PASCOS 2017 @ IFT

Study of dark matter physics in the non-universal gaugino mass scenario

based on arXiv:1703.10379

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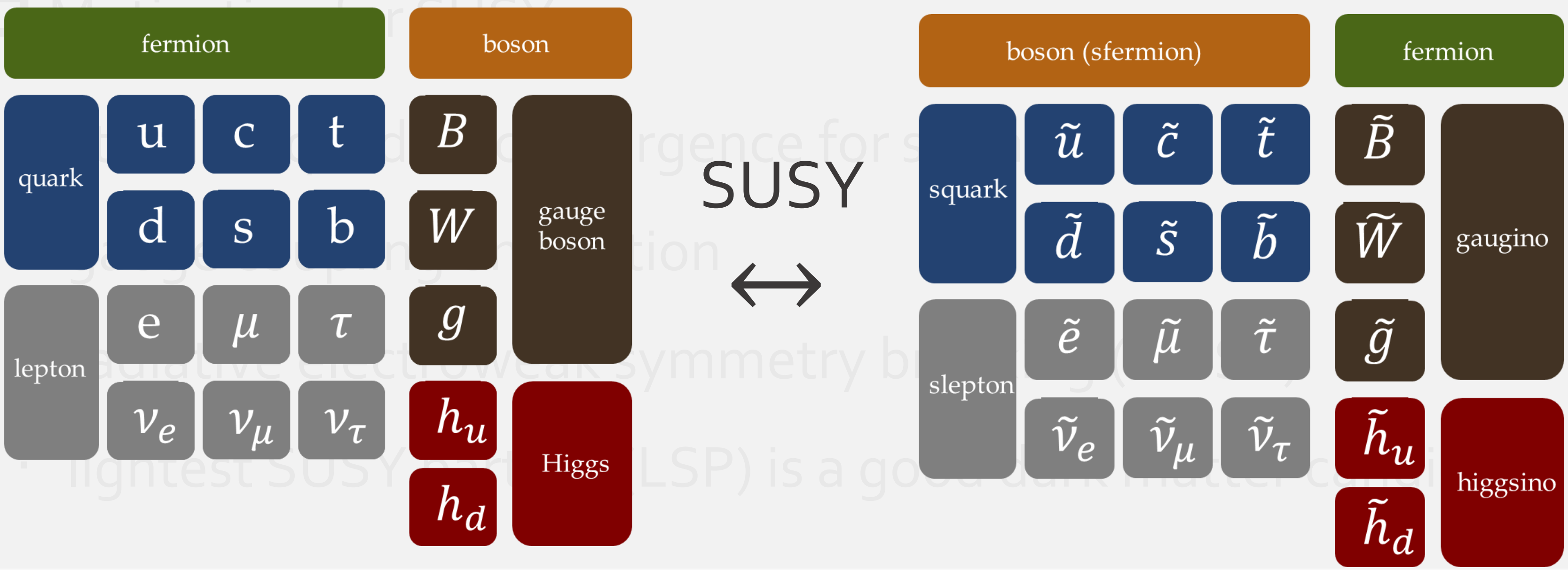
supersymmetry (SUSY)

- Motivation for SUSY
  - stabilize quadratic divergence for scalars
  - gauge coupling unification
  - radiative electroweak symmetry breaking (EWSB)
  - lightest SUSY particle (LSP) is a good dark matter candidate

supersymmetry (SUSY)



- neutralino Dark Matter
  - mixed gaugino-higgsino is easily excluded by direct detection
  - the DM is purely gaugino-like or higgsino-like

higgsino DM

□ Motivation for higgsino DM

light higgsino is necessary to explain EWSB without fine-tuning

$$m_Z^2 \simeq -2\,|\mu|^2 + 2|m_{H_u}^2|$$

higgsino mass   up-type Higgs mass

□ The Higgs boson mass 125 GeV

$$m_h^2 \simeq m_Z^2\cos^2 2\beta + \frac{3m_t^2}{8\pi^2 v_u^2}\left[\log\frac{M_{stop}^2}{m_t^2} + \frac{2A_t^2}{M_{stop}^2}\left(1 - \frac{A_t^2}{12M_{stop}^2}\right)\right]$$

- Higgs boson mass requires $M_{stop} \gtrsim 10\,\mathrm{TeV}$ if $A_t/M_{stop} \sim 0$
- heavy top squarks tend to lead heavy higgsino

Higgs boson mass in NUGM

$A_t/M_{stop} \simeq \sqrt{6}$ is necessary to avoid heavy top squark

- top squark parameters at $m_{SUSY} = 1.0$ TeV

$$m^2_{\tilde{t}_L}(m_{SUSY}) \simeq +0.35M_2^2 + 3.21\,M_3^2 + 0.60\,m_0^2$$

$$m^2_{\tilde{t}_R}(m_{SUSY}) \simeq -0.16M_2^2 + 2.77M_3^2 + 0.29m_0^2$$

unification scale

$$A_t(m_{SUSY}) \simeq -0.24M_2 - 1.42M_3 + 0.27A_0$$

$$M_{stop} \equiv \sqrt{m_{\tilde{t}_R} m_{\tilde{t}_L}}$$

- Universal Gaugino Masses

$$M_2 = M_3 \gg m_0 \quad \rightarrow \quad \frac{A_t}{M_{stop}} \simeq \frac{1.42^2 \times M_3^2}{\sqrt{3.21 \cdot 2.77} \times M_3^2} \simeq 0.67$$

✓ 125 GeV Higgs boson requires heavy top squark $\gtrsim$ sub TeV

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\`07 H.Abe, T.Kobayashi, Y.Omura

- Non-Universal Gaugino Masses (NUGM)

✓ $m_{\tilde{t}_R}(m_{SUSY})$ decreases, $|A_t(m_{SUSY})|$ increases as M_2 increases

→ $A_t/M_{stop} \lesssim \sqrt{6}$

$M_{stop} \equiv \sqrt{m_{\tilde{t}_R} m_{\tilde{t}_L}}$

higgsino mass in NUGM

- higgsino mass μ is fixed to satisfy EWSB condition:

$$m_Z^2 \simeq -2\,|\mu|^2 + 2|m_{H_u}^2|$$

- RG-running of $m_{H_u}^2$

$$m_{H_u}^2(m_{SUSY}) \simeq +0.20 M_2^2 - 0.13 M_2 M_3 \ - 1.56 M_3^2 - 0.07 m_0^2$$

$$\rightarrow \quad M_2 \simeq 3.1 \times M_3 \ \rightarrow \ m_{H_u}^2(m_{SUSY}) \simeq \mu \simeq m_{EW}$$

large wino mass reduces higgsino mass μ

summary of NUGM

- higgsino can be light due to large wino mass
- the Higgs boson mass is also enhanced by large wino mass
- both $m_h \sim 125$ GeV and $\mu \sim m_{EW}$ can be achieved

NUGM is a good scenario for light higgsino

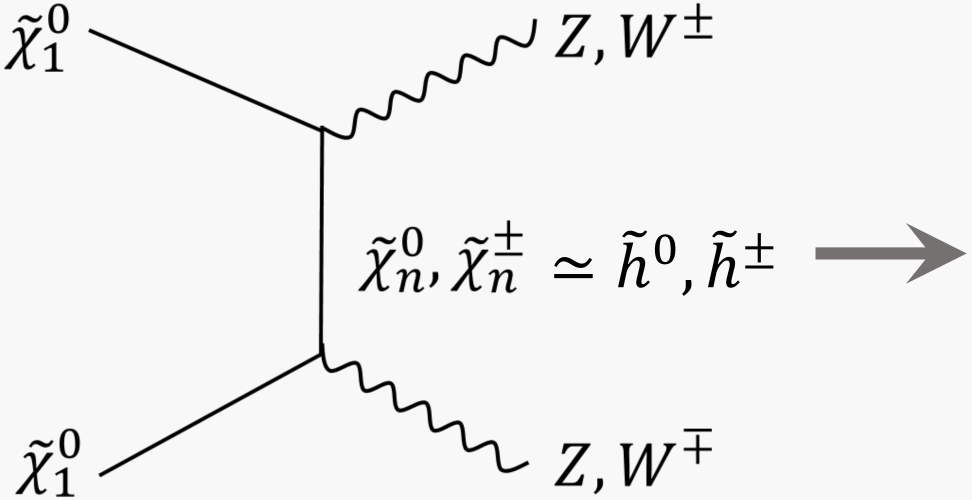
scenarios for DM relic abundance

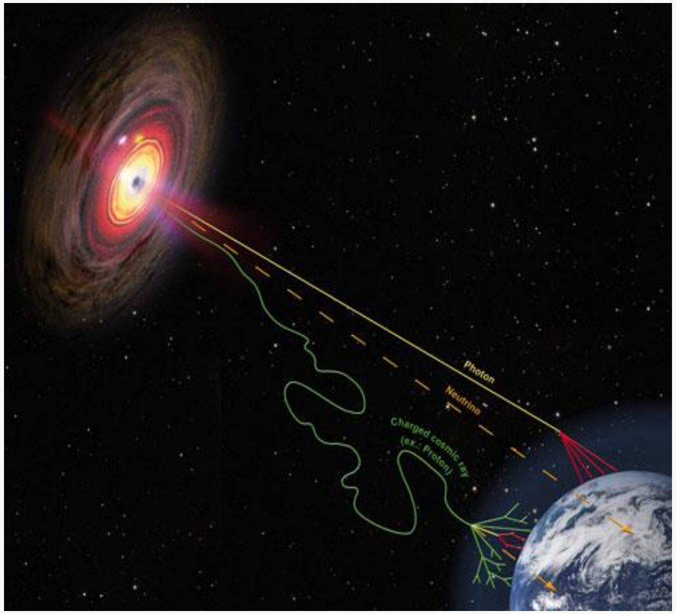
We consider “thermal” and “non-thermal” scenarios

- thermal scenario: $\Omega_{LSP} = \Omega_{thermal} \leq \Omega_{obs}$
  - $\Omega_{LSP} = \Omega_{obs}$ @ $\mu \simeq 1.0$ TeV and reduces for smaller μ
  - dark matter is augmented by other particle(s)

- Non-thermal scenario: $\Omega_{LSP} = \Omega_{obs}$
  - LSP is produced by certain non-thermal production
  - DM searches become the most efficient

constraints form indirect detection

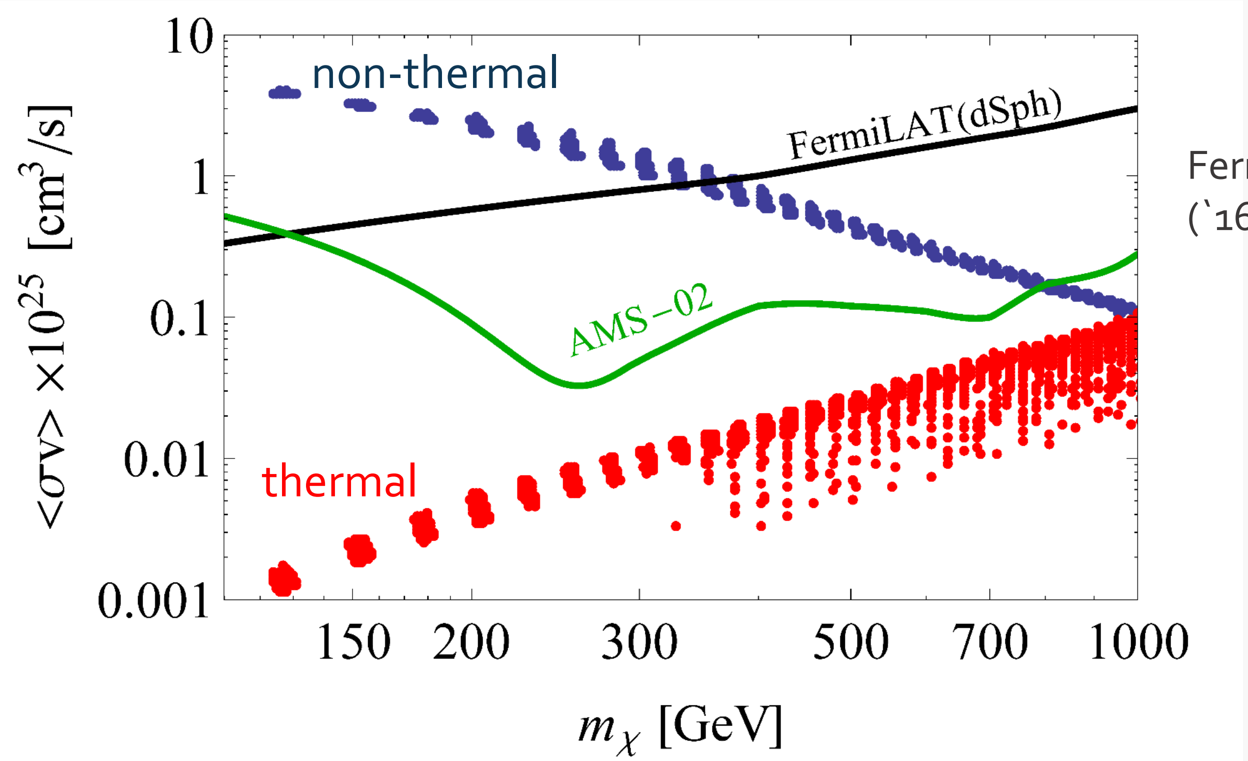




http://www.hap-astroparticle.org/184.php

$\langle \sigma v \rangle_{v=0}$ is determined by higgsino mass itself

constraints form indirect detection



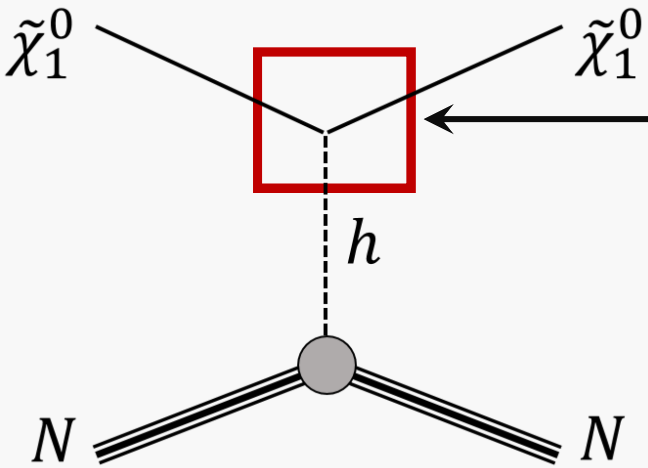
Fermi-LAT, AMS-02,
(`16 Cooco, Kramer, Tsai, Fan)

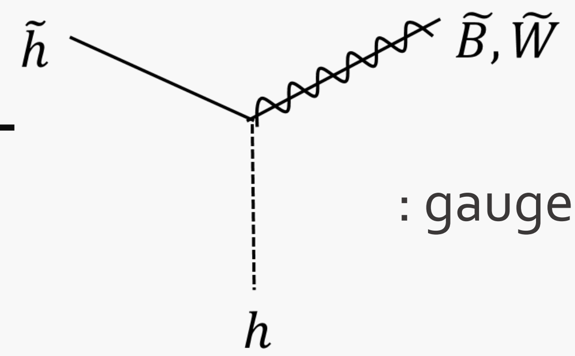
softsusy, SDECAY
micrOMEGA

- **non-thermal**: $\Omega_{LSP} = \Omega_{obs}$
  - $\mu < 300$ GeV excluded by Fermi-LAT
  - $\mu < 800$ GeV excluded by AMS-02

- **thermal**: $\Omega_{LSP} = \Omega_{thermal}$
  - no constraint on μ

direct detection for higgsino LSP





: gauge-basis

$$\lambda_{h\chi\chi} = \frac{g}{2}(1 \pm s_{2\beta})c_W\left(\frac{m_Z}{M_2 - |\mu|} + t_W^2\frac{m_Z}{M_1 - |\mu|}\right)$$

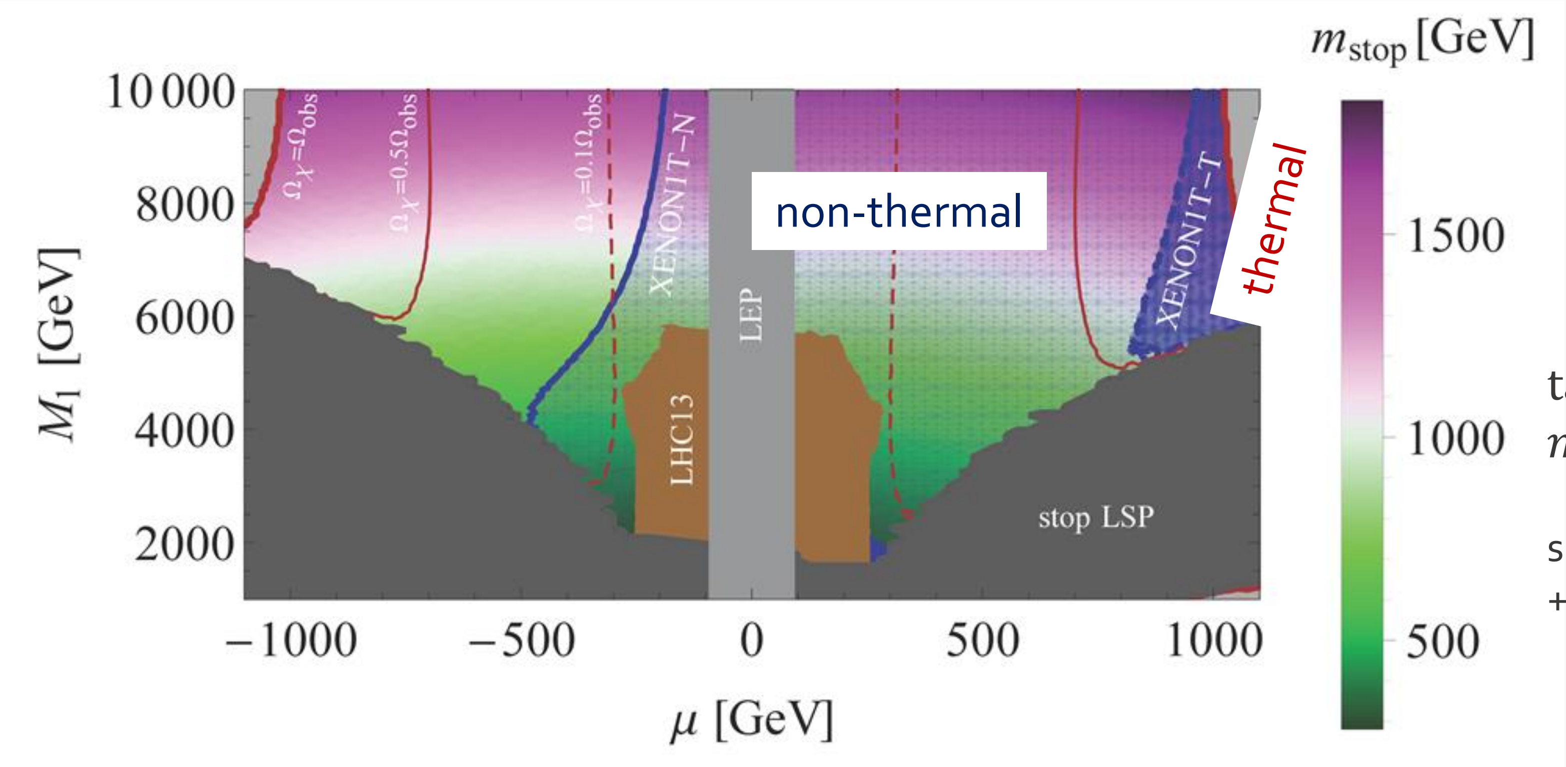
□ SI cross section

$$\sigma_{N\chi}^{SI} = \frac{g^2}{4\pi}\frac{m_N^2}{m_h^4 m_W^2}\left(1 + \frac{m_N}{m_\chi}\right)^{-2}\left[\frac{2}{9} + \frac{7}{9}\sum_{q=u,d,s} f_{T_q}^N\right]^2 \lambda_{h\chi\chi}^2$$

- gaugino masses are crucial for higgsino-gaugino mixing
- sign of μ is also important for smaller $\tan\beta$

constraints from direct detection

$M_3 = 1$ TeV and M_2 is fixed to realize μ



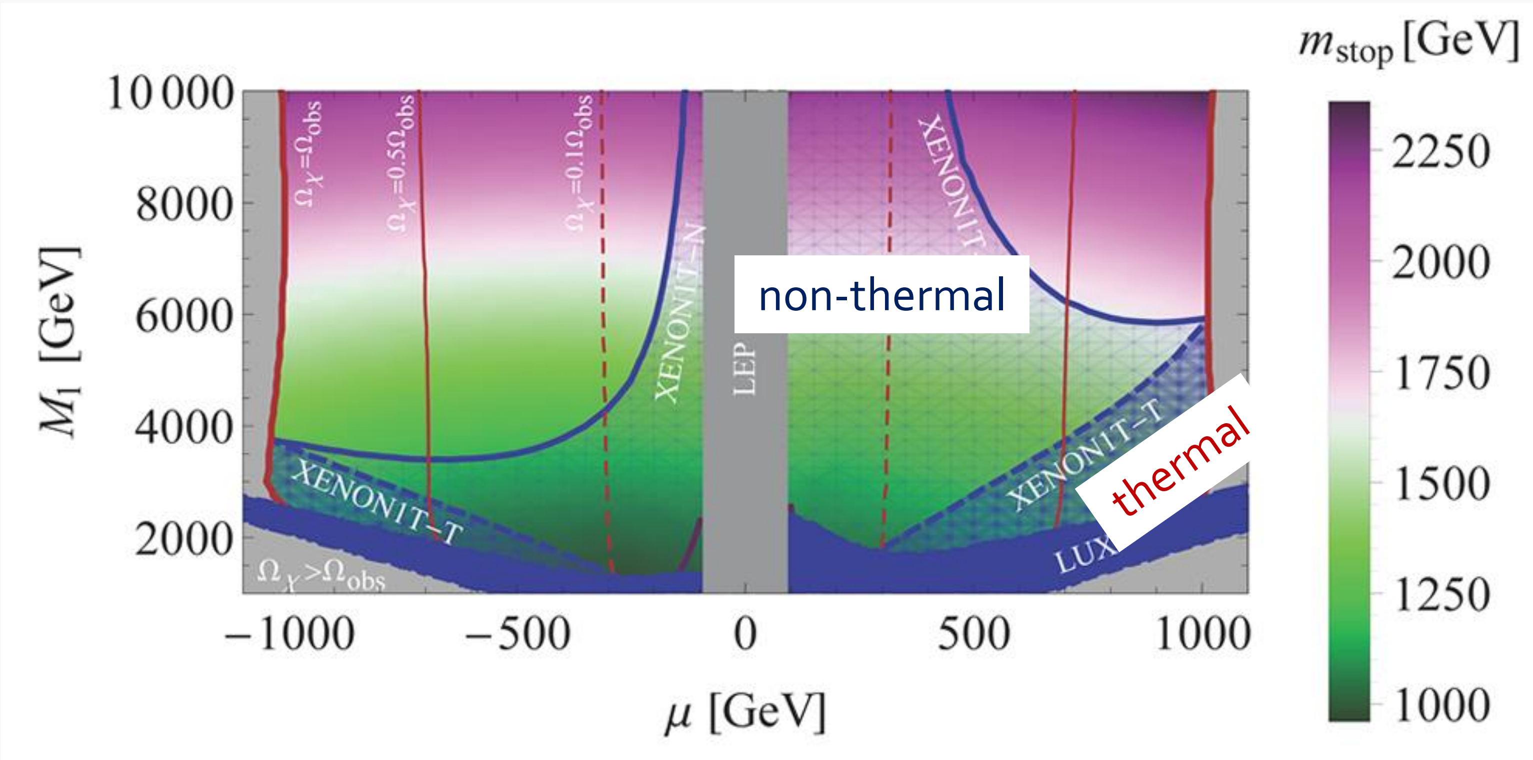
$\tan\beta = 10$
$m_0 = 1$ TeV

softsusy+sdecay
+micrOMEGA

- XENON1T fully covers $\mu > -100$ GeV in non-thermal case
- only $\mu \lesssim 1.0$ TeV is covered in thermal case
- LHC is sensitive to small μ , while DD is sensitive to large μ

constraints from direct detection

$M_3 = 1.5\,\mathrm{TeV}$ and M_2 is fixed to realize μ



$\tan\beta = 10$
$m_0 = 1\,\mathrm{TeV}$

softsusy+sdecay
+micrOMEGA

- there are significant bounds on M_1 even when $m_{\tilde{g}} \simeq 3.2\,\mathrm{TeV}$
- SI cross section is on the "neutrino floor" everywhere

`13 Billard, Strigari, Figueroa-Feliciano

Summary

- large wino accommodates light higgsino with LHC results
- DM searches directly see gaugino masses
- DM searches give strong bounds if LSP saturates universe
- direct detection and LHC play complemental roles if LSP is produced by thermal process
- note that universal gaugino mass with light gluino is immediately excluded by direct detection

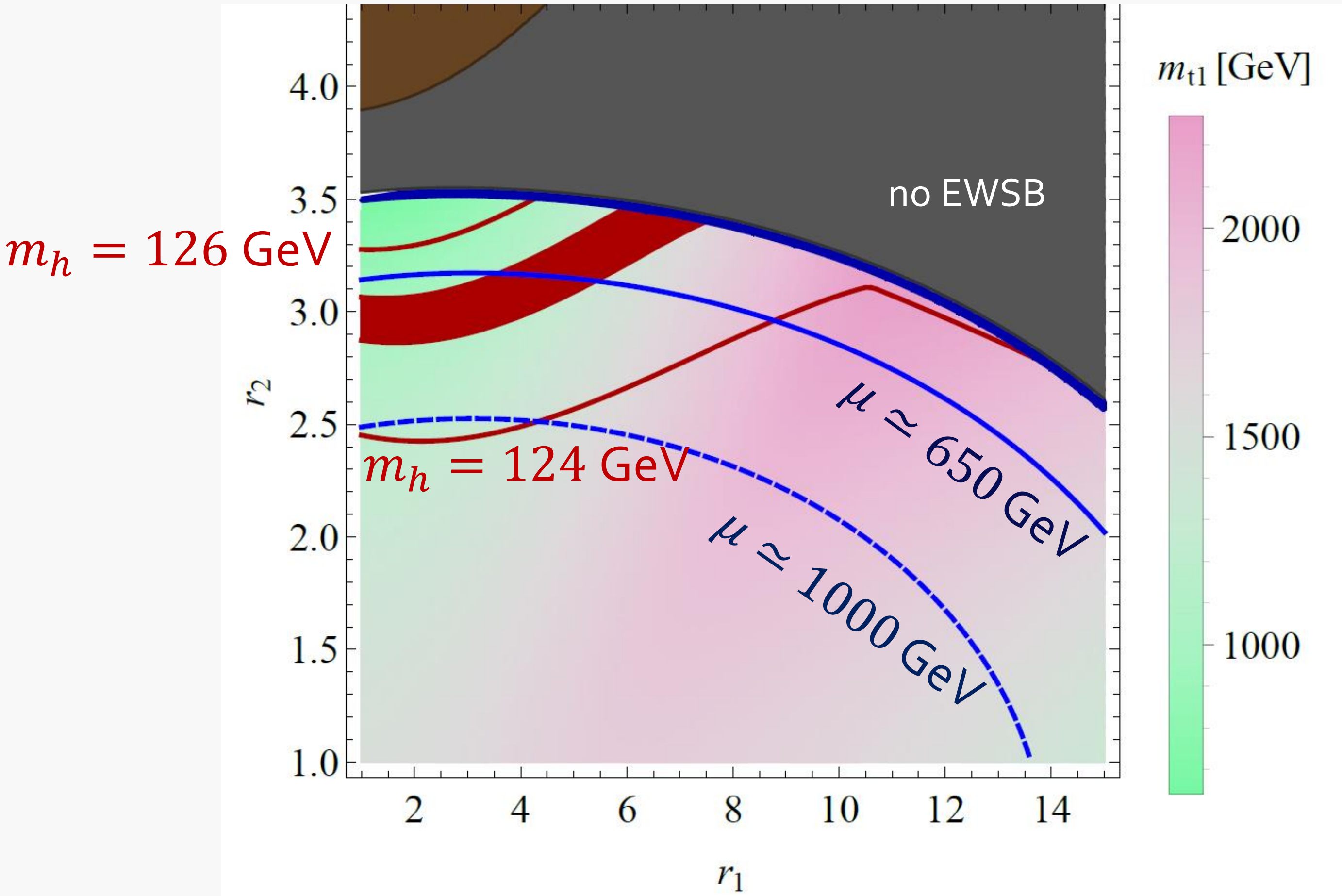
Thank you !!

backups

Higgs boson mass in NUGM

- we assume universal soft mass m_0 and A-term A_0

$$m_{SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}\ , r_i = M_i/M_3$$

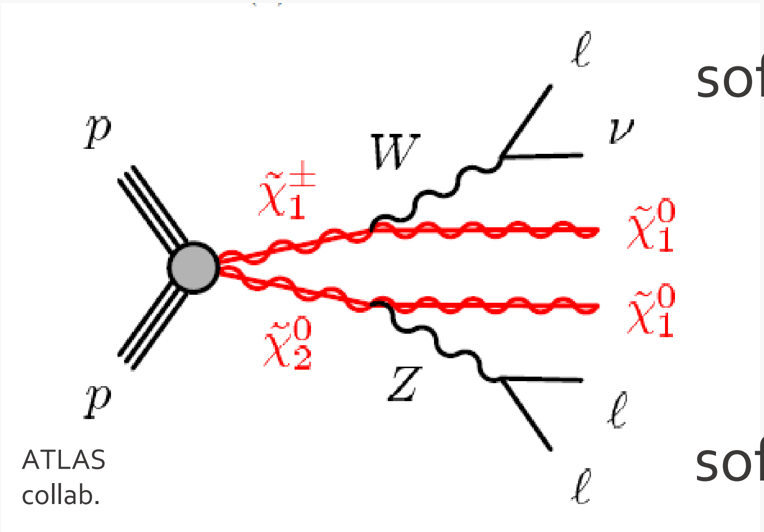


$A_0 = -1.0$ TeV
$M_3 = m_0 = 1.0$ TeV
$\tan\beta = 15$

1-loop RGE +
1-loop RG Higgs mass

decays of higgsinos at LHC

- higgsinos are light and degenerate $\Delta m_{\tilde{\chi}} \lesssim 2.0$ GeV



soft

invisible

soft

- decay products are too soft to be reconstructed
- $c\tau < O(10^{-3}cm)$: no dissapearing track unlike pure wino

higgsino search at LHC is not efficient

Realization of NUGM

- mixed moduli / anomaly mediation

`05 K.Choi, K.S.Jeong, K.Okumura
`05 R.Kitano, Y.Nomura

$$M_{1/2} = \frac{F^T}{T+\overline{T}} + \frac{g_0^2}{16\pi^2} b_a \frac{F^C}{C} \qquad b_a = \left(\frac{33}{5}, 1, -3\right)$$

- F-terms of non-trivial GUT representations

ex) $M_1 : M_2 : M_3 = 1 : 3 : -2$ for 24 of SU(5)

suitable linear combi. of F^1 and F^{24}

`12 J.E.Younkin, S.P.Martin

- non-universal gauge kinetic function

$$f_a = c_a + l_a^I T^I \qquad a = U(1)_Y, SU(2)_L, SU(3)_C$$

parameter settings

parameters

- universal soft mass and A-term: m_0, A_0
- non-universal gaugino masses : M_1, M_2, M_3
- Higgs bilinear, Higgs VEV ratio : $\mu, B\mu,\ \tan\beta = \langle H_u \rangle / \langle H_d \rangle$

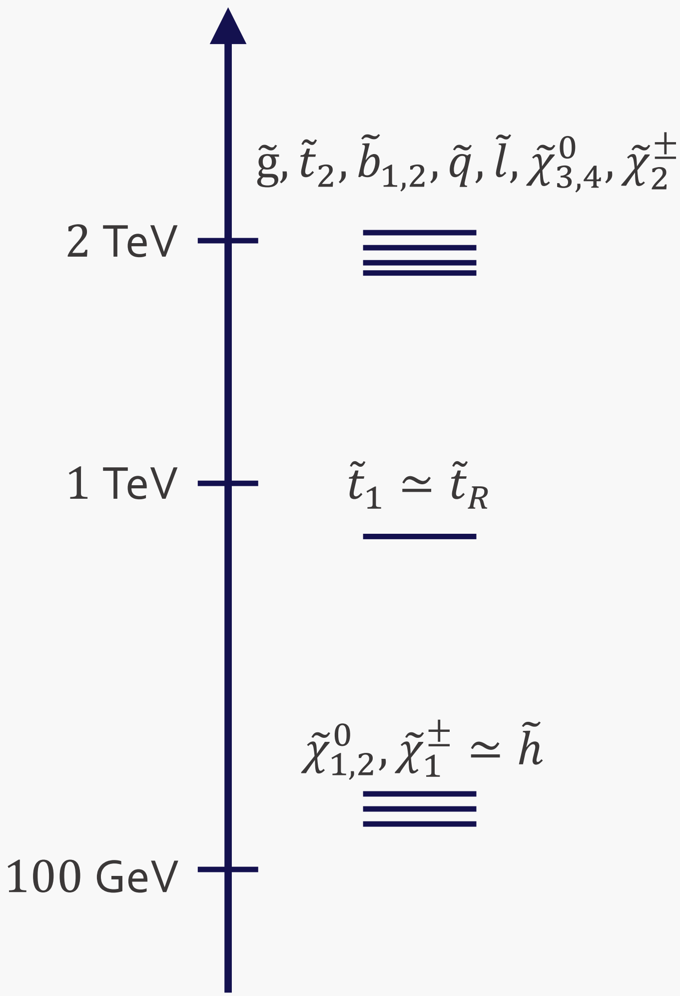
constraints

- electroweak symmetry breaking (EWSB) condition
- Higgs boson mass : $m_h = 125\ \mathrm{GeV}$

strategy

- M_2 and $B\mu$-term are tuned to satisfy EWSB condition
- A_0 is tuned to realize $m_h = 125$ GeV

typical mass spectrum



✓ most of sparticles are heavy

- these are determined by gluino mass M_3

✓ right-handed stop can be lighter than others

- as a result of large wino mass

✓ higgsinos are light

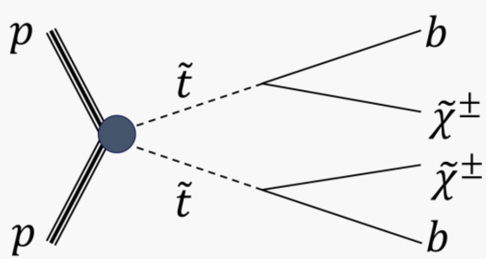
top squark decays

- right-handed top squark is light in NUGM

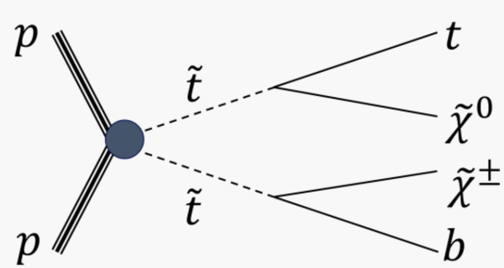
$$W_{MSSM} \ni y_t\left(t_L\, \tilde{h}_u^0 - b_L\, \tilde{h}_u^+\right) \tilde{t}_R$$

  - top squark decays to $t + \tilde{\chi}_{1,2}^0$ or $b + \tilde{\chi}_1^\pm$
  - right-handed top squark couples to quark/higgsinos universally
  - $\mathrm{Br}\left(\tilde{t}_1 \to b\, \tilde{\chi}_1^\pm\right) = 1 - \mathrm{Br}\left(\tilde{t}_1 \to t\, \tilde{\chi}_{1,2}^0\right) \simeq 0.5$ unless $m_{\tilde{t}_1} \simeq m_{\tilde{\chi}_1^\pm}$

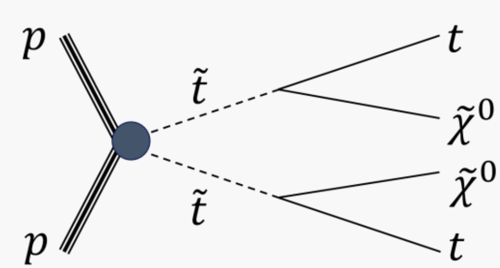
25 %



50 %



25 %

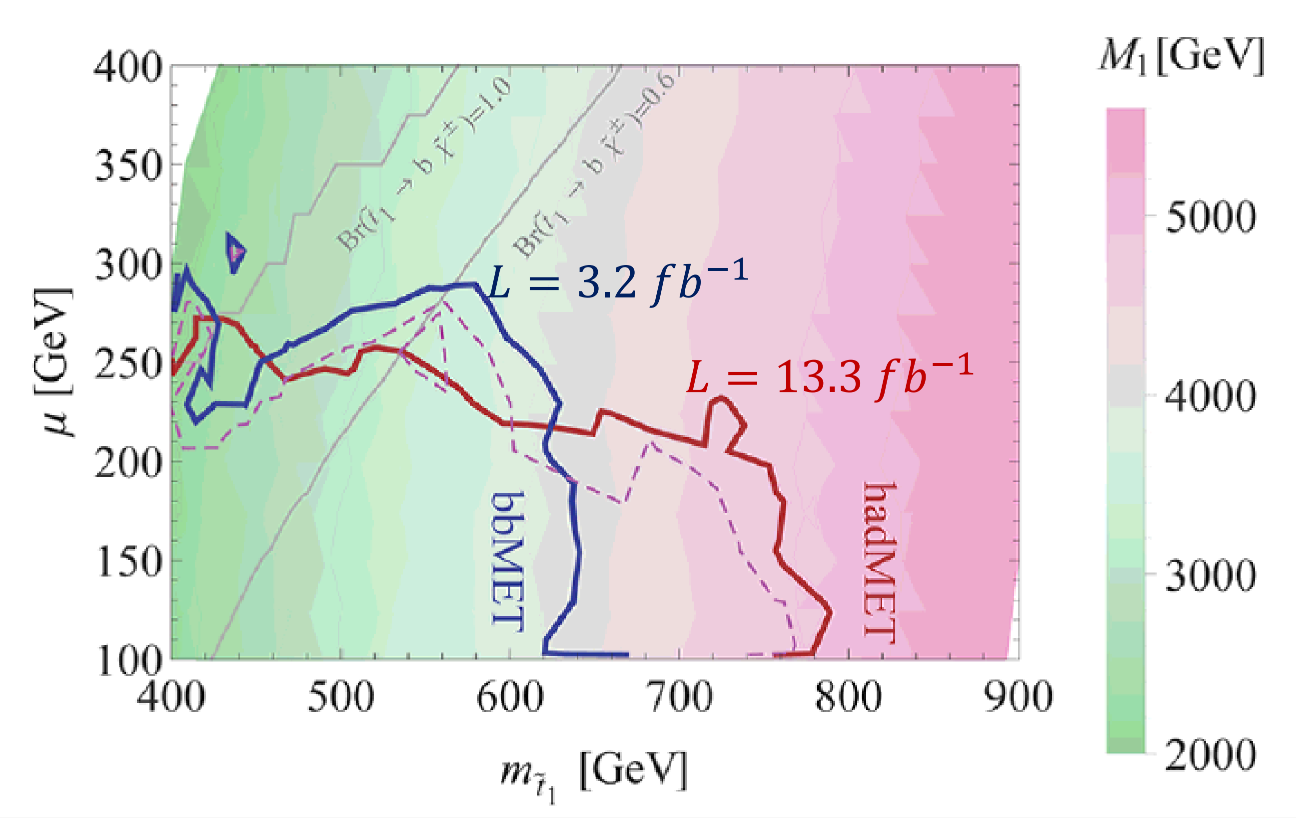


top squark search

- ✓ signals are tt (25%) / tb (50%) / bb (25%) + MET
- ✓ bb+MET channel[1] is sensitive to mass degenerate region
- ✓ (4 ≥) jets + MET channel[2] is sensitive to high-stop mass region

$\tan\beta = 15$
$m_0 = M_3 = 1$ TeV

softsusy+sdecay+MG5
+pythia6+delphes3



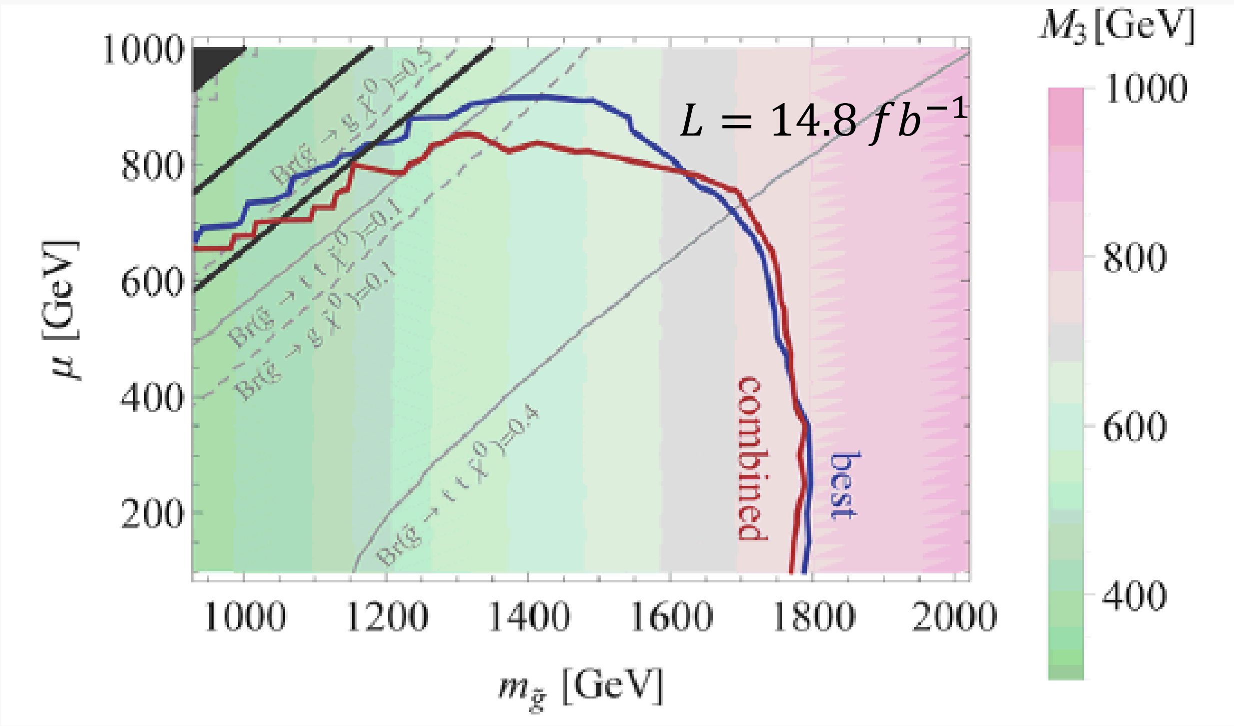
[1] ATLAS-CONF-2015-066 [2] ATLAS-CONF-2016-077

gluino search

- ✓ gluino decays to top and stop: $\tilde{g} \to t\,\tilde{t}_1 \to t + t\tilde{\chi}^0_{1,2}/b\,\tilde{\chi}^{\pm}_1$
- ✓ signals are characterized by 4 bottoms and large MET
- ✓ 13TeV data [3] cover $m_{\tilde{g}} \lesssim 1.8$ TeV for $\mu \lesssim 800$ GeV

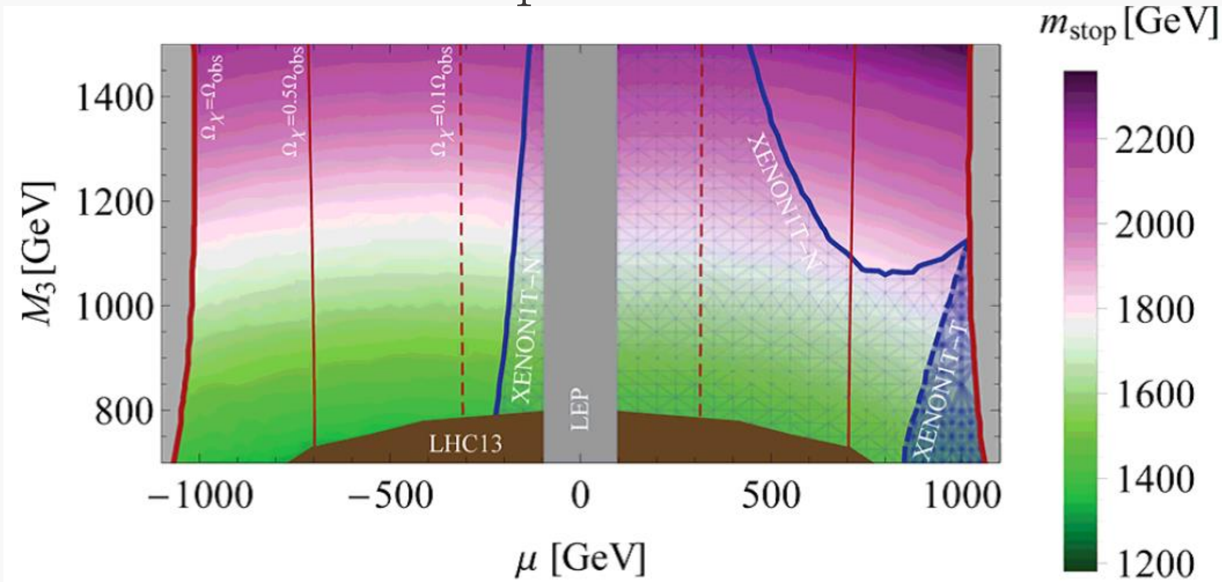
$\tan\beta = 15$
$m_0 = 1$ TeV
$M_1 = 12$ TeV

softsusy+sdecay+MG5
+pythia6+delphes3

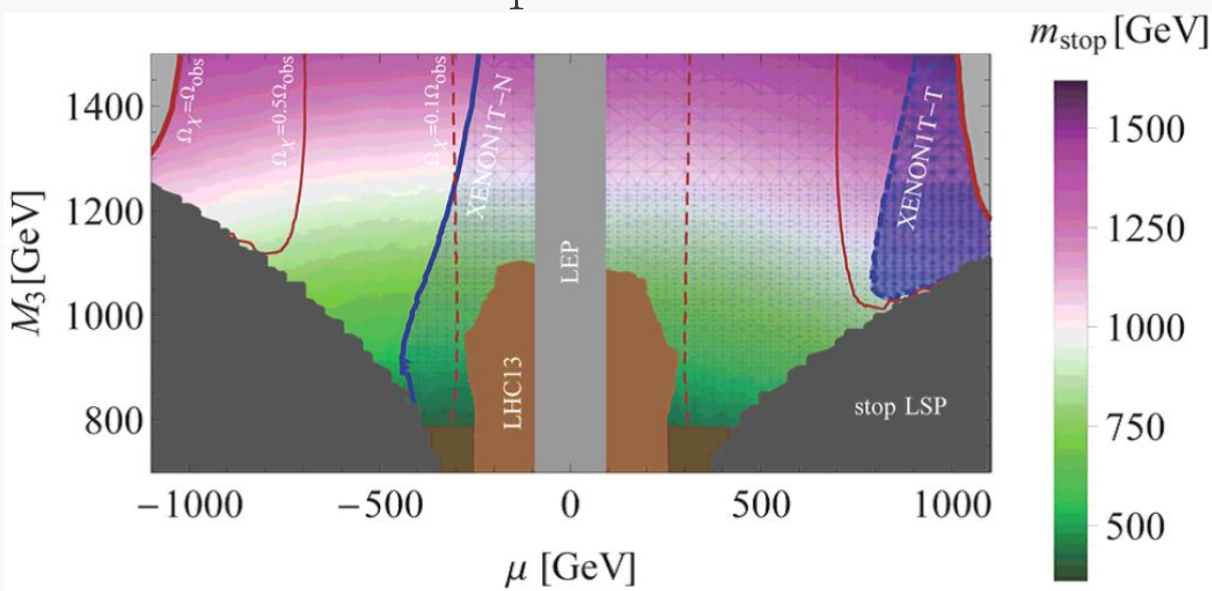


[3] ATLAS-CONF-2016-052

$M_1 = 10\,\mathrm{TeV}$



$M_1 = 5\,\mathrm{TeV}$



input [GeV]	(a)	(b)	(c)	(d)
μ	-250	250	-1000	1000
$M_1(M_U)$	10000	10000	5000	5000
$M_3(M_U)$	1000	1000	1500	1500
$m_0(M_U)$	1000	1000	1000	1000
output [GeV]				
$M_2(M_U)$	4223	4175	4698	4504
$A_0(M_U)$	-2378	-2325	-1916	-1657
mass [GeV]				
m_h	125.0	125.0	125.0	125.0
m_A	3349	3326	3351	3248
$m_{\tilde{t}_1}$	1606	1636	1431	1581
$m_{\tilde{t}_2}$	2780	2762	3582	3520
$m_{\tilde{g}}$	2250	2250	3225	3223
$m_{\tilde{\chi}_1^0}$	258.8	255.7	1016	1013
$m_{\tilde{\chi}_2^0}$	260.5	258.3	1019	1017
$m_{\tilde{\chi}_3^0}$	3438	3400	2239	2237
$m_{\tilde{\chi}_4^0}$	4455	4454	3839	3682
$m_{\tilde{\chi}_1^\pm}$	260.5	257.1	1018	1015
$m_{\tilde{\chi}_2^\pm}$	3439	3400	3840	3682
observables				
$\Omega_\chi h^2$	7.82×10^{-3}	7.58×10^{-3}	1.14×10^{-1}	1.16×10^{-1}
$\langle\sigma v\rangle_0 \times 10^{25}$[cm^3/s]	1.39	1.42	0.104	0.105
$\mathrm{Br}(\chi\chi \to W^+W^-)$	0.533	0.535	0.488	0.489
$\mathrm{Br}(\chi\chi \to ZZ)$	0.436	0.435	0.408	0.407
$\sigma_{\mathrm{SD}} \times 10^{-6}$[pb]	1.096	1.138	0.1677	0.1757
$\sigma_{\mathrm{SI}} \times 10^{-11}$[pb]	3.499	8.505	8.918	22.37
$\sigma^h_{\mathrm{SI}} \times 10^{-11}$[pb]	3.302	7.793	7.853	19.50