PPP2017@Kyoto

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

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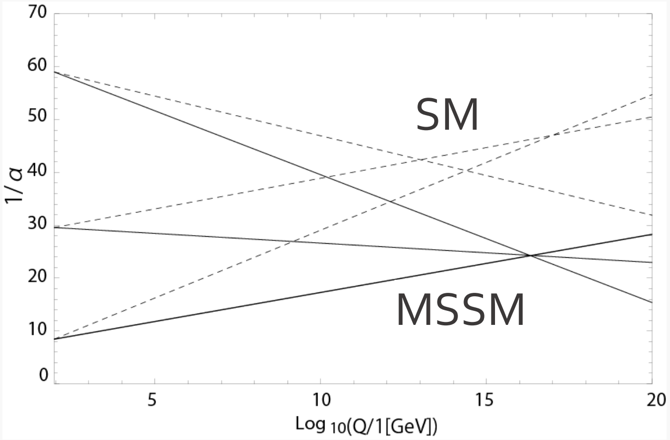
Outline

1. **Brief review of MSSM**
2. Non-universal gaugino mass scenario
3. Phenomenology of NUGM
4. Conclusion

Minimal Supersymmetric Standard Model

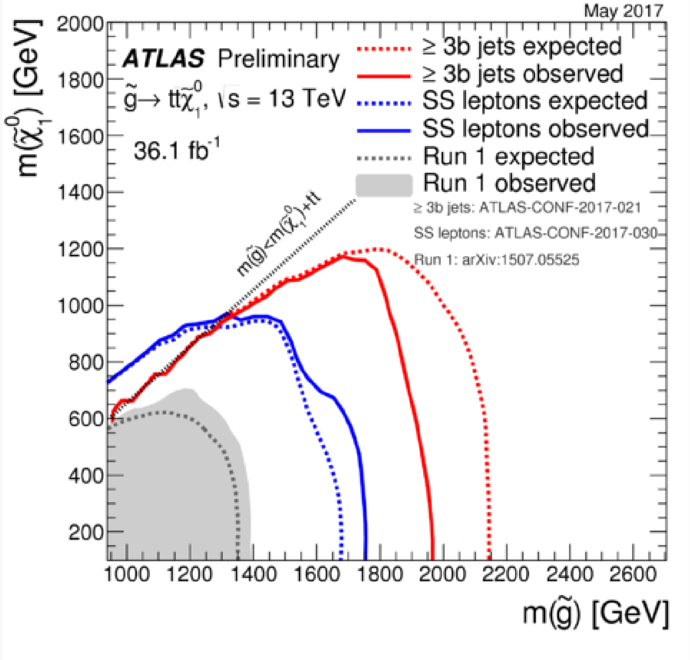
- Every SM particle has superpartner
- radiative electroweak symmetry breaking (EWSB)
- gauge coupling unification
- dark matter candidate



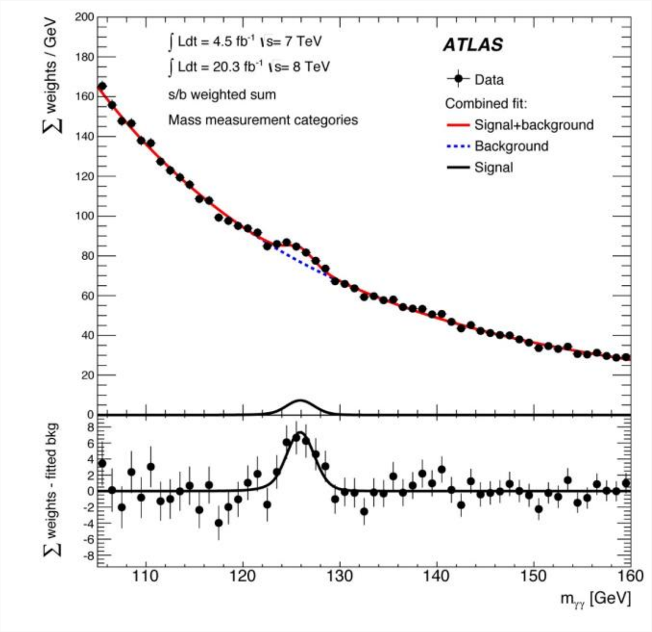
MSSM is promising candidate for beyond SM

low-scale SUSY

- motivation
  - little hierarchy problem
  - testability at LHC
- LHC bound: e.g.) $m_{\tilde{g}} > 2.0$ TeV



- Higgs mass 125 GeV



SM-like Higgs boson mass

$$M_{stop} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$
$$\mathcal{L} \supset y_t A_t \, H_u \, \tilde{t}_L \, \tilde{t}_R$$

- MSSM Higgs boson mass

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

125 GeV needs large quantum correction (~ 35 GeV)

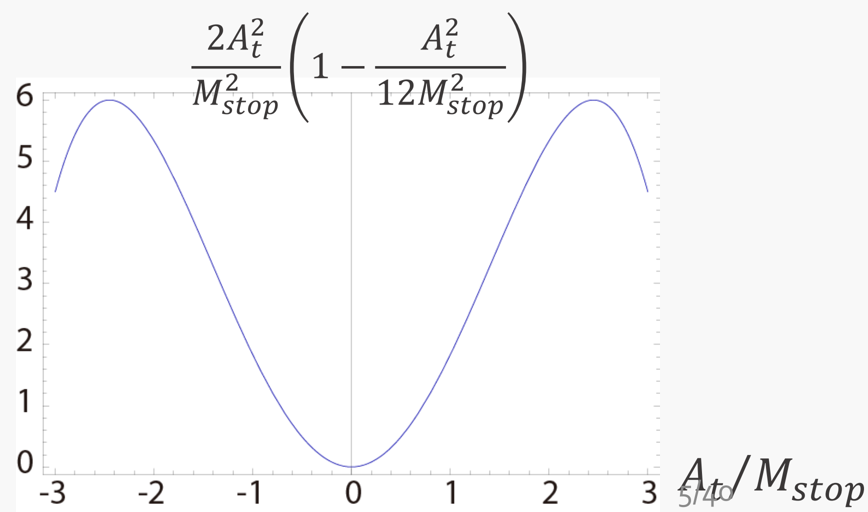
$\rightarrow$ $M_{stop} \simeq 10$ TeV if $A_t / M_{stop} \ll 1$

- maximal mixing scenario

last term is maximized at

$$A_t / M_{stop} \sim \sqrt{6}$$

(maximal mixing)



little hierarchy problem

SUSY searches and Higgs mass indicate high-scale SUSY

→ hierarchy between SUSY scale and EW scale

- Higgs potential minimization condition

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

EW scale SUSY scale

μ : higgsino mass
$m_{H_u}^2$: up-type Higgs mass

✓ fine-tuning is required if $m_Z \ll \mu,\ m_{H_u}$

✓ at least μ must be small since it's unique SUSY parameter

✓ small μ means small m_{H_u} around EW scale

Higgs mass vs little hierarchy

little hierarchy problem relates to the Higgs boson mass

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

$$16\pi^2 \frac{dm_{H_u}^2}{dt} \simeq 6y_t^2 \left(m_{H_u}^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + A_t^2\right) - 6g_2^2|M_2|^2 - \frac{6}{5}g_1^2|M_1|^2$$

- top squark parameters $m_{\tilde{t}_L}^2, m_{\tilde{t}_R}^2, A_t$ appear
- heavy top squark leads larger $|m_{H_u}^2|$

✓ 10 TeV top squark forces 10^{-3} % tuning

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What we need for low-scale SUSY?

- little hierarchy problem

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

$|m_{H_u}(m_{SUSY})| \simeq \ |\mu| \simeq m_Z$ to avoid the fine-tuning

- MSSM Higgs boson mass

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{8\pi^2 v_u^2}\left[\log\frac{M_{stop}^2}{m_t^2} + \frac{2A_t^2}{M_{stop}^2}\left(1 - \frac{A_t^2}{12M_{stop}^2}\right)\right]$$

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

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

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

- Universal Gaugino Masses

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

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

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

Higgs boson mass in NUGM

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

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- Non-Universal Gaugino Masses (NUGM)

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

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

→ $A_t/M_{stop} \lesssim \sqrt{6}$

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

✓ upper bound is $M_2/M_3 \lesssim 4.2$ for $m^2_{\tilde{t}_R}(m_{SUSY}) > 0$

naturalness in NUGM

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

$$m_{H_u}^2(m_{SUSY}) \simeq +0.20M_2^2 - 0.13M_2M_3 - 1.56M_3^2 - 0.07m_0^2$$

unification scale

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

large wino mass reduces $\left|m_{H_u}^2\right| \simeq |\mu|^2$

+

large wino mass enhances the Higgs boson mass

Higgs boson mass in NUGM

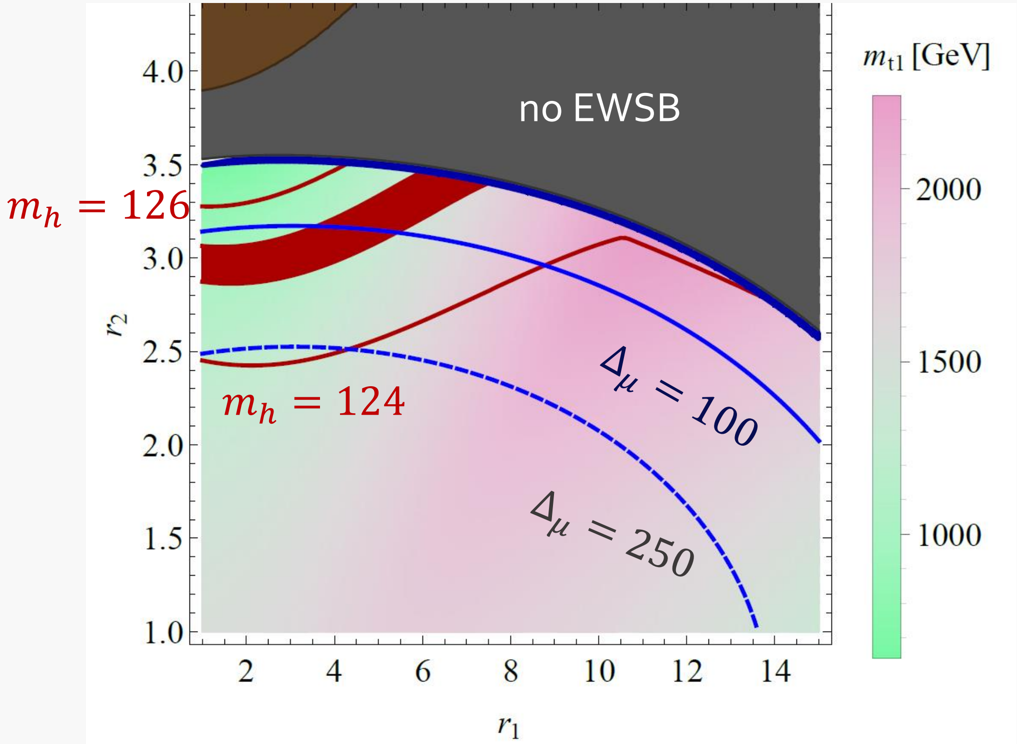
- we assume universal soft mass m_0 and A-term A_0

$M_3 = m_0 = 1.0\,\text{TeV}$
$\tan\beta = 15$

$$m_{SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}\ , r_i = M_i/M_3 \qquad \Delta_\mu \equiv \left| \frac{d \ln m_Z^2}{d \ln \mu(\Lambda_{GUT})^2} \right|$$

1-loop RGE +
1-loop RG Higgs mass

$A_0 = -1.0\,\text{TeV}$



summary of NUGM

- μ-parameter can be small 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
- the degree of tuning is relaxed above 1% level,
  once gaugino mass ratios are fixed

NGUM is a good scenario for low-scale SUSY

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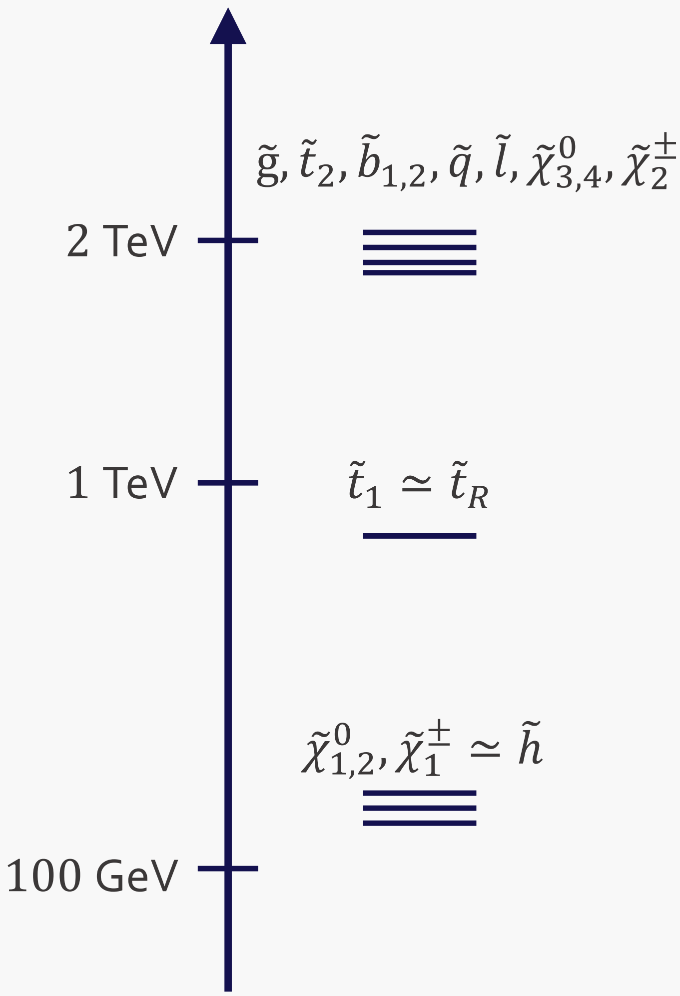
typical mass spectrum



✓ most of sparticles are heavy

- these are determined by gluino mass M_3

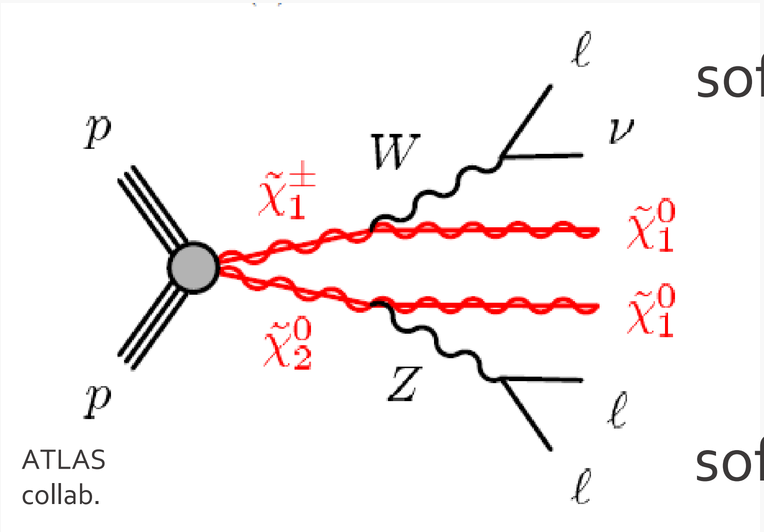
✓ right-handed stop can be lighter than others

- as a result of large wino mass

✓ higgsinos are light

decays of higgsinos

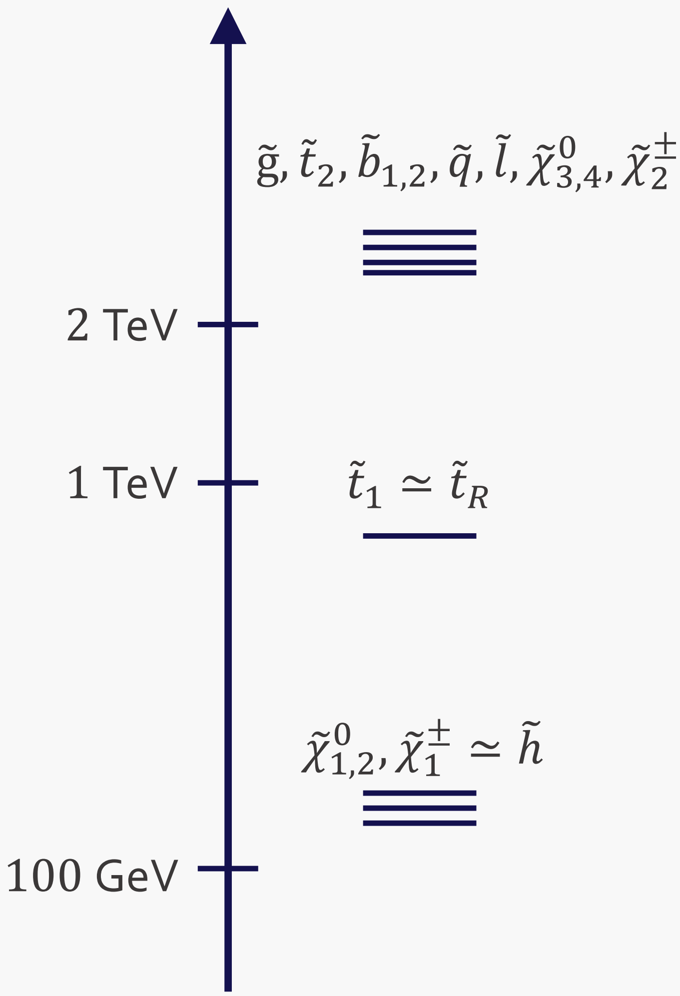
- ☐ higgsinos are light and degenerate $\Delta m_{\tilde{\chi}} \lesssim 2.0$ GeV



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

higgsino searches are difficult at LHC

typical mass spectrum



✓ most of sparticles are heavy

- these are determined by gluino mass M_3

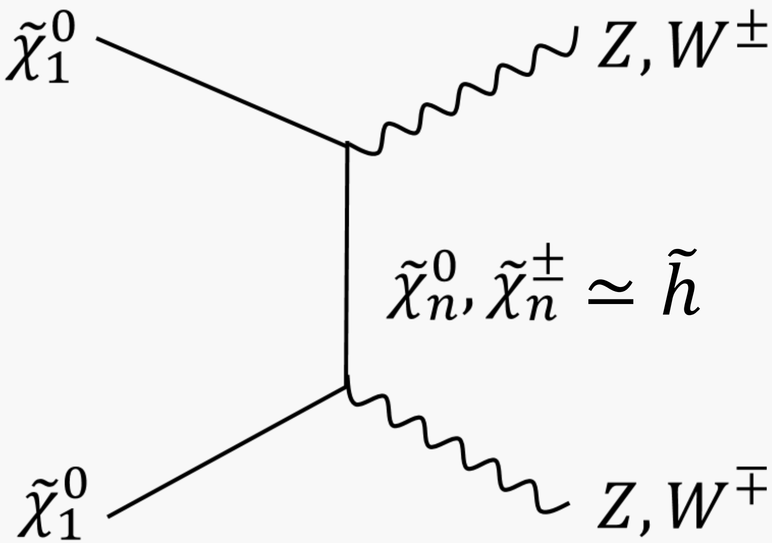
✓ right-handed stop is lighter than others

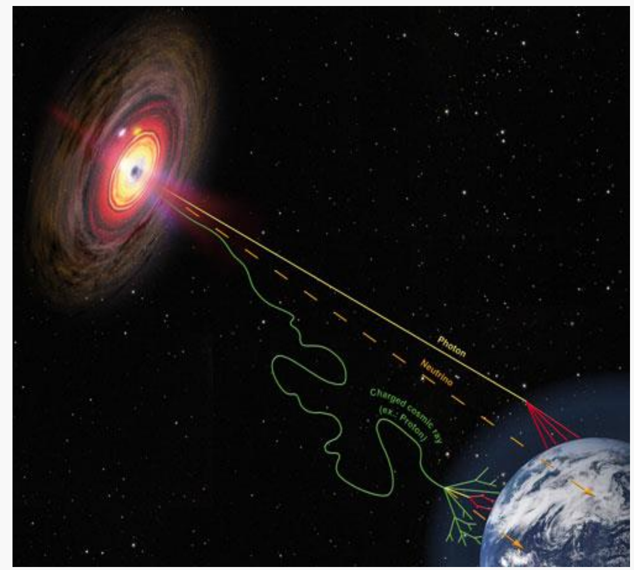
- due to large wino mass

✓ higgsinos are light, but suitably degenerate

- DM searches are important

constraints form indirect detection



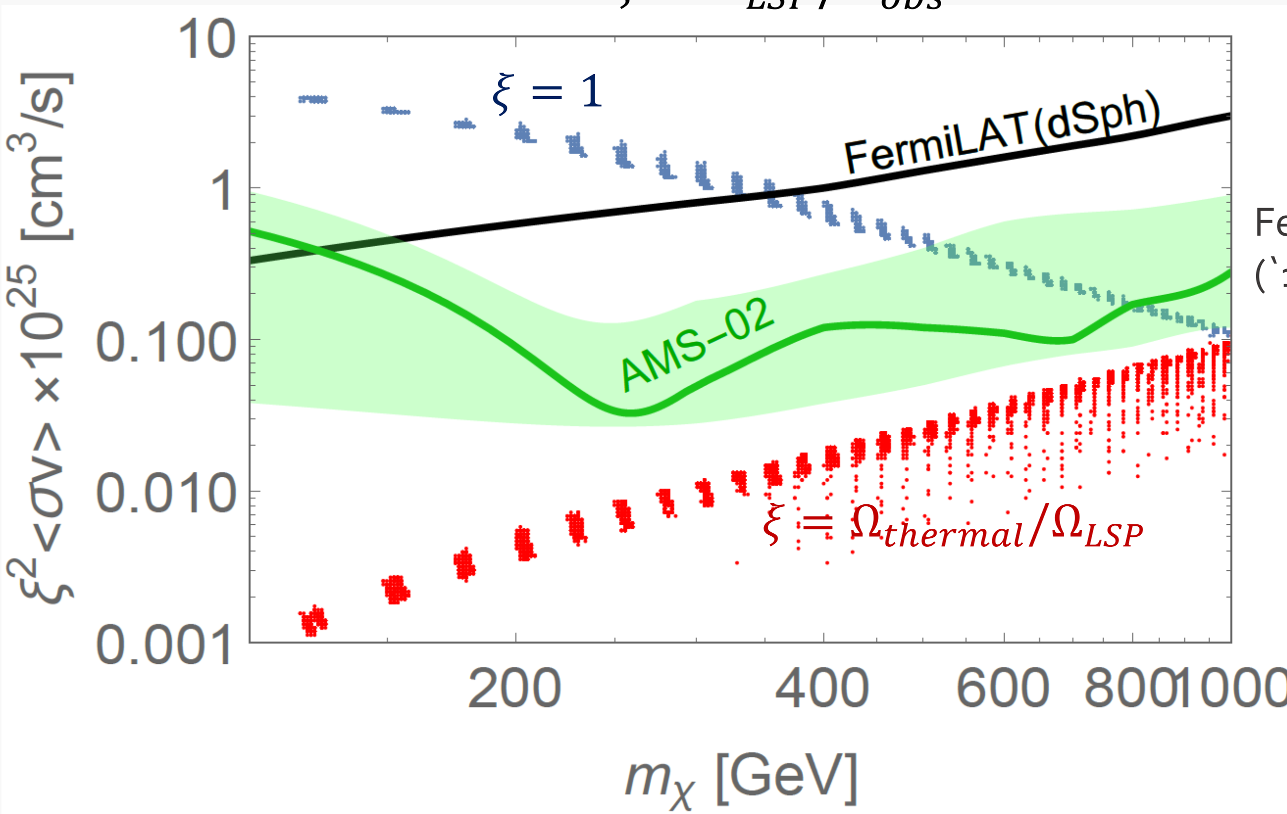


http://www.hap-astroparticle.org/184.php

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

constraints form indirect detection

$\xi \equiv \Omega_{LSP}/\Omega_{obs}$



Fermi-LAT, AMS-02,
(`16 Cooco, Kramer et.al.)

softsusy, SDECAY
micrOMEGA

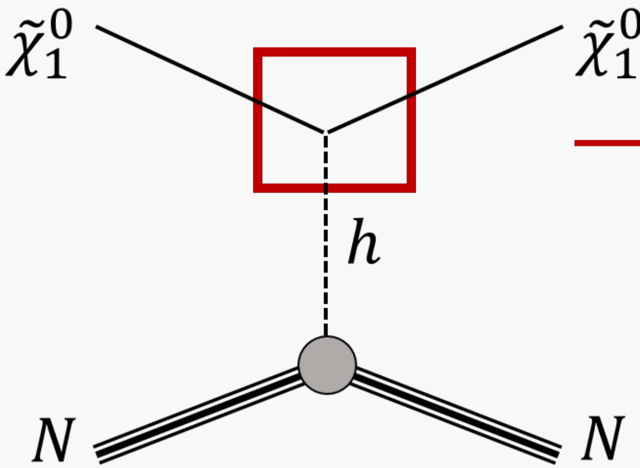
non-thermal: $\Omega_{LSP} = \Omega_{obs}$

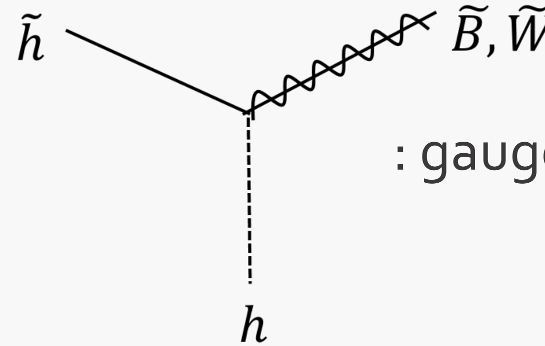
- $\mu < 300$ GeV excluded by Fermi-LAT
- $\mu < 800$ GeV excluded by AMS-02

thermal: $\Omega_{LSP} = \Omega_{thermal}$

- no constraint on μ

direct detection for higgsino LSP





: gauge-basis

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

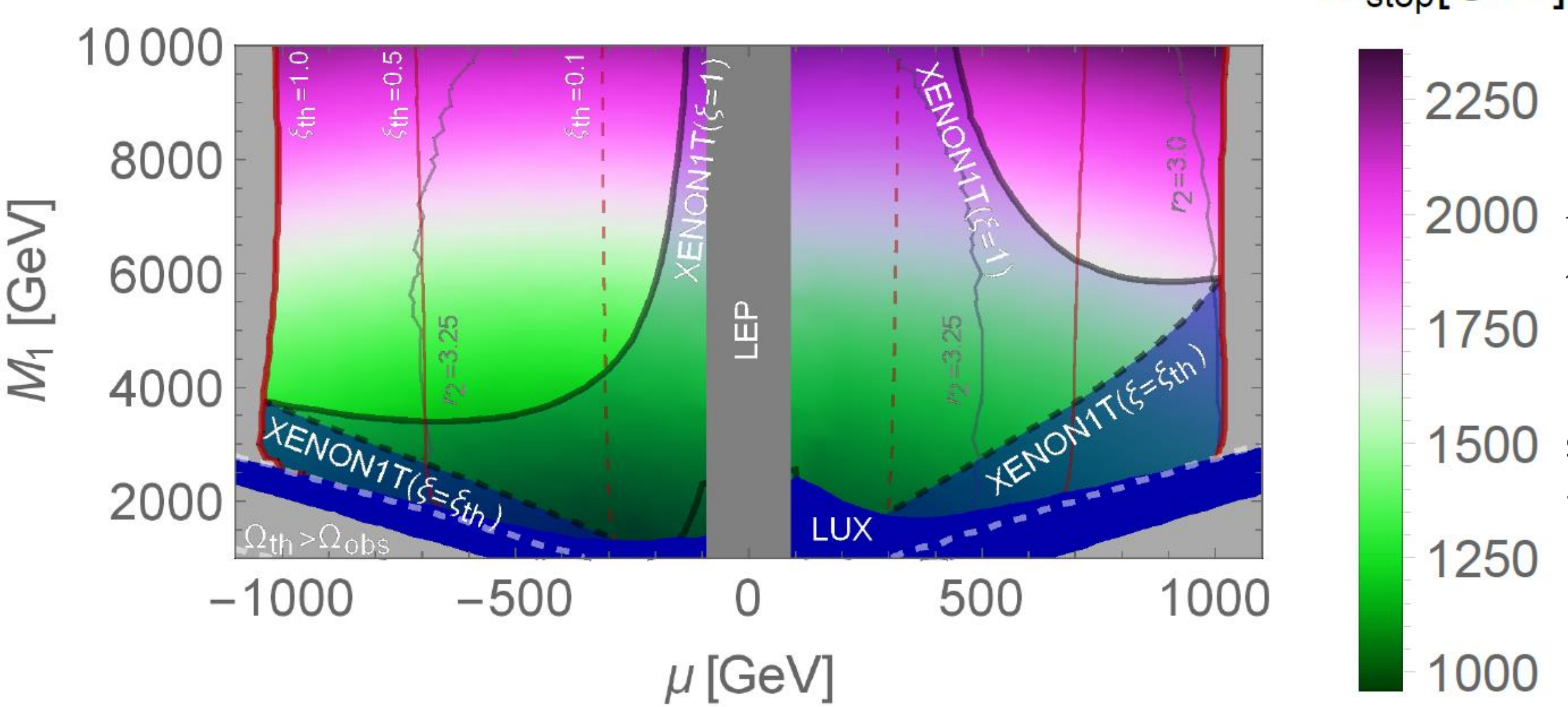
☐ cross section

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

- gaugino masses are crucial for higgsino-gaugino mixing
- sign of μ is also important for smaller tanβ

constraints from direct detection

$M_3 = 1.5\,\text{TeV}, M_2 \sim 4.5\,\text{TeV}$



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

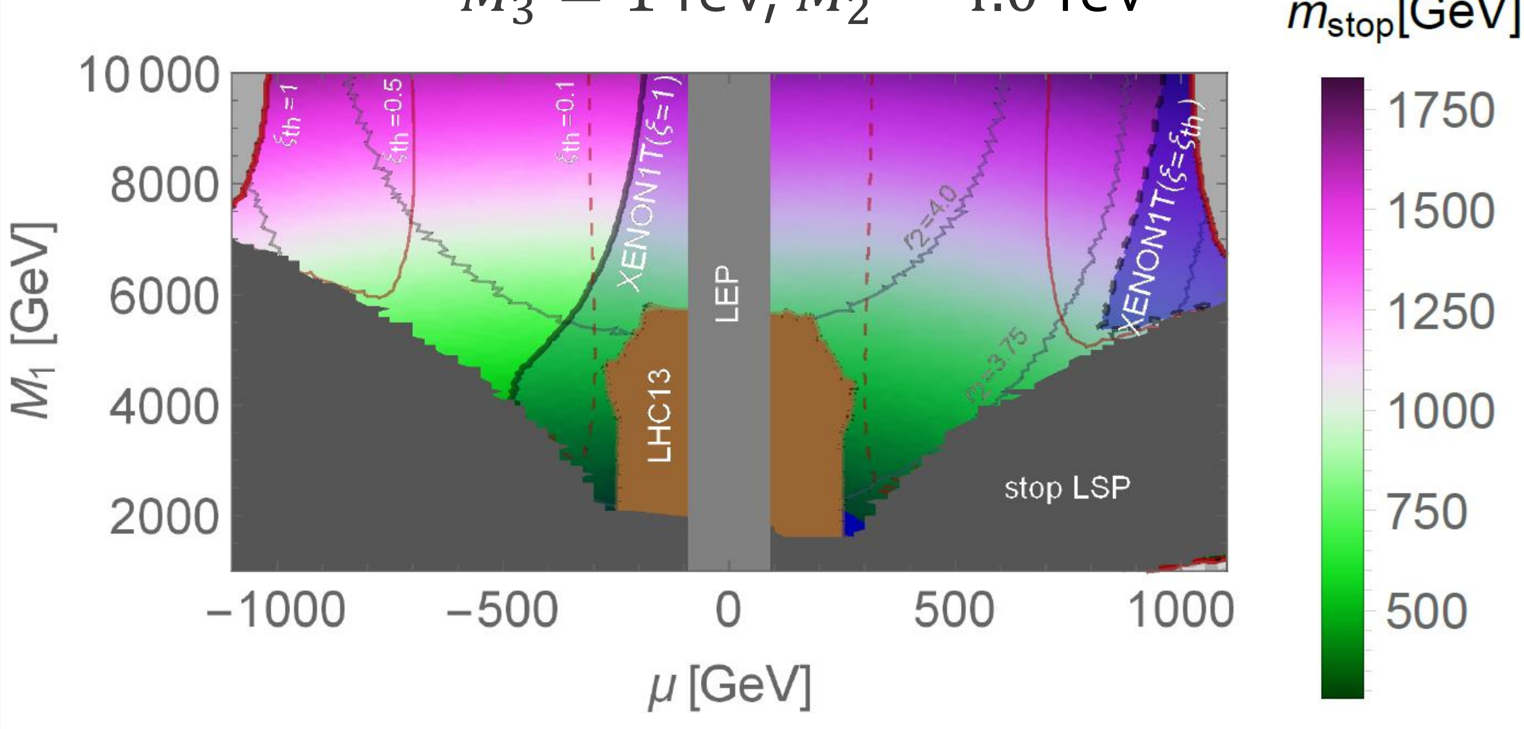
softsusy+sdecay
+micrOMEGA

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

`13 Billard, Strigari, Figueroa-Feliciano

constraints from direct detection

$M_3 = 1\,\text{TeV}, M_2 \sim 4.0\,\text{TeV}$

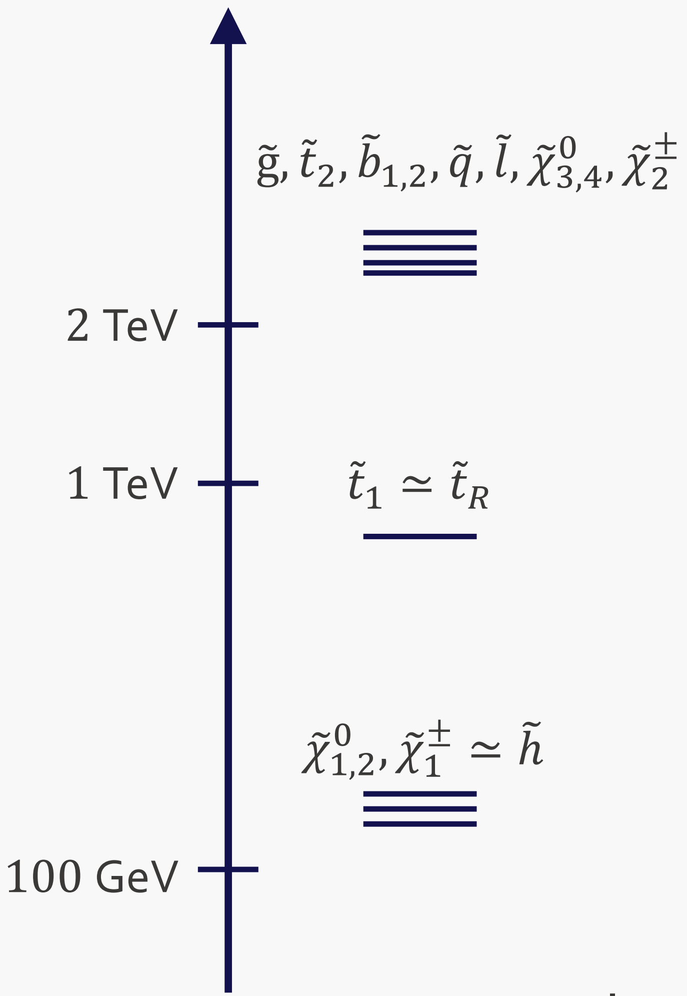


$\tan\beta = 10$
$m_0 = 1\,\text{TeV}$

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

typical mass spectrum



✓ most of sparticles are heavy

- these are determined by gluino mass M_3

✓ right-handed stop is lighter than others

- due to large wino mass

✓ higgsinos are light, but suitably degenerate

- DM searches are important
- large bino/wino is necessary for $M_{\tilde{g}} \lesssim 3.0$ TeV

stop / gluino searches are important at LHC

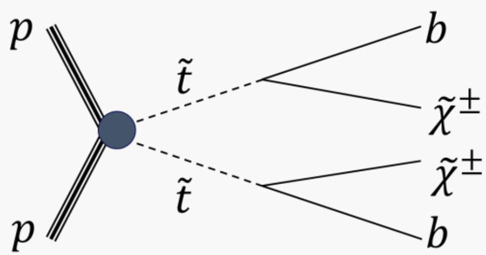
top squark decays

- right-handed top squark is light in NUGM

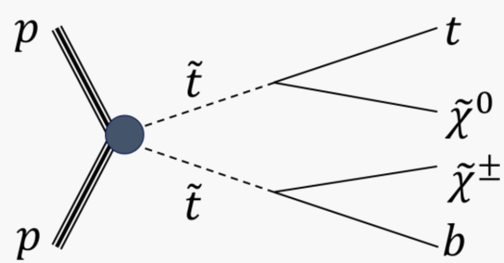
$$W_{MSSM} \ni y_t\left(t_L\, \tilde{h}_u^0\ - b_L\, \tilde{h}_u^+\right) \tilde{t}_R$$

  - top squark decays to $t + \tilde{\chi}^0_{1,2}$ or $b + \tilde{\chi}^\pm_1$
  - right-handed top squark couples to quark/higgsinos universally
  - $\mathrm{Br}\left(\tilde{t}_1 \to b\, \tilde{\chi}_1^\pm\right) = 1 - \mathrm{Br}\left(\tilde{t}_1 \to t\, \tilde{\chi}^0_{1,2}\right) \simeq$ 0.5 unless $m_{\tilde{t}_1} \simeq m_{\tilde{\chi}_1^\pm}$

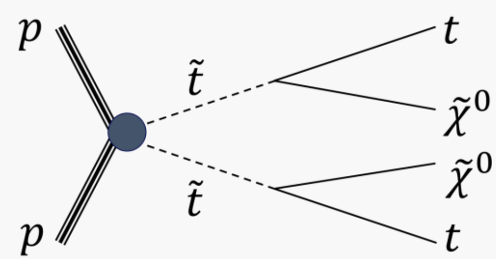
25 %



50 %



25 %

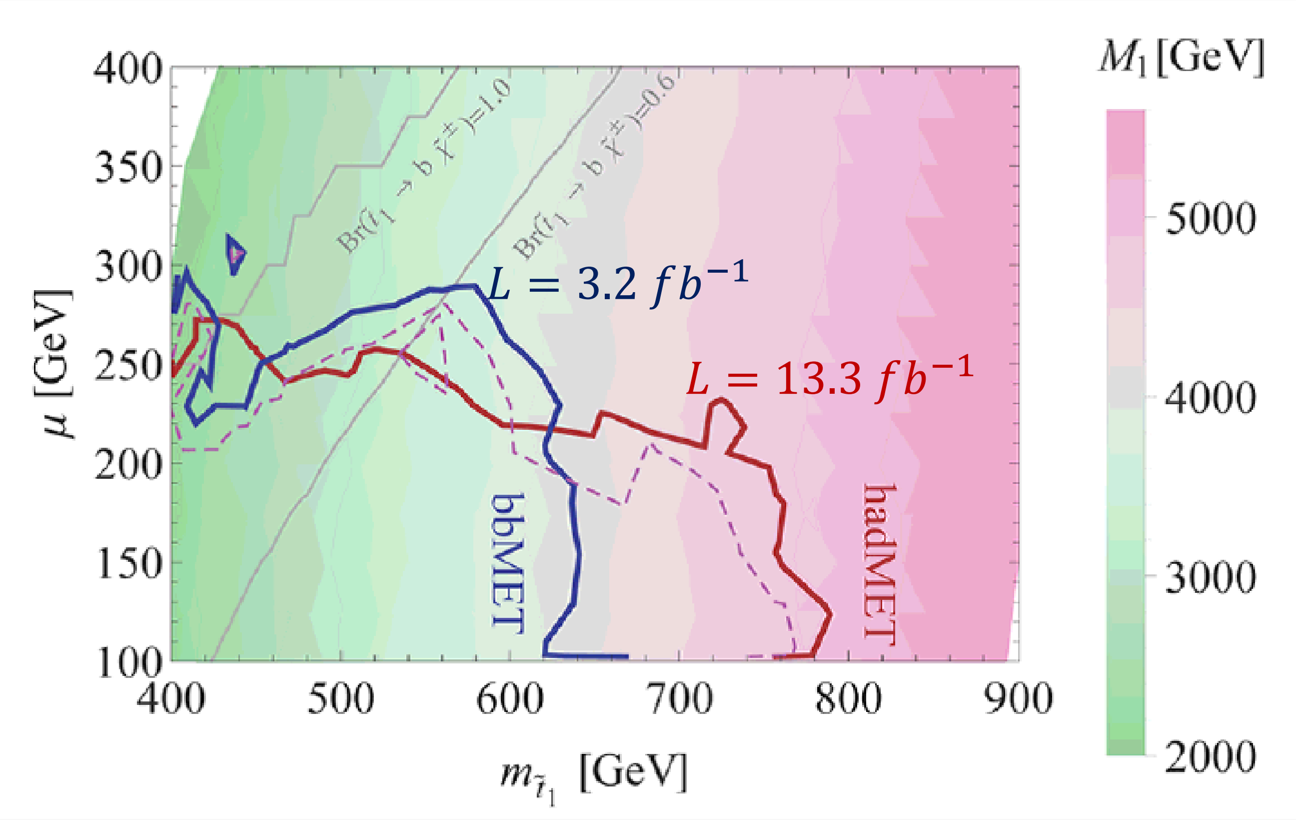


top squark search

- ✓ signals are tt (25%) / tb (50%) / bb (25%) + MET
- ✓ bb+MET channel[1] is sensitive to mass degenerate region
- ✓ had + 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

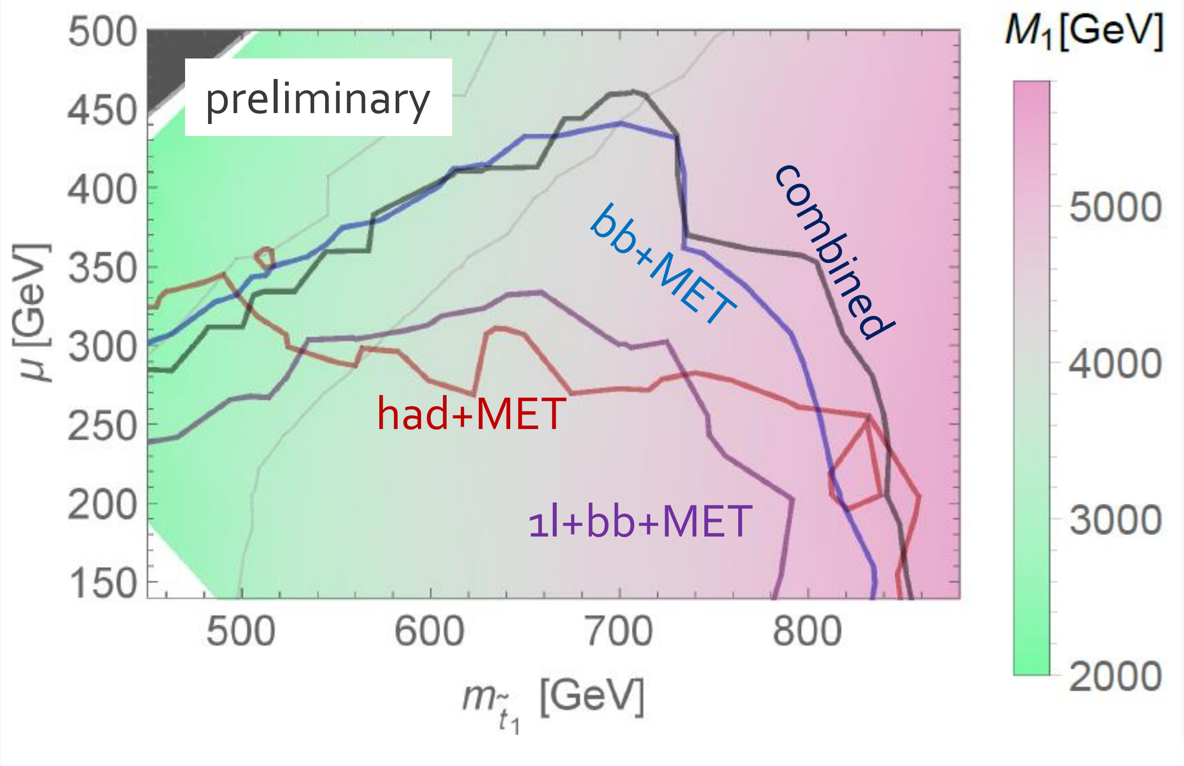
top squark search

- ✓ signals are tt (25%) / tb (50%) / bb (25%) + MET
- ✓ bb+MET channel[3] is sensitive to heavy higgsino region
- ✓ had + MET channel[4] is sensitive to light higgsino region

$L = 36.1\, fb^{-1}$

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

softsusy+sdecay+MG5
+pythia6+delphes3



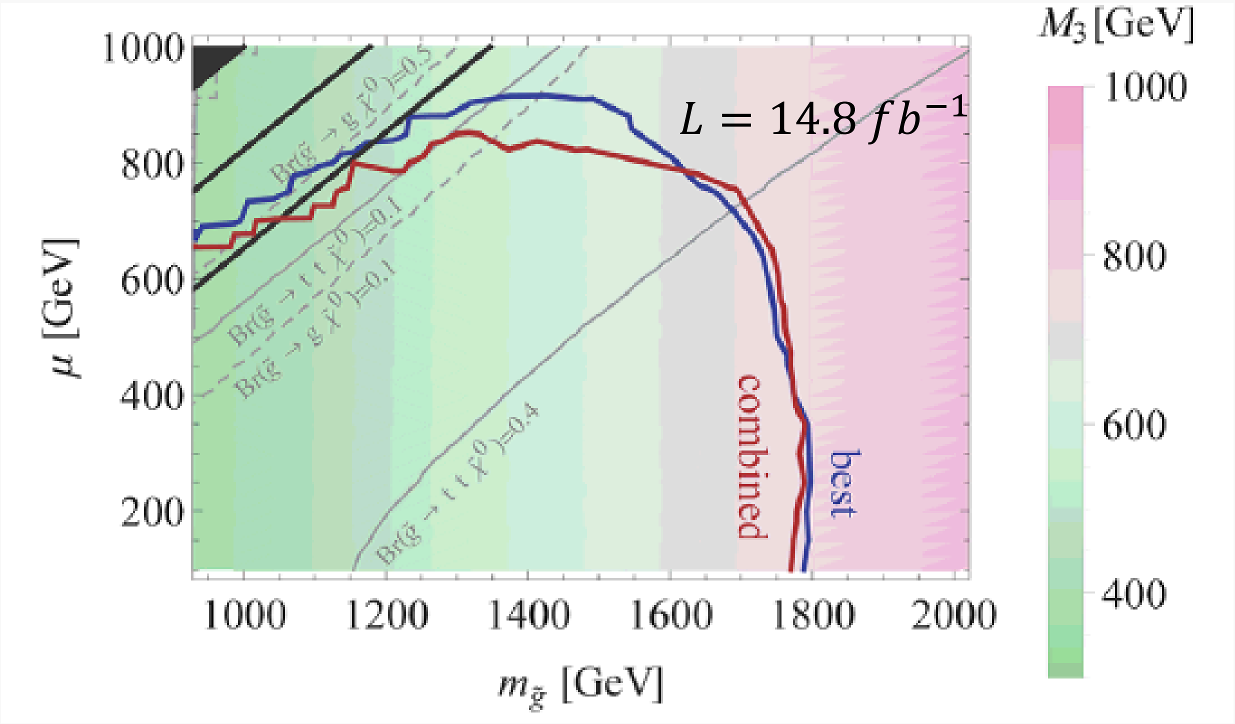
[3] ATLAS-CONF-2017-038 [4] ATLAS-CONF-2017-020

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 $4b$ + jets or lepton + MET
- ✓ 13TeV data [5] with 14.8 fb^{-1} cover $m_{\tilde{g}} \leq 1.8$ TeV for $\mu \leq 800$ GeV

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

softsusy+sdecay+MG5
+pythia6+delphes3



[5] ATLAS-CONF-2016-052

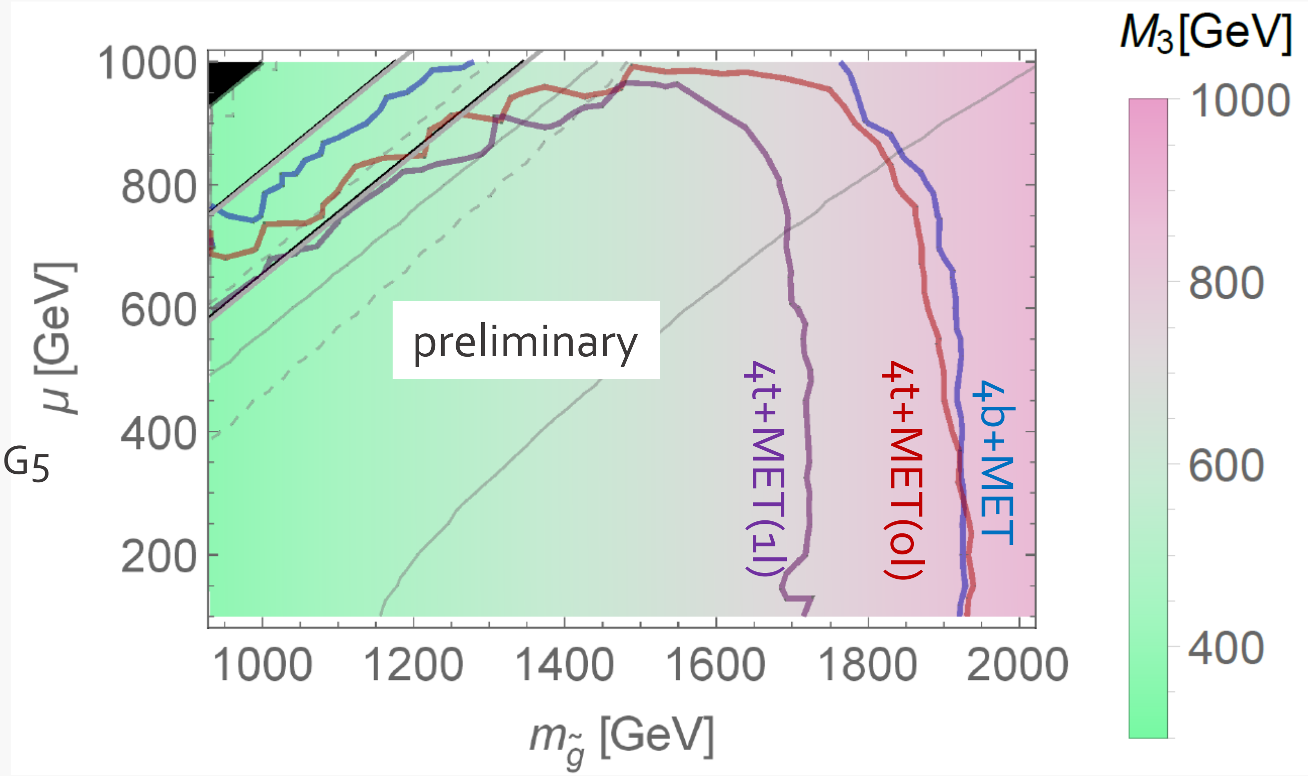
gluino search

- ✓ 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
- ✓ latest 13TeV data [6] cover $m_{\tilde{g}} \leq 1.9$ TeV for $\mu \leq 1000$ GeV

$L = 36.1\ fb^{-1}$

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

softsusy+sdecay+MG5
+pythia6+delphes3



[6] ATLAS-CONF-2017-021

Conclusion

- NUGM realize 125 GeV Higgs and small μ-parameter
- stop/gluino searches are important for NUGM scenario
- DM searches exclude wide region if DM is dominated by LSP
- heavy bino/wino help to avoid the direct detection constraints
- $m_{\tilde{t}_1} \lesssim 860$ GeV, $m_{\tilde{g}} \lesssim 1.9$ TeV are excluded by the 2017 data

backup

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

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

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

tuning of soft parameters

- degree of tuning $\Delta_a \equiv \left|\frac{d \ln m_Z^2}{d \ln a(\Lambda_{GUT})^2}\right|$

1. all parameters are independent

$$\Delta_1 = \max_a \Delta_a \qquad a \in \{M_1, M_2, M_3, m_0, A_0, \mu\}$$

2. gaugino mass ratio and scalar parameters ratio are fixed

$$\Delta_2 = \max_a \Delta_a \qquad a \in \{M_{1/2}, m_{scal},\ \mu\}$$

3. all ratios are fixed

$$\Delta_3 = \max_a \Delta_a \qquad a \in \{m_{SUSY},\ \mu\}$$

Remark: $\sum_a \Delta_a = 1$ at tree level $\rightarrow$ $\Delta_3 \sim \Delta_{m_{SUSY}} \sim \Delta_\mu$

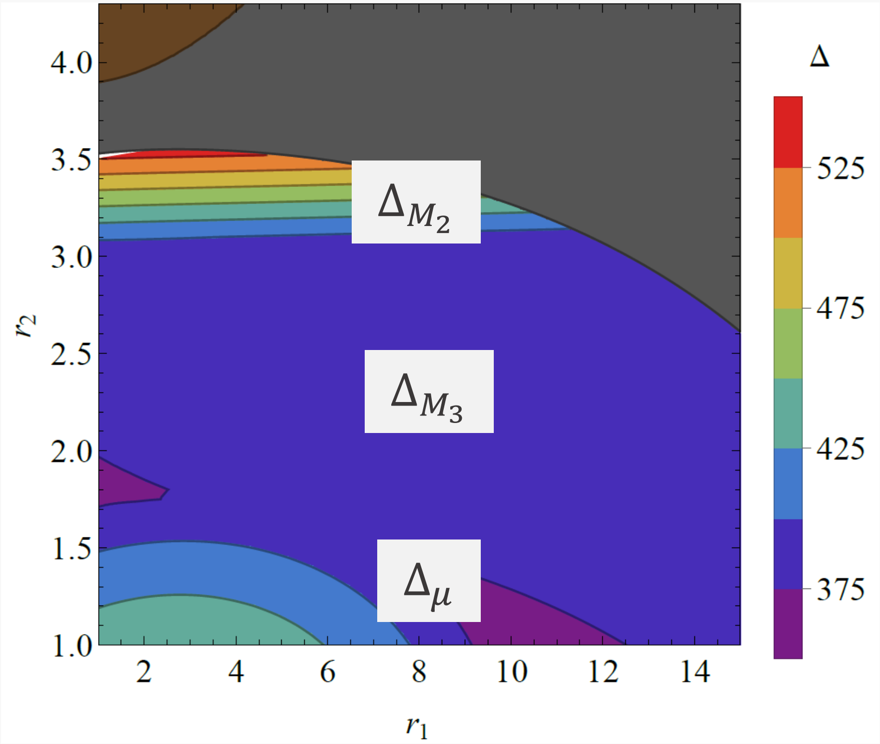
tuning of soft parameters

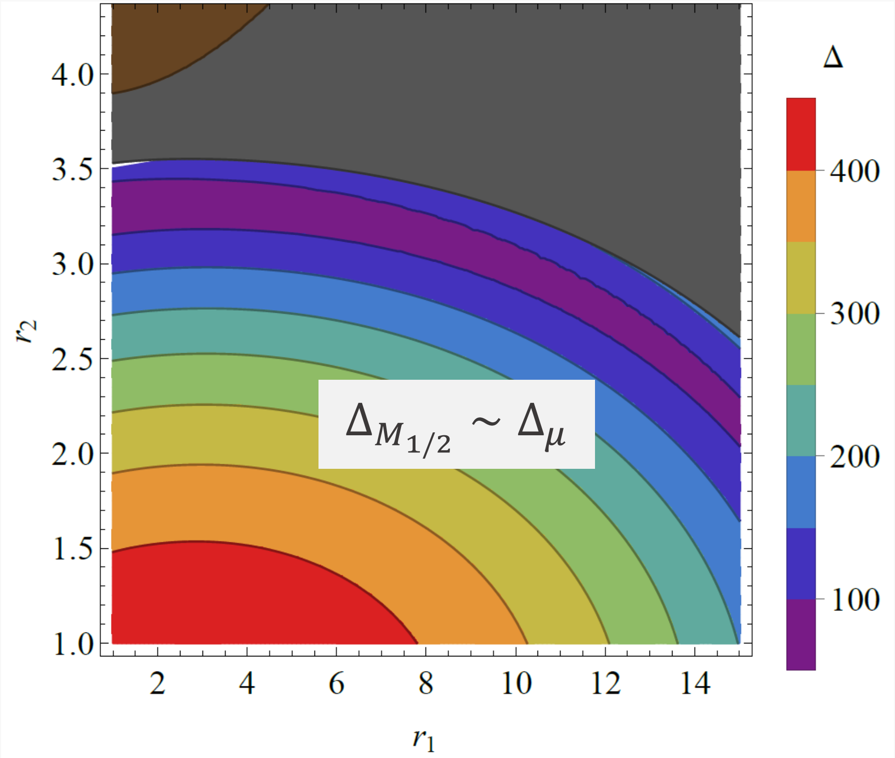
$M_3 = m_0 = -A_0 = 1.0$ TeV

1-loop RGE +
1-loop EWSB

$\Delta_1 = \max_a \Delta_a \quad a \in \{M_1, M_2, M_3, m_0, A_0, \mu\}$

$\Delta_2 = \max_a \Delta_a \quad a \in \{M_{1/2}, m_{scal}, \mu\}$



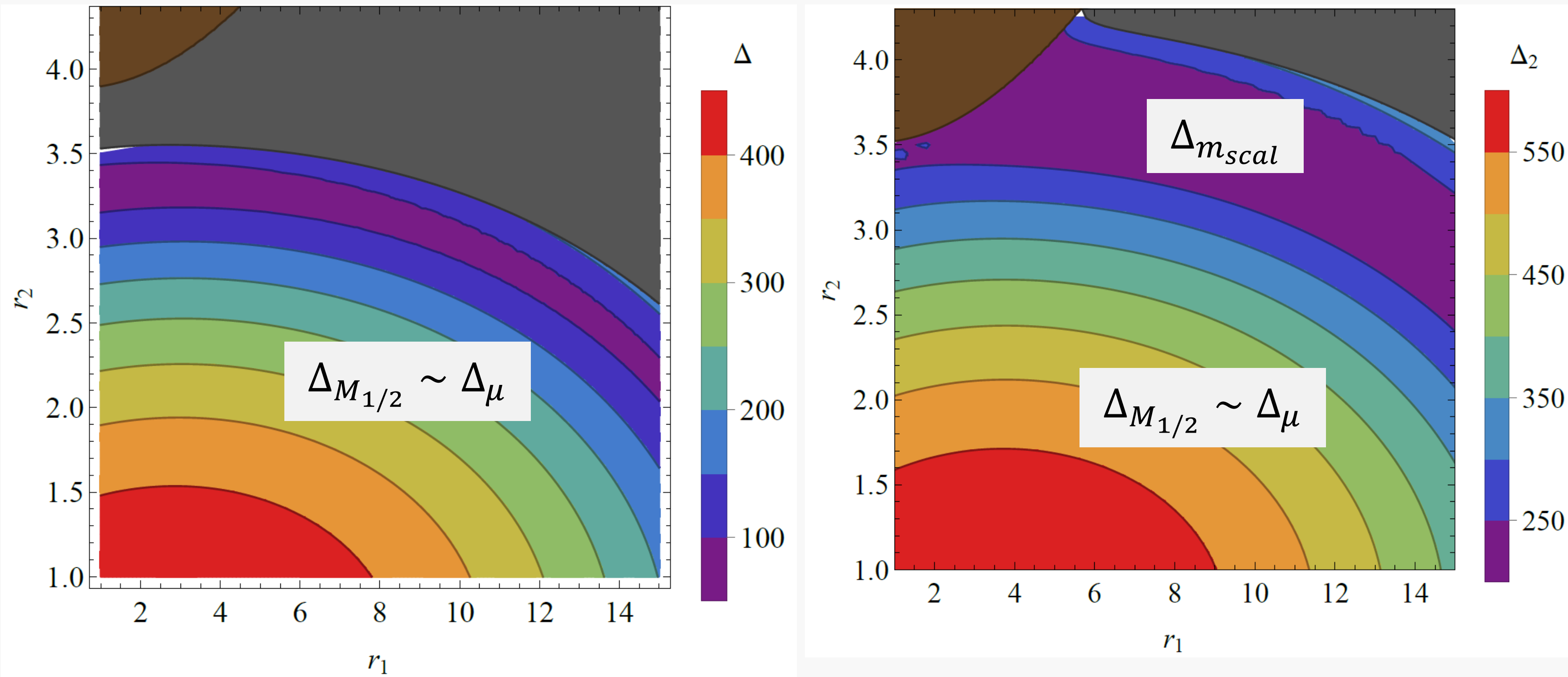


Δ_2 can be small if $r_2 \sim 3.2$

tuning of A-term

$M_3 = m_0 = 1.0\,\text{TeV} \quad \Delta_2 = \max_a \Delta_a \quad a \in \{M_{1/2}, m_{scal},\ \mu\}$

$A_0 = -1.0\,\text{TeV}$ $\qquad$ $A_0 = -2.0\,\text{TeV}$

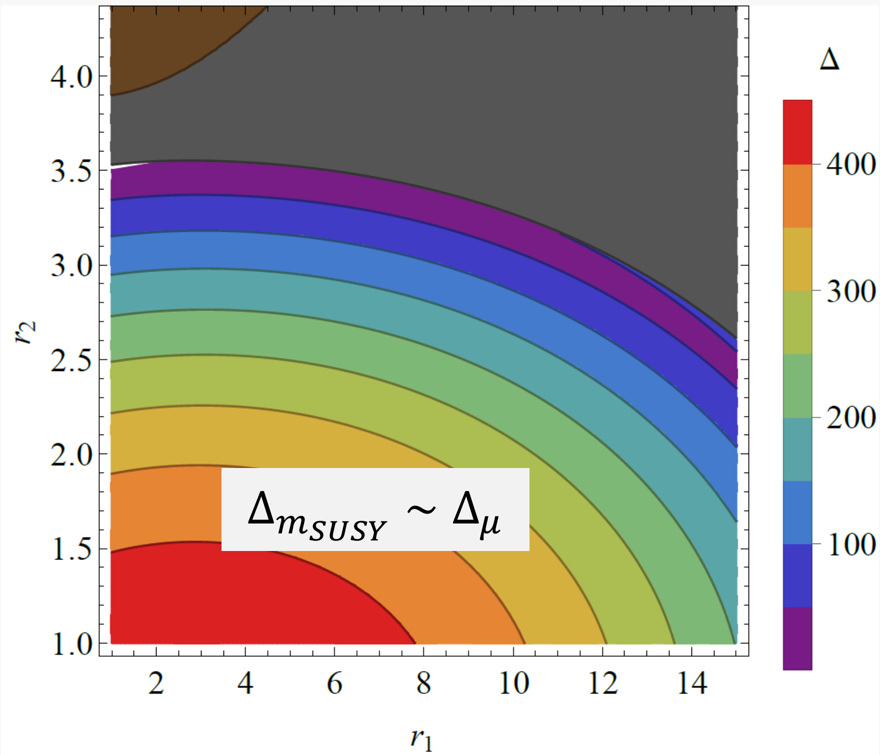


Δ_2 can not be small if $A_0 = -2.0\,\text{TeV}$

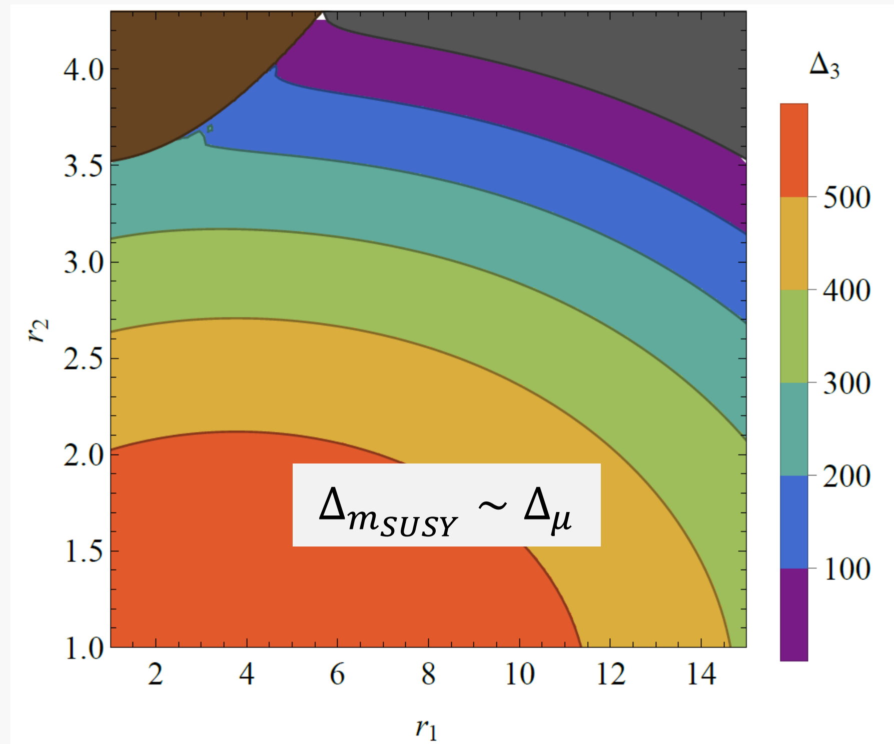
tuning of soft parameters

$M_3 = m_0 = 1.0\,\mathrm{TeV}$ $\Delta_3 = \max_a \Delta_a \quad a \in \{m_{SUSY},\ \mu\}$

$A_0 = -1.0\,\mathrm{TeV}$



$A_0 = -2.0\,\mathrm{TeV}$



Δ_3 can be small in both cases

parameter settings

parameters

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

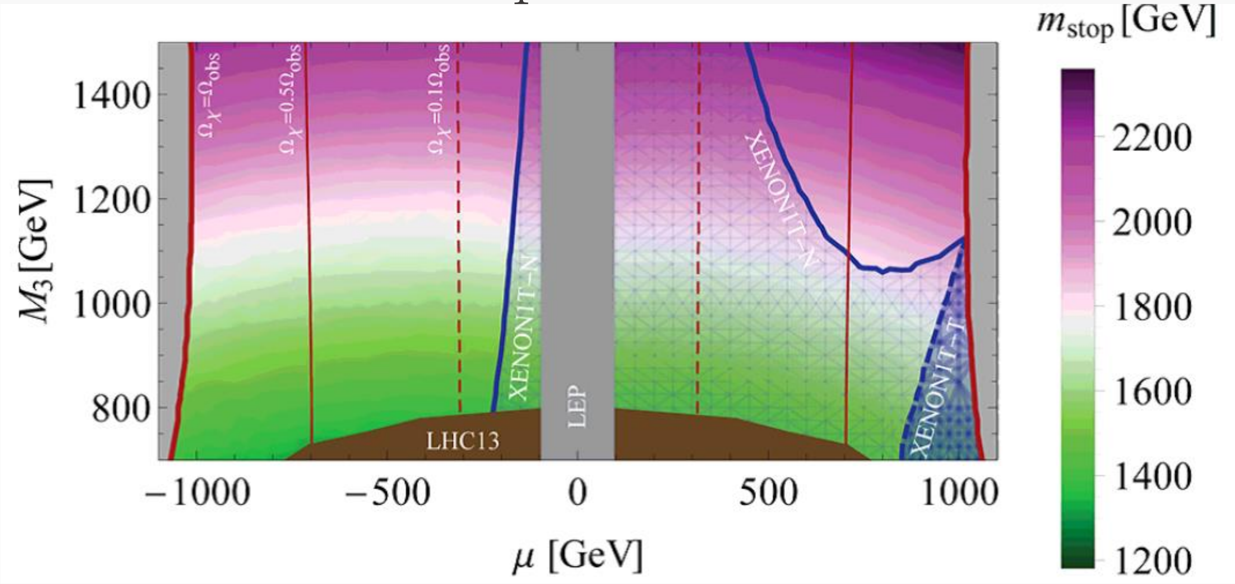
constraints

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

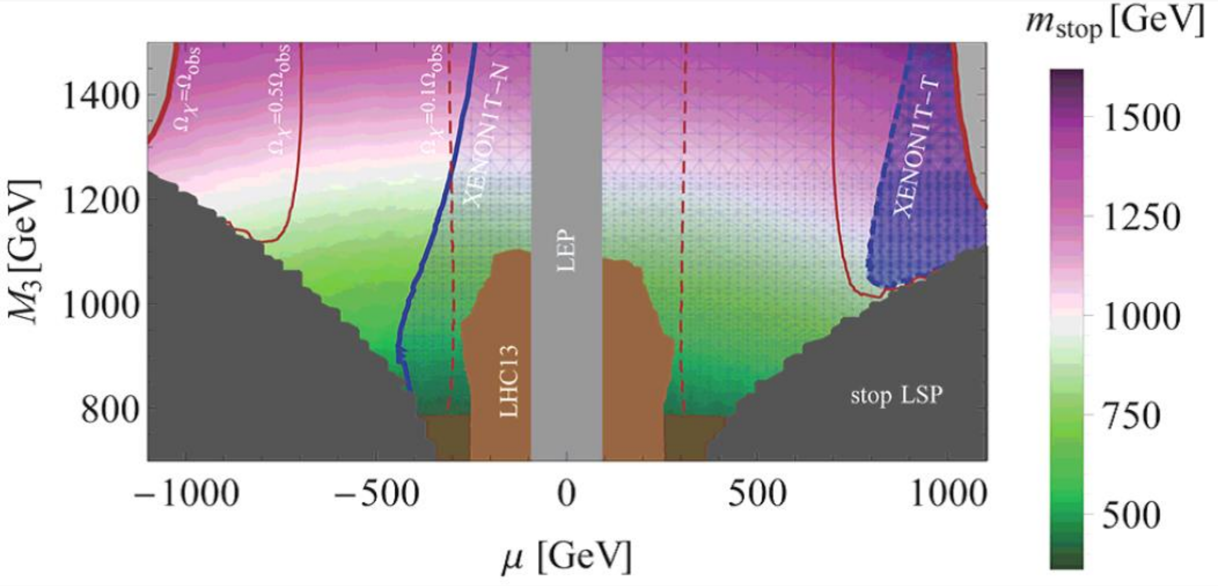
strategy

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

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



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



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}
$\langle\sigma v\rangle_0 \times 10^{25}[\mathrm{cm}^3/\mathrm{s}]$	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
$\sigma_{\mathrm{SD}} \times 10^{-6}[\mathrm{pb}]$	1.096	1.138	0.1677	0.1757
$\sigma_{\mathrm{SI}} \times 10^{-11}[\mathrm{pb}]$	3.499	8.505	8.918	22.37
$\sigma_{\mathrm{SI}}^h \times 10^{-11}[\mathrm{pb}]$	3.302	7.793	7.853	19.50