# Light Stop scenarios and their phenomenology in one-loop order

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Beijing, Sept. 18, 2014

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# Introduction

—- status of SUSY —-

- Theoretically: SUSY appealing
  - Unification of the three forces
  - Hierarchy problem
  - Naturalness problem
- Experimentally: No evidence of SUSY
  - sfermion mass(1st and 2nd generations) $\gtrsim$ 1 TeV
  - Stop mass $\gtrsim$ 300 GeV
  - gluino mass $\gtrsim$ 1.4 TeV
  - chargino, neutralino
  - Higgs (126 GeV) SUSY Higgs/ SM Higgs

—-Why light stop ? ——

- Any SUSY model contains two stops
- large top mass + large mixing $\rightarrow$ light stop ( a kind of see-saw mechanism)
- Experimental bound of stop $\approx$ 300 GeV
- The simplest SUSY model(MSSM) contains more than 20 parameters. Model independent determination of the magnitude of any parameter is very difficult.
- $WW$ excess at LHC (about 20%)
- Light stop $\rightarrow$ potentially interesting physics at energies accessible at LHC, ILC.

Is a light stop possible?

$$M_h^2 = M_h^{tree,2} + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left(\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}(1 - \frac{X_t^2}{12M_S^2})\right) + \cdots$$

where

$$M_h^{tree,2} \approx M_Z^2 \cos^2 2\beta \approx M_Z^2, \qquad v = 174 \text{ GeV},$$

and

$$X_t = A_t - \mu \cot\beta,$$

Assumed: $M_s \equiv M_{\tilde{t}_L}^2 + m_t^2 = M_{\tilde{t}_R}^2 + m_t^2$

$$\begin{pmatrix} M_S^2 + M_Z^2 \cos 2\beta(\frac{1}{2} - \frac{2}{3}s_W^2) & m_t X_t \\ m_t X_t & M_S^2 + M_Z^2 \cos 2\beta \frac{2}{3} s_W^2 \end{pmatrix}$$

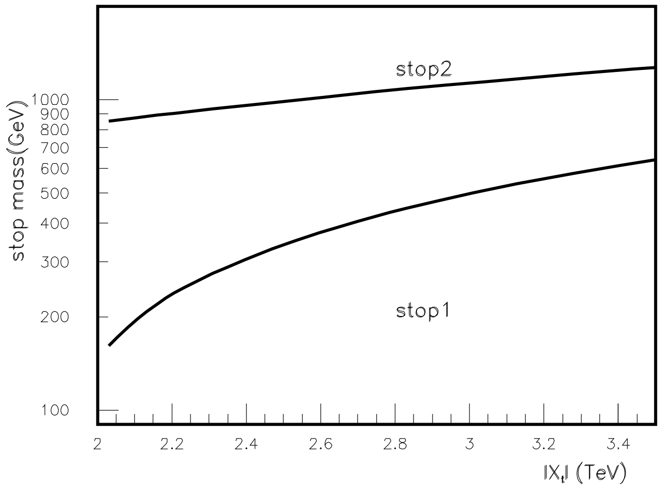


Figure 1: Expected stop masses implied by Higgs at 126 Gev in the framework of MSSM.

- Light stop possible if $|X_t| \gtrsim 3$TeV
- Large mixing in the stop mass matrix
- The other stop $\gtrsim$1 TeV

# Light stop scenario

- MSSM (but not strongly dependent on the detail of MSSM)
- R-parity conservation
- Unification of the three coupling constants at GUT energy is assumed.
- No unification assumption for scalar masses, fermion masses, nor triple couplings (no CMSSM, no NUHM)
- Stop mass is as light as the experimental bound
- LSP is neutralino or sneutrino
- $m_H$=126 GeV scalar is identified as the lightest CP even Higgs particle
- Constraints from the known experiments
  - muon $g-2$
  - $b \to s\gamma$
  - $\mathrm{Br}(B_s \to \mu\mu)$
  - WMAP and PLANCK result of $\Omega_{DM}h^2$
    $\Omega_{DM}h^2 = 0.1199 \pm 0.0027$
  - IceCube

MSSM: (Most SUSY masses are free parameters)

Our analysis does not depend so crucially on the specific nature of MSSM. Most important feature of MSSM is that the Higgs interaction is fully fixed by the gauge couplings.

As a benchmark mass spectrum, we consider two cases.

| scenario 1 | | | | scenario 2 | | | |
|---|---|---|---|---|---|---|---|
| h | H | A | $H^+$ | h | H | A | $H^+$ |
| 126.3 | 1500 | 1500 | 1502.4 | 126.3 | 1500 | 1500 | 1502.4 |
| gluino | | | | gluino | | | |
| 1500 | | | | 1500 | | | |
| $\tilde{\chi}_1^+$ | $\tilde{\chi}_2^+$ | | | $\tilde{\chi}_1^+$ | $\tilde{\chi}_2^+$ | | |
| 336 | 451 | | | 336 | 451 | | |
| $\tilde{\chi}_1^0$ | $\tilde{\chi}_2^0$ | $\tilde{\chi}_3^0$ | $\tilde{\chi}_4^0$ | $\tilde{\chi}_1^0$ | $\tilde{\chi}_2^0$ | $\tilde{\chi}_3^0$ | $\tilde{\chi}_4^0$ |
| 174.1 | 336.7 | 405.0 | 451.2 | 174.1 | 336.7 | 405.0 | 451.2 |
| $\tilde{t}_1$ | $\tilde{t}_2$ | $\tilde{b}_1$ | $\tilde{b}_2$ | $\tilde{t}_1$ | $\tilde{t}_2$ | $\tilde{b}_1$ | $\tilde{b}_2$ |
| 325.7 | 2083.0 | 800.2 | 2061 | 325.7 | 2083.0 | 800.2 | 2061 |
| $\tilde{u}_1$ | $\tilde{u}_2$ | $\tilde{d}_1$ | $\tilde{d}_2$ | $\tilde{u}_1$ | $\tilde{u}_2$ | $\tilde{d}_1$ | $\tilde{d}_2$ |
| 1720.0 | 1739.0 | 1740.0 | 1741.0 | 1720.0 | 1739.0 | 1740.0 | 1741.0 |
| $\tilde{\tau}_1$ | $\tilde{\tau}_2$ | $\tilde{\nu}_\tau$ | | $\tilde{\tau}_1$ | $\tilde{\tau}_2$ | $\tilde{\nu}_\tau$ | |
| **335.7** | **392.5** | **359.6** | | **181.9** | **272.6** | **221.4** | |
| $\tilde{e}_1$ | $\tilde{e}_2$ | $\tilde{\nu}_e$ | | $\tilde{e}_1$ | $\tilde{e}_2$ | $\tilde{\nu}_e$ | |
| 362.5 | 367.9 | 359.6 | | 362.5 | 367.9 | 359.6 | |
| $\mu$=400, $\tan\beta$=28.72 | | | | $\mu$=400, $\tan\beta$=28.72 | | | |

Table 1: Two possible scenarios of the light stop model.

Other parameters (in unit of GeV)

$$M_1 = 177.0, M_2 = 380.0, \quad A_t = -3670, A_b = -3000$$
$$A_\tau = -300, A_\ell = A_q = -100$$

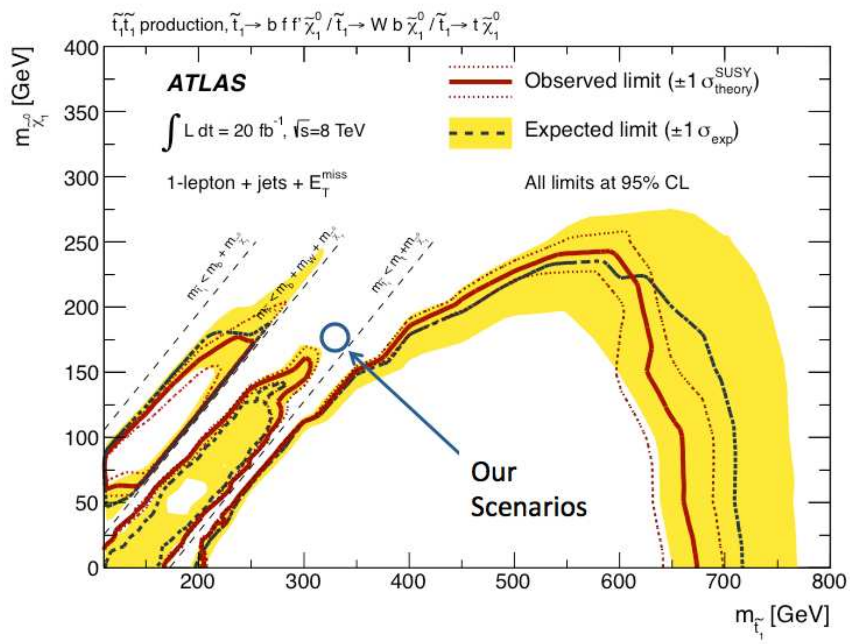


Figure 2: Our scenario shown in the ATLAS.

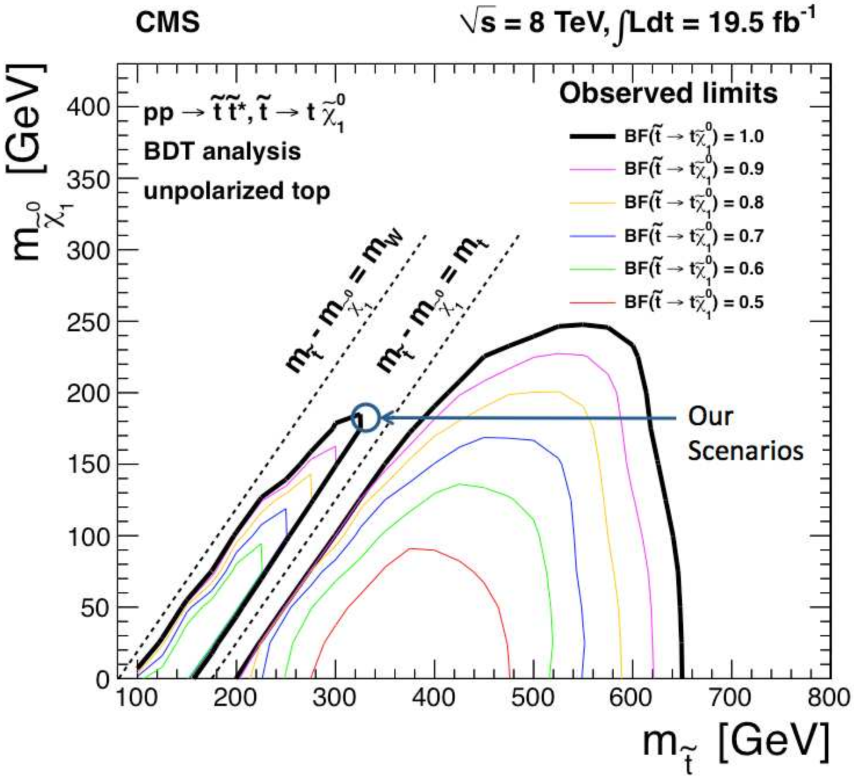


Figure 3: Our scenario shown in the CMS LHC run2 prospect.

Our mass parameters satisfy the constraints.

- Experimentally known SUSY mass bound
- light $\tilde{\mu}$, which is allowed by the assumption that $\delta(g-2)_\mu$, the discrepancy between the SM and experiment, is due to SUSY.
  experiment: $\delta(g-2)_\mu = 25.1 \times 10^{-10}$
  our scenario: $\delta(g-2)_\mu = 24.9 \times 10^{-10}$
- $\mathrm{BR}(b \to s\gamma) = 2.4 \times 10^{-4}$
- $\mathrm{BR}(B_s \to \mu\mu)$
  experiment: $\mathrm{BR}(B_s \to \mu\mu) = (2.9\,^{+1.10}_{-1.0}) \times 10^{-9}$ (LHCb)
  our scenario:$\mathrm{BR}(B_s \to \mu\mu) = 3.85 \times 10^{-9}$ (minimal flavor violation)
- Relic density of Dark matter
  experiment: $0.09 < \Omega_{DM} h^2 < 0.13$
  our scenario 1: 0.6, scenario 2: 0.1

# Phenomenology of the light stop

**Decays**(SUSPECT2.4 SUSYhit GRACE/SUSY)

**stop decays**

Table 2: $\tilde{t}_1$ decay width and the branching ratio.

| | scenario 1 | | scenario 2 | |
|---|---|---|---|---|
| decay channel | partial width (MeV) | Branching ratio | partial width (MeV) | branching ratio |
| $\tilde{t}_1 \to bW^+\tilde{\chi}_1^0$ | 0.437 | 99.97 | 0.436 | 69.80 |
| $\tilde{t}_1 \to c\tilde{\chi}_1^0$ | $1.18\times10^{-4}$ | 0.03 | $1.19\times10^{-4}$ | 0.02 |
| $\tilde{t}_1 \to b\tilde{\tau}_1^+\nu_\tau$ | 0 | 0 | 0.129 | 20.69 |
| $\tilde{t}_1 \to b\tilde{\nu}_\tau\tau^+$ | 0 | 0 | $5.93\times10^{-2}$ | 9.48 |

- No two-body decay at tree level.
- $\Gamma_{tot}(\tilde{t}_1) \approx 0.5$ MeV
- scenario 1: $\tilde{t}_1 \to bW^+\chi_1^0$ 100%
- scenario 2: $\tilde{t}_1 \to bW^+\chi_1^0$ and $\tilde{t}_1 \to b\tilde{\tau}_1^+\nu_\tau$
- flavor changing two-body decay( through RC)

## Chargino and neutralino decays

Table 3: The decay widths and the branching ratios of $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$ .

| | scenario 1 | | scenario 2 | |
|---|---|---|---|---|
| decay channel | partial width (GeV) | Branching raio (%) | partial width (GeV) | branching raio (%) |
| $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 W^+$ | 0.0707 | 76.02 | 0.0708 | 8.09 |
| $\tilde{\chi}_1^+ \to \tilde{t}_1 \bar{b}$ | 0.0223 | 23.98 | 0.0224 | 2.56 |
| $\tilde{\chi}_1^+ \to \tilde{\tau}_1 \nu_\tau$ | 0 | 0 | 0.3961 | 45.30 |
| $\tilde{\chi}_1^+ \to \tilde{\nu}_\tau \tau^+$ | 0 | 0 | 0.3694 | 42.13 |
| $\tilde{\chi}_1^+ \to \tilde{\tau}_2 \nu_\tau$ | 0 | 0 | 0.0168 | 1.92 |
| $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ | 0.0609 | 85.00 | 0.0609 | 7.16 |
| $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$ | 0.0107 | 15.00 | 0.0108 | 1.26 |
| $\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau$ | 0 | 0 | 0.4916 | 57.76 |
| $\tilde{\chi}_2^0 \to \tilde{\nu}_\tau \bar{\nu}_\tau$ | 0 | 0 | 0.2419 | 28.42 |
| $\tilde{\chi}_2^0 \to \tilde{\tau}_2 \tau$ | 0 | 0 | 0.0460 | 5.40 |

- $\chi_1^0$ is LSP in our scenario $\longrightarrow$ stable
- If $\tilde{\tau}_i$ is lighter than $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$ (scenario 2),

$$\tilde{\chi}_1^+ \to \tilde{\tau}_1 \nu_\tau, \quad \tilde{\nu}_\tau \tau^+,$$
$$\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau^+, \quad \tilde{\nu}_\tau \bar{\nu}_\tau$$

are the dominant decay modes of $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$

## sbottom decays

Table 4: $\tilde{b}_1$ decay widths and the branching ratios.

| | scenario 1 and 2 | |
|---|---|---|
| decay channel | partial width (GeV) | Branching ratio (%) |
| $\tilde{b}_1 \to \tilde{\chi}_1^- t$ | 0.8480 | 24.45 |
| $\tilde{b}_1 \to \tilde{\chi}_2^- t$ | 0.5437 | 15.68 |
| $\tilde{b}_1 \to \tilde{\chi}_1^0 b$ | 0.4780 | 13.78 |
| $\tilde{b}_1 \to \tilde{\chi}_2^0 b$ | 0.4750 | 13.70 |
| $\tilde{b}_1 \to \tilde{\chi}_3^0 b$ | 0.7824 | 22.56 |
| $\tilde{b}_1 \to \tilde{\chi}_4^0 b$ | 0.3405 | 9.82 |

- $\Gamma_{tot}(\tilde{b}_1) = 3.47$ GeV.
- Many competing decay channels. $\longrightarrow$ difficult to identify $\tilde{b}_i$.

**gluino decay**

- $\Gamma_{tot}(\tilde{g}) = 53.79$ GeV at tree level
- $\tilde{g} \to \tilde{t}_1\bar{t} + \tilde{t}_1 t$: 65% $\to$ 45%
- $\tilde{g} \to \tilde{b}_1\bar{b} + \tilde{b}_1 b$: 35% $\to$ 55%
- Gluino mass dependence of the branching ratios
  Gluino mass ($M_3$) is independent from any other SUSY mass, we can variate the gluino mass without changing the mass of other SUSY particles.

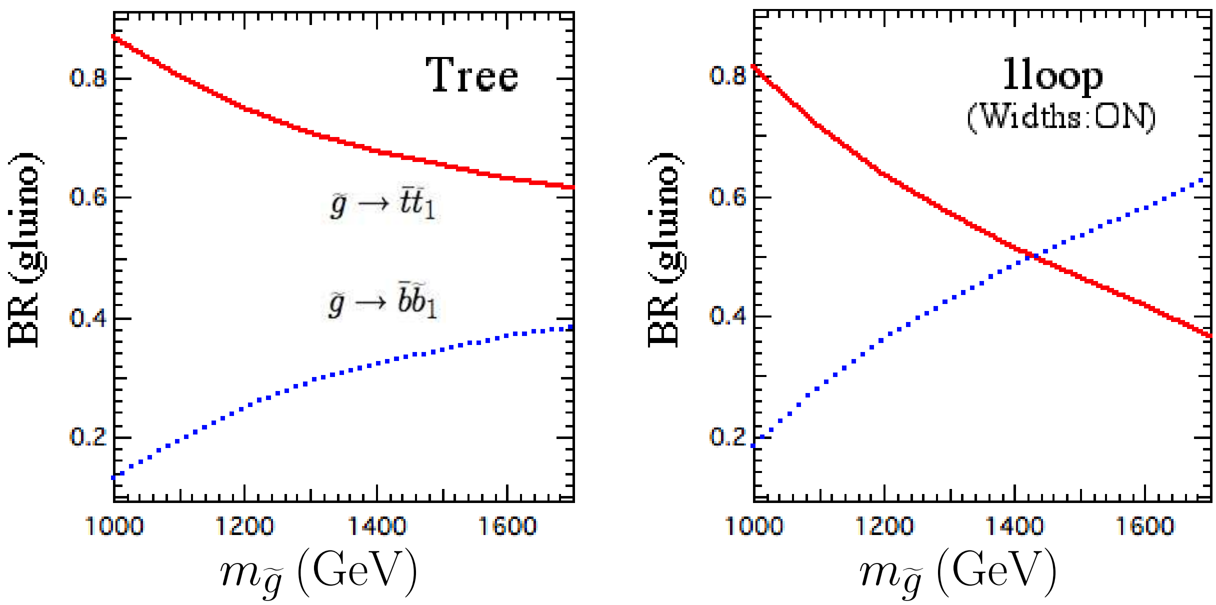


Figure 4: Gluino mass dependence of the branching ratio of gluino.

## $WW$ **excess at LHC**

$$\sigma(pp \to WW + X) = 51.9 \pm 2.0 \pm 3.9 \text{ pb}$$

c.f. SM: $44.7 \pm {}^{2.1}_{1.9}$ pb.

$$\text{our scenario :} \quad pp \;\to\; \tilde{t}_1 \tilde{t}_1^* + X$$
$$\to\; (bW^+\tilde{\chi}_1^0)(\bar{b}W^-\tilde{\chi}_1^0) + X$$

### ILC experiments

We used `GRACE/SUSY-1loop` for the numerical evaluation.

- ILC: First phase $\sqrt{s} = 250\text{GeV} \quad \rightarrow \quad \sqrt{s} = 500$ GeV
- A light stop pair is not produced by ILC ($\sqrt{s} \lesssim 500$)
- Through the radiative correction to top pair production ($e^+e^- \rightarrow t\bar{t}$)
  threshold at $\sqrt{s} = 343$ GeV,
  peak at $\sqrt{s} = 400$ GeV, **0.68pb**
  SUSY effect: about -4%
- Expected integrated luminosity = 500 fb$^{-1}$ $\longrightarrow 2.5 \times 10^5$ top pair productions.

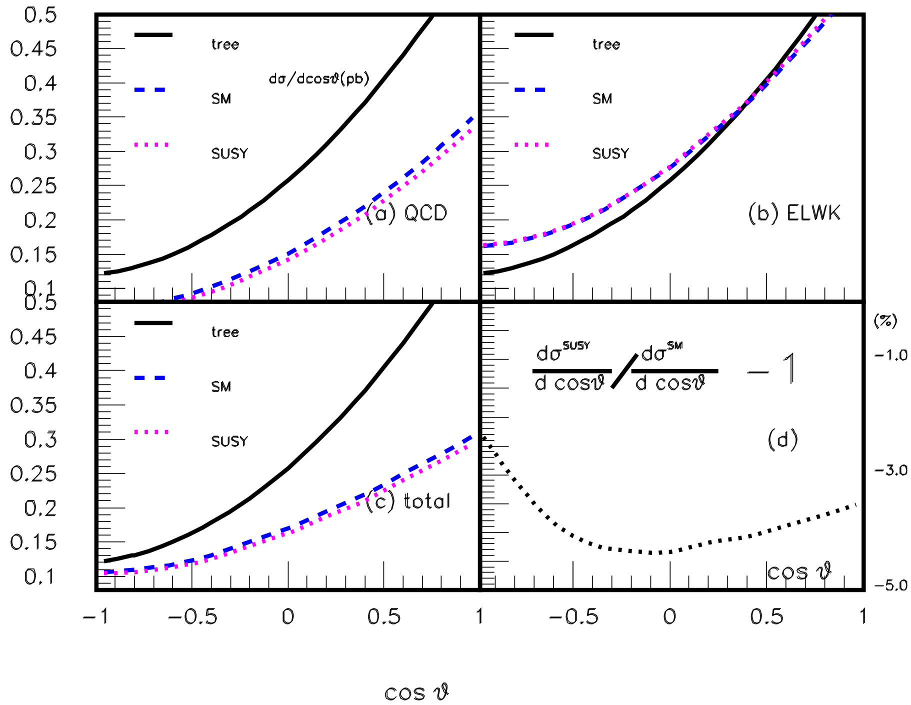


Figure 5: Top pair production cross section at ILC($\sqrt{s} = 500$ GeV), including (a) QCD corrections, (b) electroweak corrections, and (c) the total corrections. Fig. 5d shows the relative difference of SUSY and SM.

# Conclusions

1. A light stop is not excluded.
2. A light stop will not be easily excluded in the near future experiments.
3. Possilbe rich spectrun under TeV region
4. Sbottom physics is correlated to stop. How to detect sbottoms
5. The present analysis is based on MSSM, but the essential feature of the analysis is independend from the specific properties of MSSM.
6. Model for a light stop; GMSB with a light gravitino? Higher symmetry?

## References


- J. Ellis et al., EPJ C74(2014)2947
- D. Curtin et al., arXiv:1406.0848 ( WW excess)
- A. Delgado, arXiv:1212.6847v1[hep-ph]
- A. Belyaev et al, arXiv:1312.1935v3[hep-ph]
- F. Brümmer et al., arXiv:1312.0935v2[hep-ph]
- M. Czakon et al, arXiv:1407.1043 [hep-ph]
- Julia Harz, SUSY2014, Manchester
- O.Buchmeuller et al., arXiv:1312.5250v1[hep-ph] (CMSSM,NUHM)
- S.S. Abdessalam et al., Eur.Phys. J. C71 (2011) 1835 (NUHM)
- G.L. Kane et al., arXiv:hep-ph/0310042v1 ($B_s \to \mu\mu$)
- G-C. Co et al., arXiv:1104.1769v2[hep-ph] (g-2)
- S.P. Martin, hep-ph/0703093(Dark Matter)
- The ATLAS Collaboration, arXiv:1407.0583 [hep-ex]
- The CMS Collaboration, Eur. Phys. J. C 73 (2013) 2677, arXiv 1310.4554(hep-ex).
- ATLAS, arXiv 1210.2979 (hep-ex) (WW excess)
- D. Asner et al( HFAG), arXiv 1010.1589 (hep-ex) ($b \to s\gamma$)
- LHCb, arXvi1307.5024(hep-ex) ($B_s \to \mu^+\mu^-$)