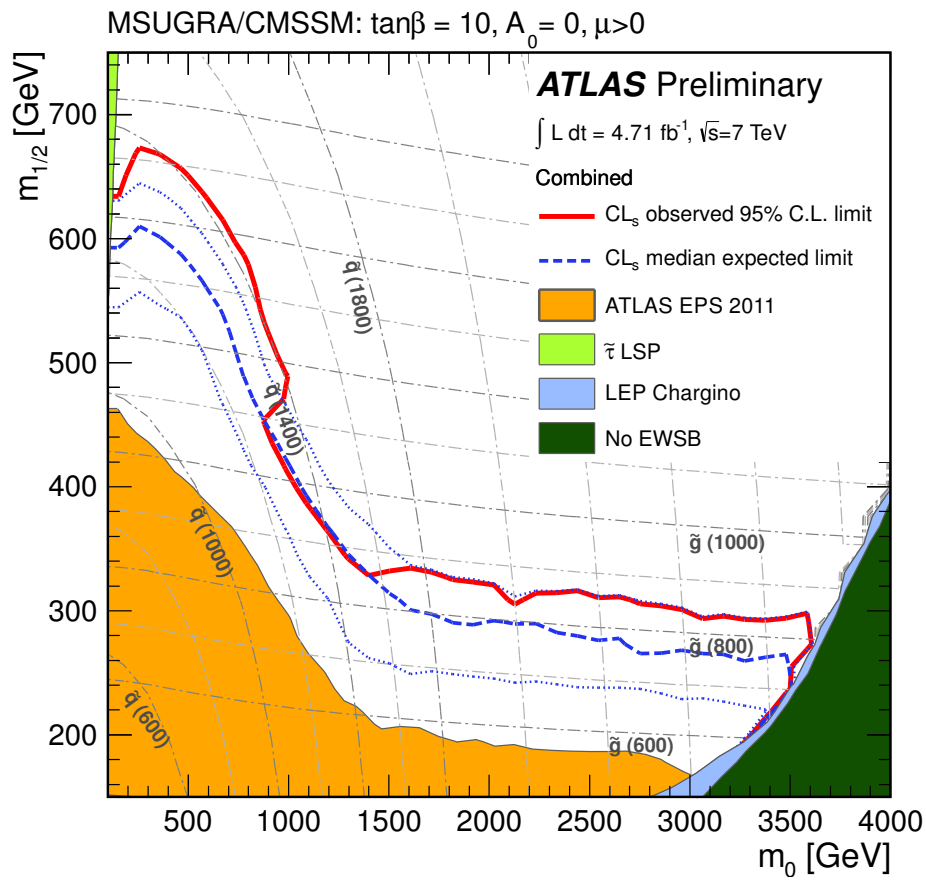
(ii) SUSY particle masses are nearly degenerate or

(iii) R-parity is violated

(i) Heavy squark and gluino

0 lepton + >=(2-6) jets + Etmiss

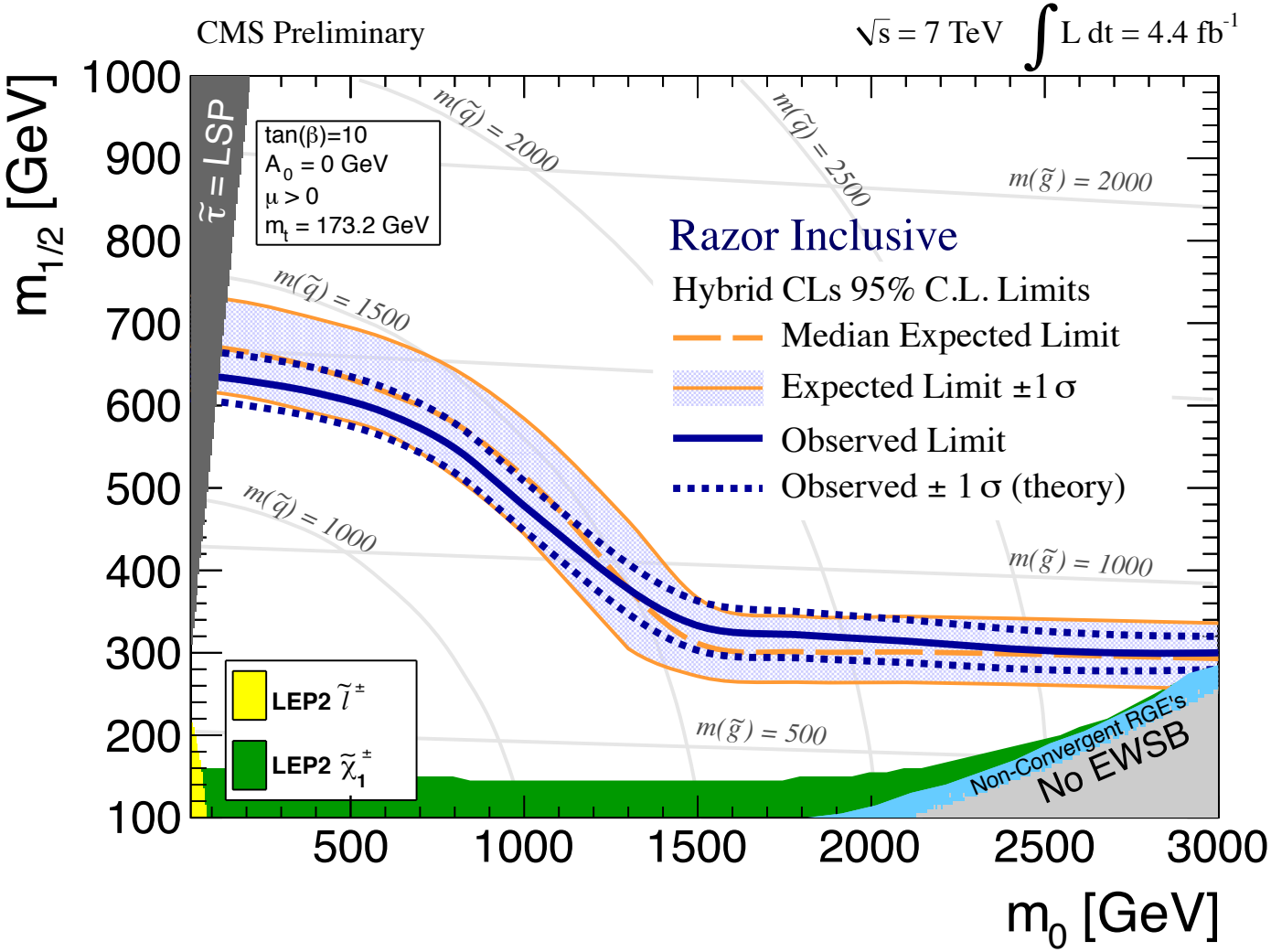




[ATLAS-CONF-2012-033 '12]

Squark $\gtrsim 1.5$ TeV

Gluino $\gtrsim 850$ GeV



[CMS SUS-12-005 '12]

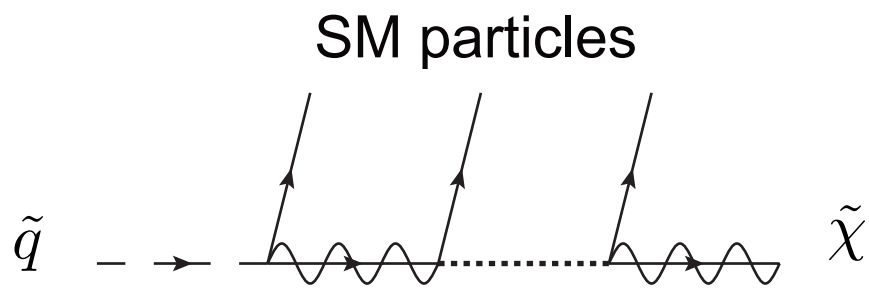
Squark $\gtrsim 1.35$ TeV

Gluino $\gtrsim 800$ GeV

In the other cases, squark/gluino are produced but no large $\not{E}_T$ is observed

(ii) Degenerate SUSY particles

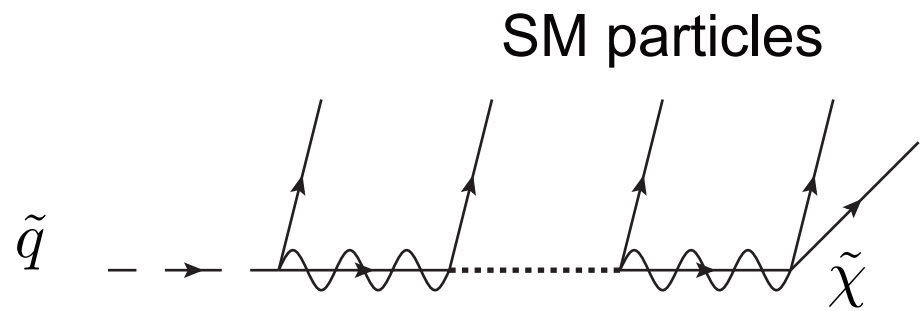
$\not{E}_T$ is too small to be triggered as SUSY signal



$\not{E}_T \sim m_{\tilde{q}/\tilde{g}} - m_{\mathrm{LSP}}$

(iii) R-parity violation (RPV)

LSP decays, so no large $\not{E}_T$



In a nutshell, SUSY search at the LHC implies

(i) Squark/gluino $\gtrsim$ TeV

(ii) Degenerate SUSY spectrum

(iii) RPV

How to discriminate those scenarios?

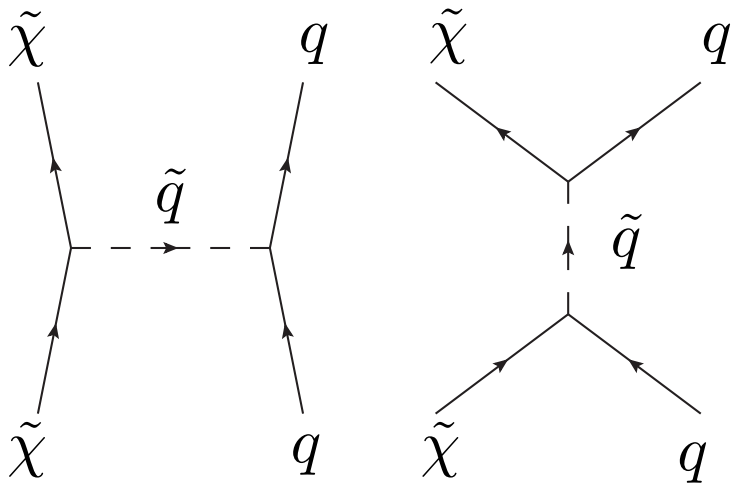
(i) → Wait for more data and 14 TeV run

(ii) → DM direct detection experiment may be useful

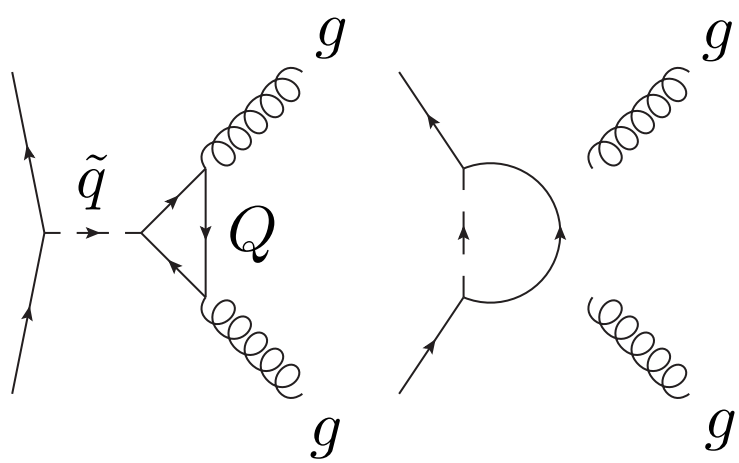
(iii) → Basically more data is needed (but an exotic decay may be observed at the LHC in some cases)

(ii) Degenerate scenario

Cross section of DM (LSP) with nucleon is enhanced due to squark exchange

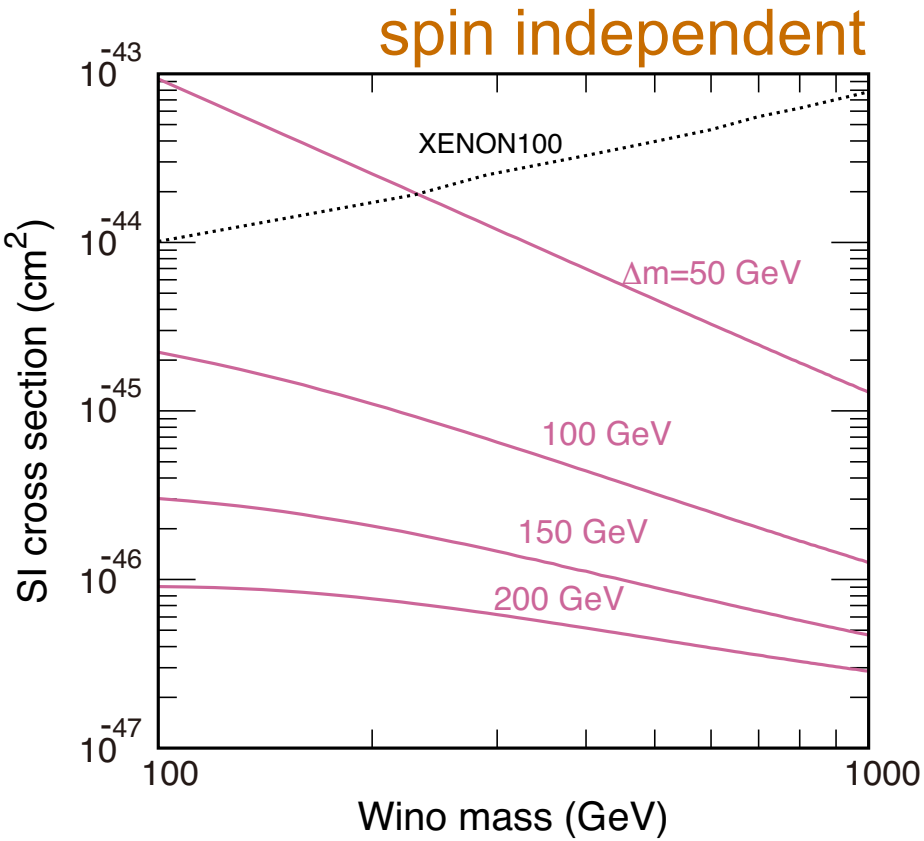


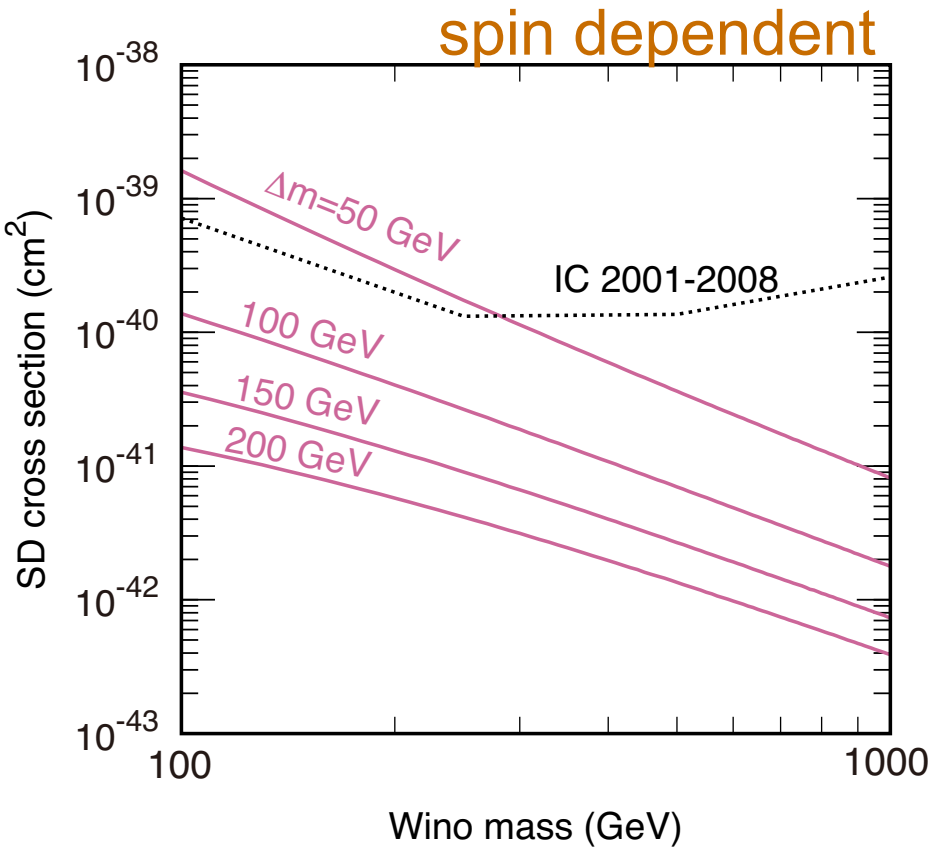
$$\propto \frac{1}{(m_{\tilde{q}}^2 - M_{\rm DM}^2)^2}$$



$$\text{or } \frac{1}{m_{\tilde{q}}^2 - M_{\rm DM}^2}$$

e.g., Wino DM case





[Hisano,KI,Nagata '11]

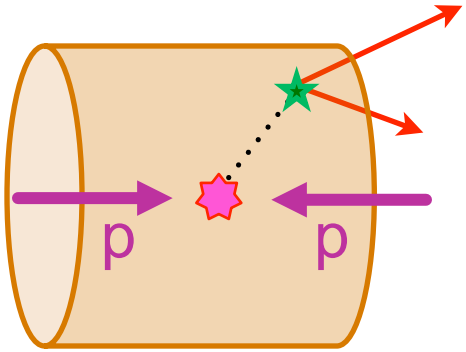
Highly degenerate scenario, which is difficult to be probed at the LHC, could be searched in the future

(iii) RPV scenario

One of the interesting scenarios is gravitino LSP in RPV

[Takayama,Yamaguchi '00]

- Gravitino can be DM
- Next-LSP decays before big-bang nucleosynthesis
- Next-LSP is long-lived in collider and may decay at a displaced vertex from the interaction point [KI,Ito,Moroi '08]



Counting those events, lifetime of NLSP can be determined

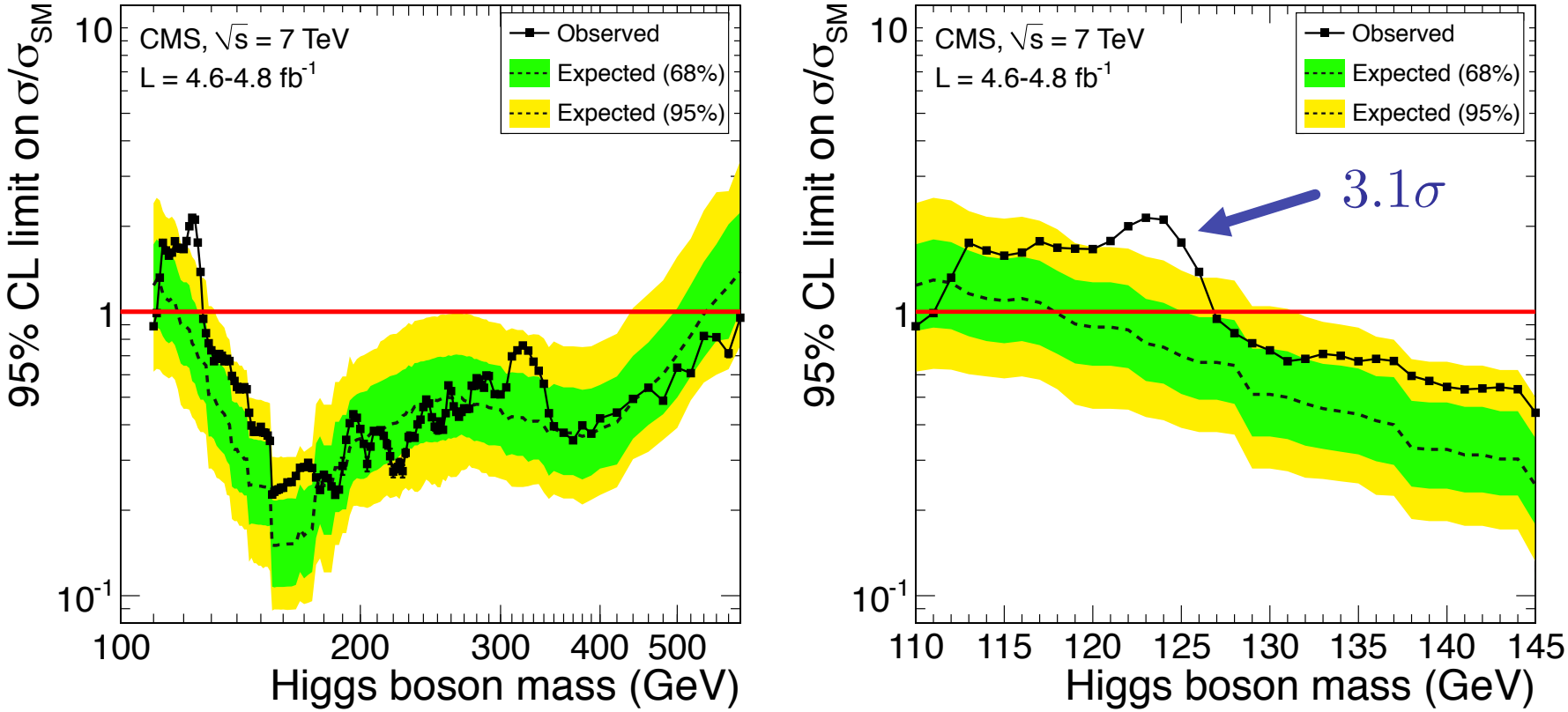
- It can explain cosmic-ray (CR) positron excess

[e.g., KI,Matsumoto,Moroi '07, '11]

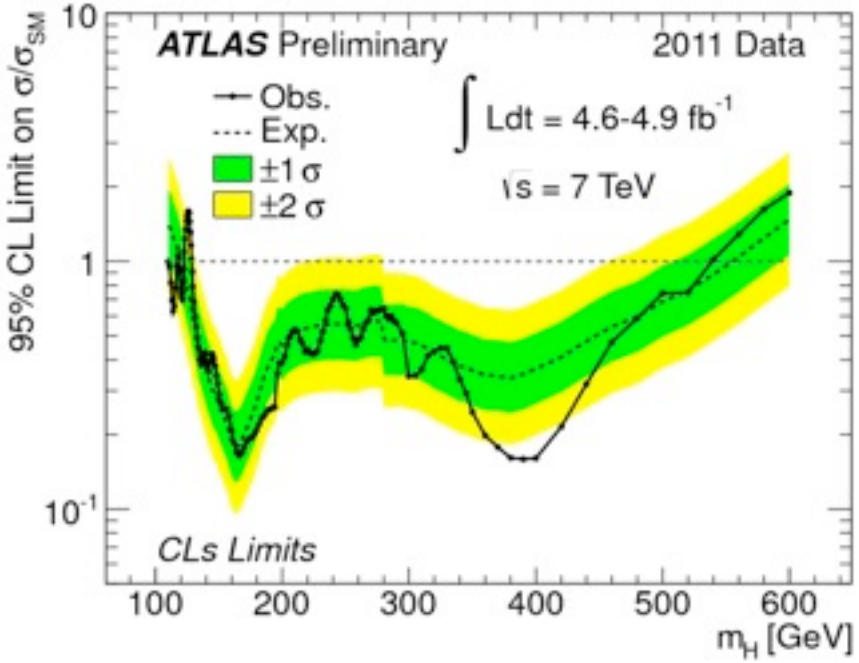
→ Various CR observations are going on, like Fermi-LAT, PAMELA and AMS-02, and may give us some implications [See Jenny's talk tomorrow for Fermi LAT experiment]

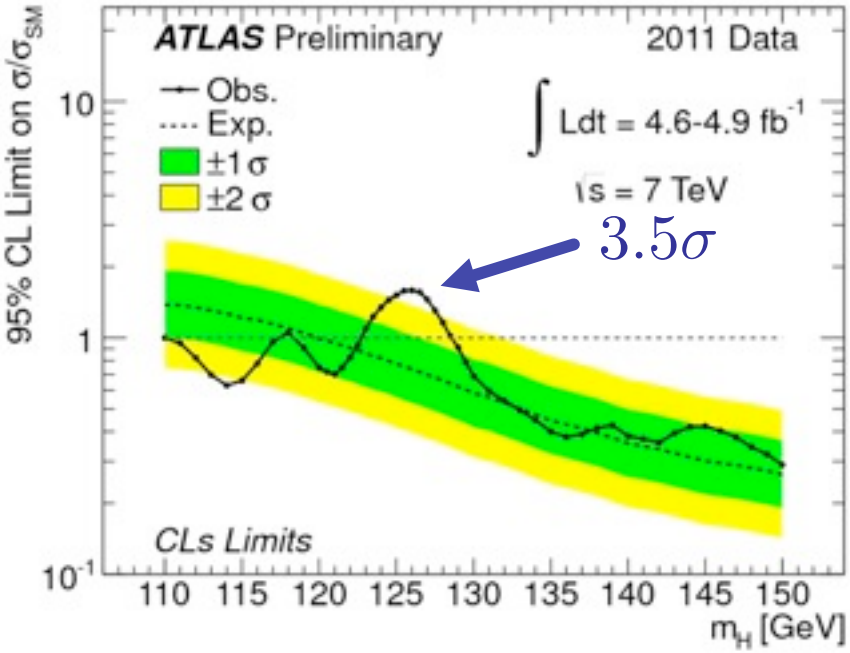
3. 125 GeV Higgs in SUSY

124 and 126 GeV Higgs signal is reported at CMS and ATLAS, respectively



[CMS arXiv:1202.1487 '12]





[ATLAS-CONF-2012-019 ’12]

What does this mean in SUSY?

Higgs mass in the MSSM:

$$m_h^2 = m_Z^2 \cos^2 2\beta + \delta$$

Since tree-level Higgs mass can't exceed Z mass, large loop correction is needed for 125 GeV Higgs

1-loop correction: $\delta \propto \log(m_{\tilde{t}}),\ A_t^2$, so we need

(i) Heavy stop, or

(ii) Large A_t , or

(iii) Extension of the MSSM

However,

- Large stop mass/A_t is not favored in terms of naturalness

- Consistency with other experiments, like B physics or muon g-2, should be checked in such a parameter region (e.g., constraint from $b \to s\gamma$ implies that large A_t is disfavored) [KI,Yokozaki,Nagata '11]

- ~~SUSY~~ scenario to realize such a desired parameter should be addressed

(i) Heavy stop

Naturalness → Too Bad

Muon g-2 → Possible (O(100 GeV) slepton)

DM → Lightest neutralino/gravitino

(ii) Large A_t

Naturalness → <1% fine-tuning

Muon g-2 → Possible

DM → Lightest neutralino/gravitino

However, large A_t is constrained by $b \to s\gamma$, thus finding consistent parameter region is not so easy

[Based on discussion at YITP workshop '12 and private communication with N. Yokozaki]

(iii) Extension of the MSSM

- Next-to-MSSM (NMSSM)

An extra singlet raises Higgs mass

$$W = W^{\mathrm{MSSM}} + \lambda S H_u H_d \longrightarrow m_h^2 = m_h^{(\mathrm{MSSM})2} + \lambda^2 v^2 \sin^2 2\beta$$

Naturalness → ~10% fine-tuning

Muon g-2 → Difficult (due to small $\tan\beta$)

DM → Singlino-like

- Extra vector-like matter
- Extra gauge symmetry

References (discussing naturalness)

- MSSM

Focus point [Feng,Stanford ’12]

SuperWIMP gravitino [Feng,Surujon,Yu ’12]

- NMSSM (-type)

MSSM vs. NMSSM [Hall, Pinner,Ruderman ’11]

5D AdS brane world [Larsen, Nomura, Roberts’12]

Flavor symmetry [Craig,McCullough,Thaler ’12]

Composite [Csaki,Randall,Terning ’12]

- Extra vector-like matter

[Moroi,Okada ’92; Babu,Gogoladze,Kolda ’04; Babu,Gogoladze,Rehman,Shafi ’08; Martin 10’]

[Endo,Hamaguchi,Iwamoto,Yokozaki ’12; Moroi,Sato,Yanagida etc.]

- Extra gauge symmetry

1,2 and 3 gen. has different symmetry [Craig,Dimopolous,Gherghetta ’12]

4. Summary

- LHC SUSY search implies heavy squark/gluino or degenerate SUSY spectrum or RPV

- LHC Higgs search implies the MSSM needs fine-tuning or some extension

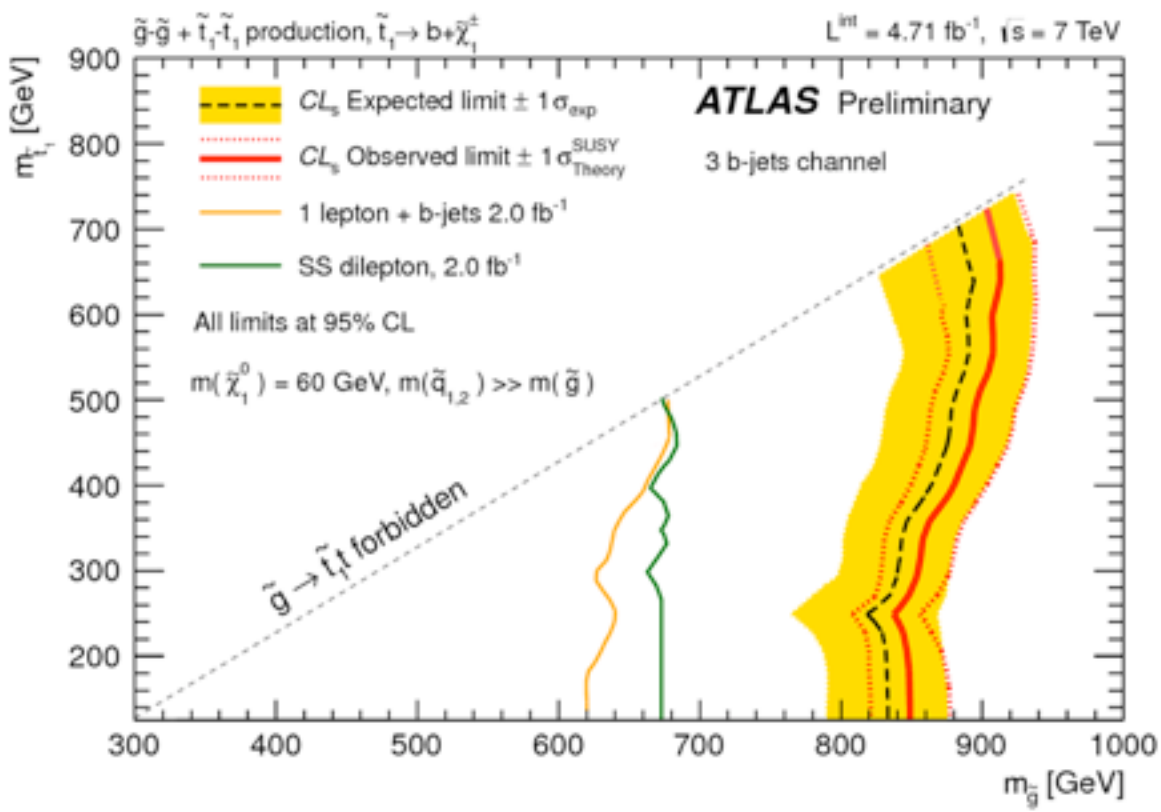
  - Still various DM candidates are possible
  - More data from DM direct/indirect detection experiment, as well as the LHC, will give hint to SUSY

Backups

Stop search

- To avoid little hierarchy problem, stop should be light
- Stop mass is very important to predict Higgs mass

3bjets + 0lepton + jets + Etmiss

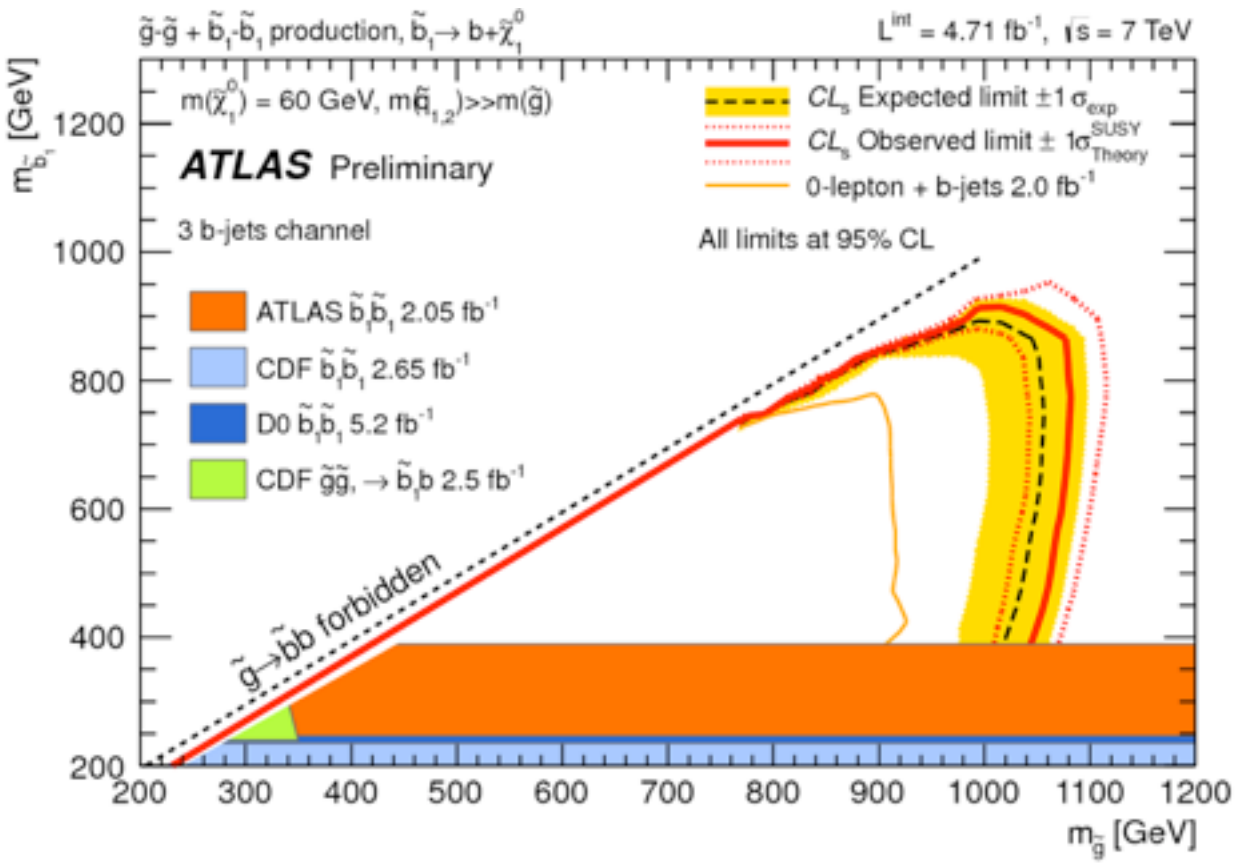


[ATLAS-CONF-2012-058]

Gluino $\gtrsim 820$ GeV

Sbottom search

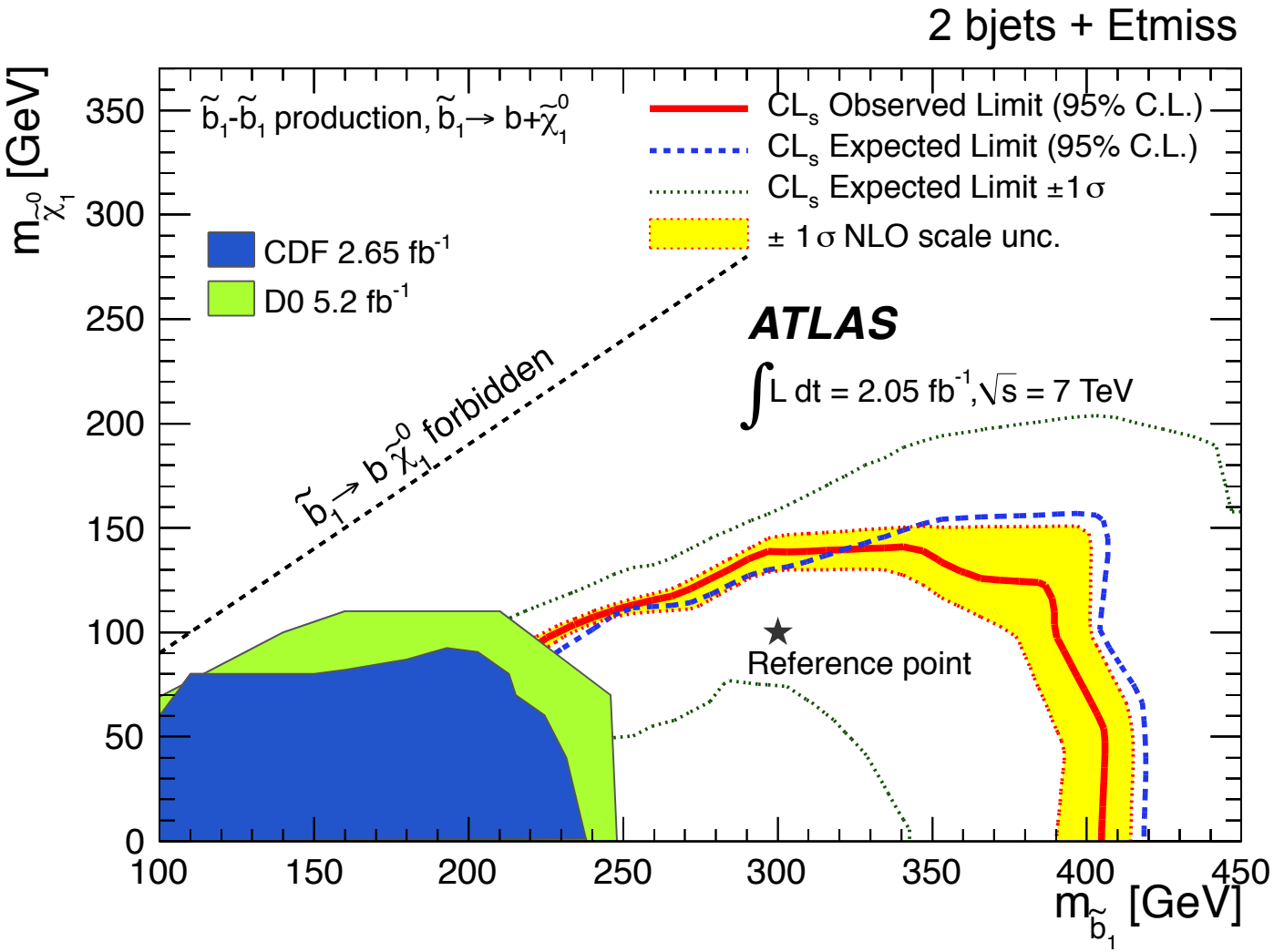
3bjets + 0lepton + jets + Etmiss



[ATLAS-CONF-2012-058]

Gluino $\gtrsim 1$ TeV

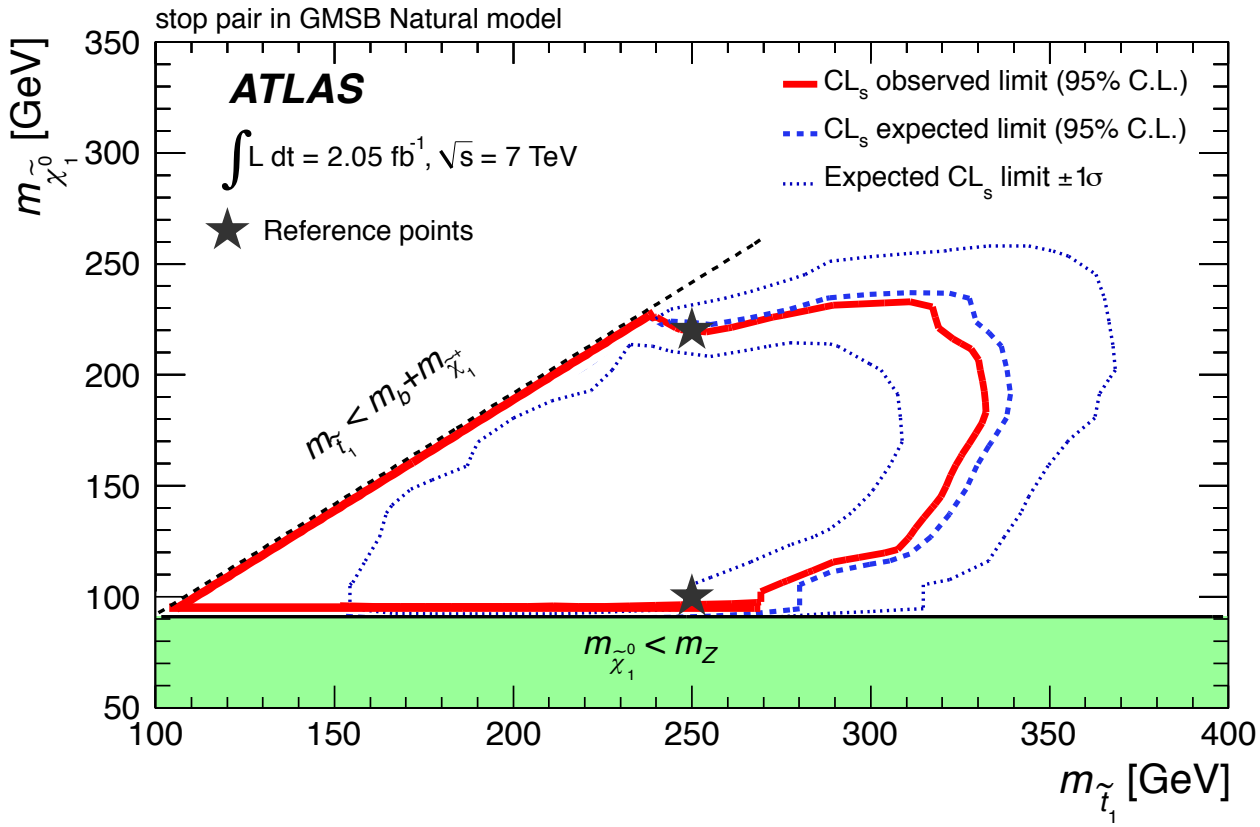
Direct sbottom search



[ATLAS arXiv:1112.3832 '11]

$m_{\tilde{\chi}_1^0} \lesssim 60$ GeV and $m_{\tilde{b}_1} \lesssim 390$ GeV excluded

Direct Stop search



$$\tilde{t}_1 \to b\tilde{\chi}_1^+, \ (\text{or } t\tilde{\chi}^0_{1(2)})$$

$$\tilde{\chi}_1^0 \to Z\psi_{3/2}$$

b-jet + $(ee, \mu\mu)$

The analysis is assuming gauge mediation

Higgs mass in the MSSM

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left[\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

$$X_t \equiv A_t - \mu \cot\beta$$

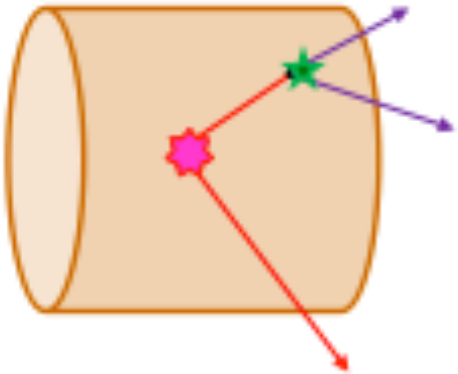
$$M_s \equiv (m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2}$$

NLSP decay at LHC

In the gravitino DM scenario, NLSP decay can be detected at the LHC although its decay length is much larger than the detector size

When $\tau \lesssim 10^{-(3-5)}$ sec , the number of decaying NLSP is expected to be $\gtrsim O(10)$ for $\chi_1^0, \tilde{\tau}$ cases

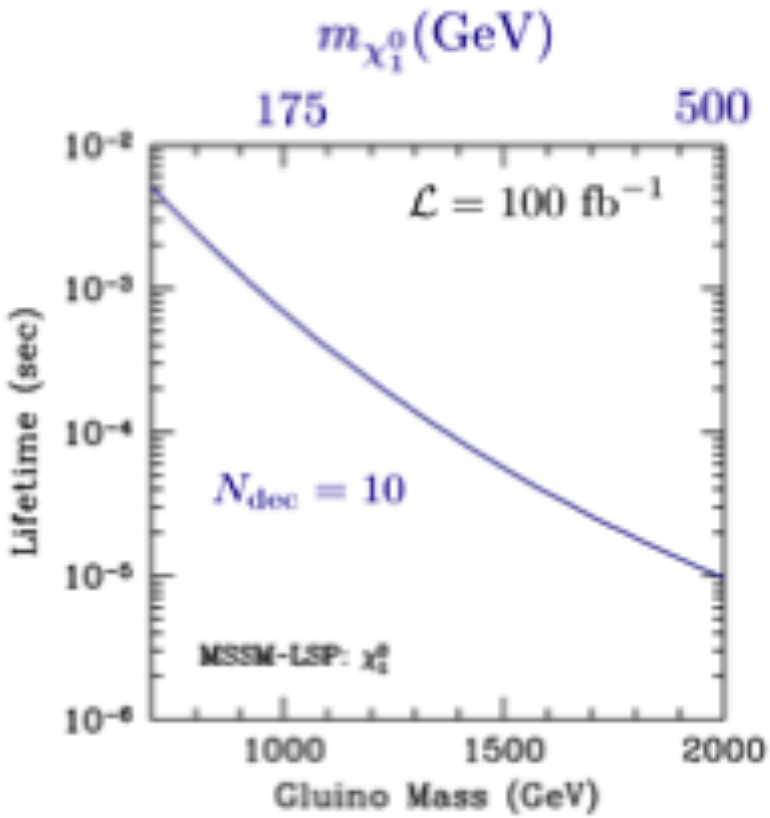
[K.I.,Ito,Moroi]

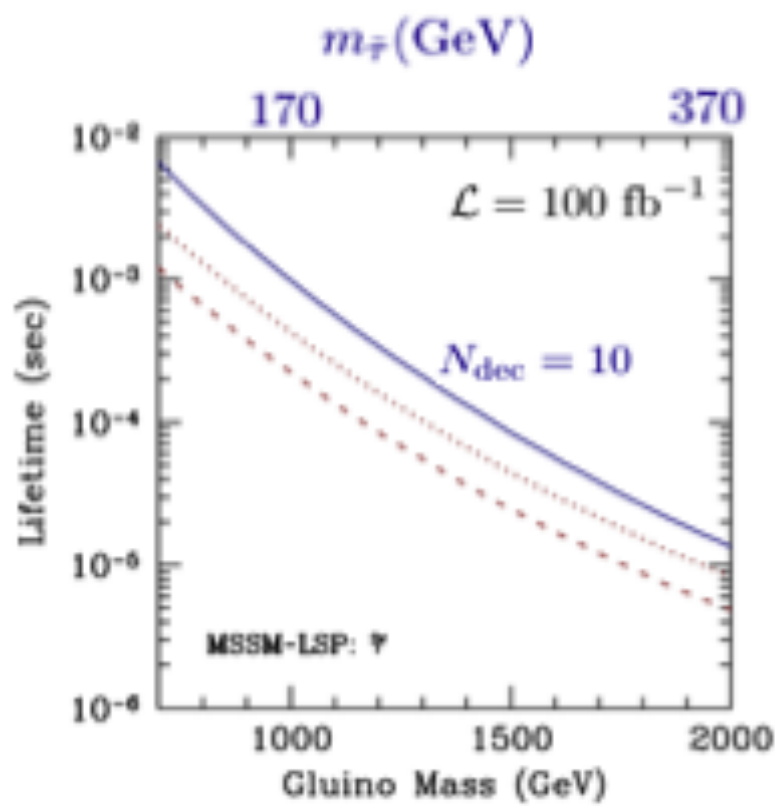


- χ_1^0 -NLSP: $\tau \simeq 1 \times 10^{-6}\ \mathrm{sec} \times \left(\frac{\kappa}{10^{-9}}\right)^{-2} \left(\frac{m_{\chi_1^0}}{200\ \mathrm{GeV}}\right)^{-1}$
- $\tilde{\tau}$ -NLSP: $\tau \simeq 3 \times 10^{-5}\ \mathrm{sec} \times \left(\frac{\kappa}{10^{-9}}\right)^{-2} \left(\frac{m_{\tilde{\tau}}}{200\ \mathrm{GeV}}\right)^{-1} \left(\frac{m_{\tilde{B}}}{300\ \mathrm{GeV}}\right)^{2}$

→ The number of NLSP decay is expected to be $\gtrsim O(10)$ for the wide parameter region in this scenario

NLSP decay at LHC





SUSY event simulated by HERWIG package in minimal gauge mediation (mass spectrum is given by ISAJET package)