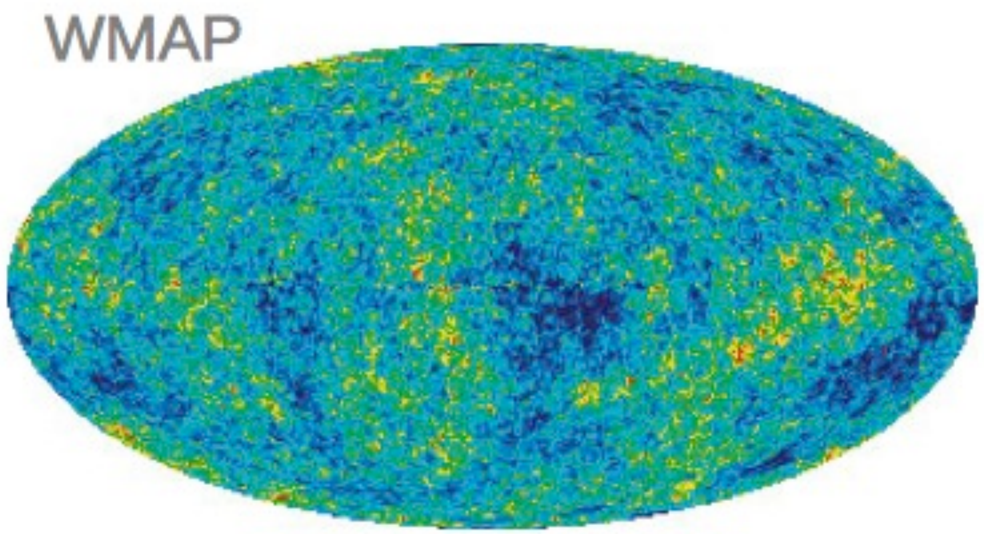
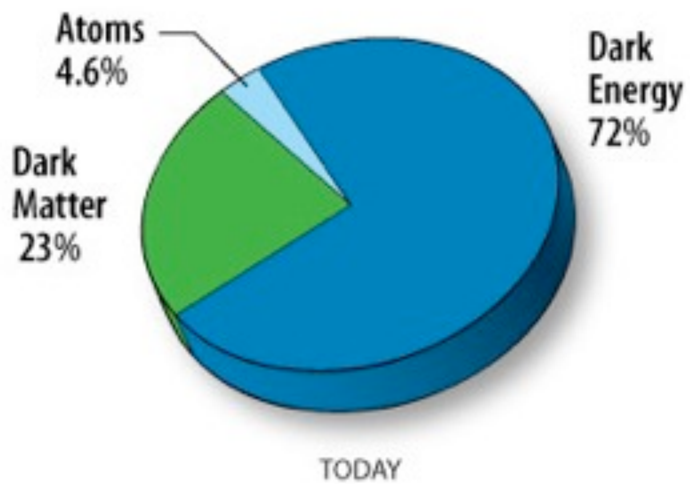
Supersymmetric Dark Matter

Pearl Sandick
University of Utah





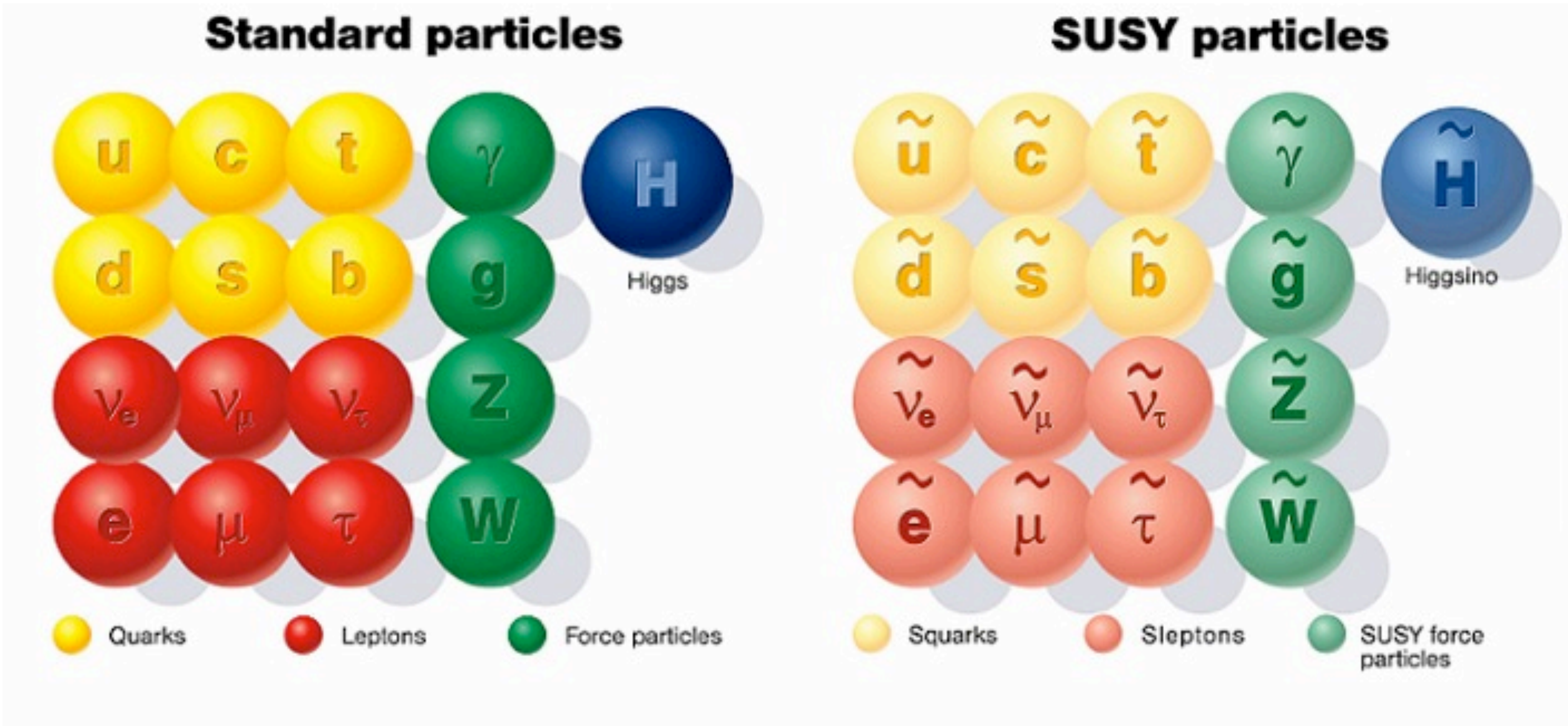
- The Standard Model contains no viable explanation for dark matter.
- Dark matter does not have to be a supersymmetric particle... BUT IT MIGHT BE.
- ~46,000 papers. Let's remember why.

Why Study SUSY

- Aesthetically pleasing extension
- Stabilizes the Higgs v.e.v. (Hierarchy Problem)
- Gauge coupling unification
- Predicts a light Higgs boson

Why Study SUSY

- Aesthetically pleasing extension



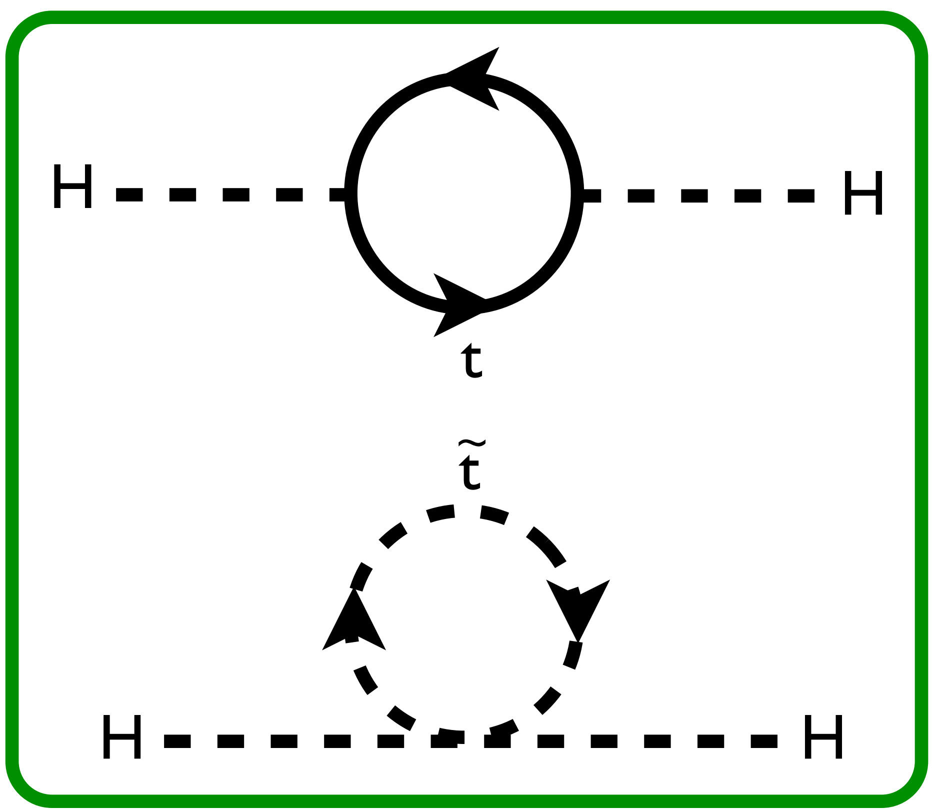
Supersymmetry is the only non-trivial extension of the space-time symmetries in a consistent 4-dimensional QFT.

Why Study SUSY

- Aesthetically pleasing extension
- Stabilizes the Higgs v.e.v. (Hierarchy Problem)

SM:

SUSY:

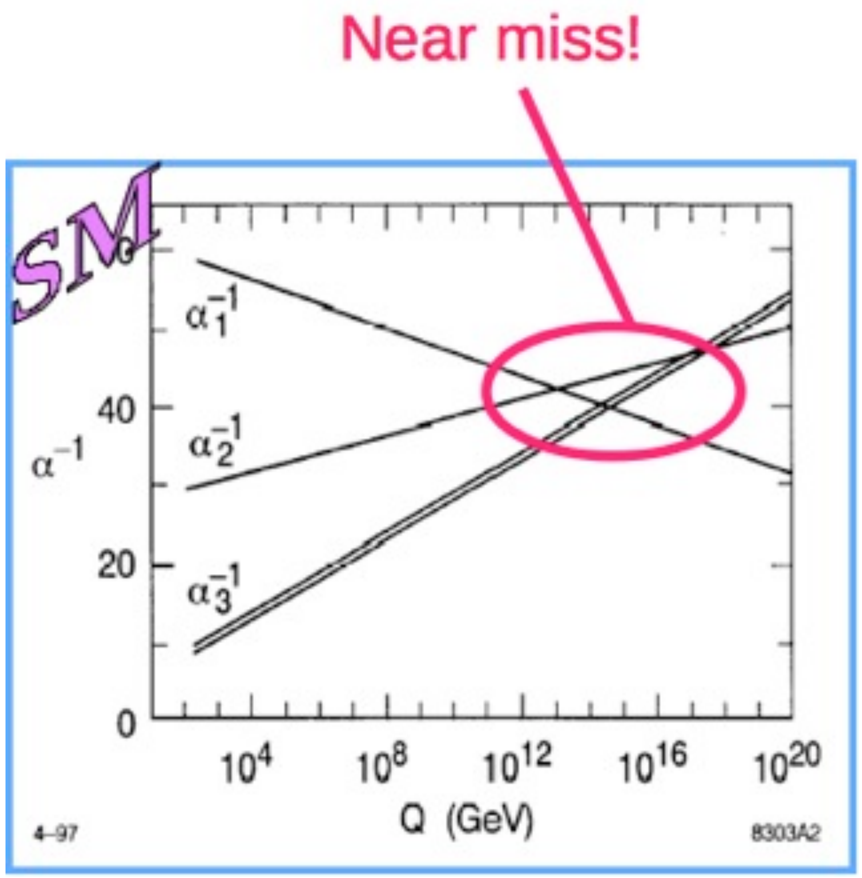


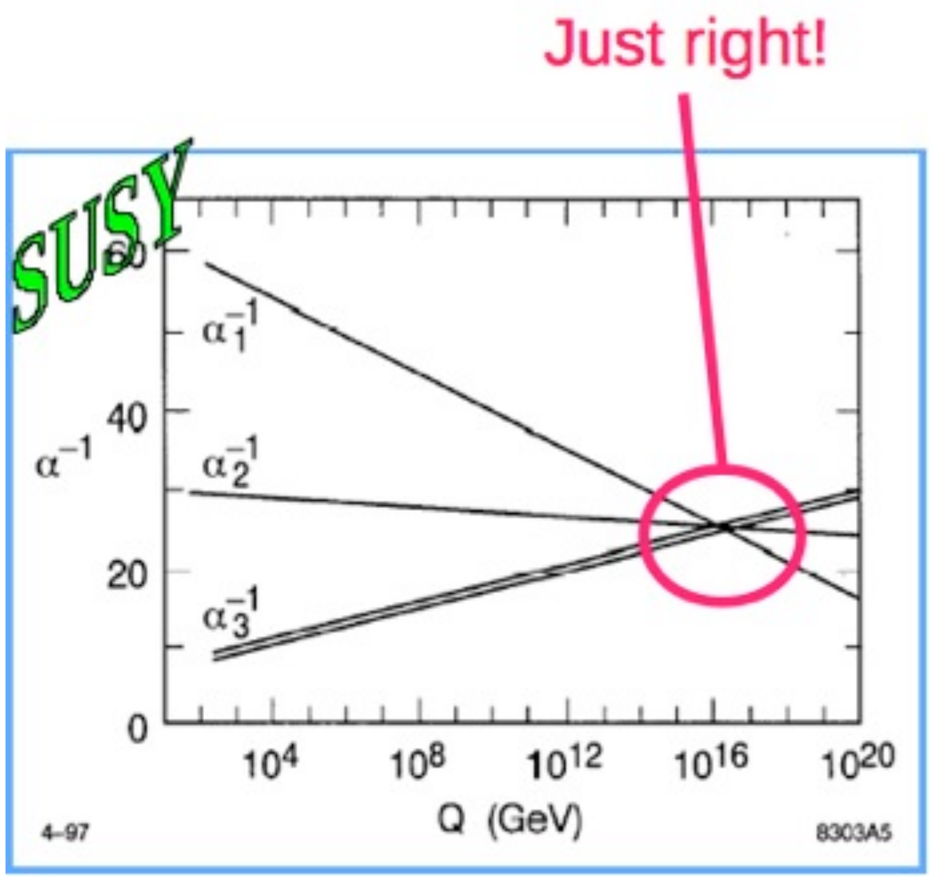
$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\left(m_{\tilde{f}}^2 - m_f^2\right)\ln\left(\Lambda/m_{\tilde{f}}\right) + \ldots$$

SUSY maintains the hierarchy of mass scales.

Why Study SUSY

- Aesthetically pleasing extension
- Stabilizes the Higgs v.e.v. (Hierarchy Problem)
- Gauge coupling unification





Why Study SUSY

- Aesthetically pleasing extension
- Stabilizes the Higgs v.e.v. (Hierarchy Problem)
- Gauge coupling unification
- Predicts a light Higgs boson

Tree level: $m_h < m_Z \cos(2\beta)$

$105\ \text{GeV} \lesssim m_h \lesssim 130\ \text{GeV}$

LHC: $m_h = 125$ GeV ??

The MSSM

Slightly BMSSM

	particle	spin
axion	a	0
saxion	s	0
axino	$\tilde{a}$	1/2
graviton	G	2
gravitino	$\tilde{G}$	3/2

particle	sparticle	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_i$	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_i$	3	2	$\frac{1}{6}$
u_i^c	$\tilde{u}_i^c$	$\bar{3}$	1	$-\frac{2}{3}$
d_i^c	$\tilde{d}_i^c$	$\bar{3}$	1	$\frac{1}{3}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_i$	$\begin{pmatrix} \tilde{\nu} \\ \tilde{e} \end{pmatrix}_i$	1	2	$-\frac{1}{2}$
e_i^c	$\tilde{e}_i^c$	1	1	1
W	$\tilde{W}$	1	3	0
g	$\tilde{g}$	8	1	0
B	$\tilde{B}$	1	1	0
$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$	1	2	$\frac{1}{2}$
$\begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$	1	2	$-\frac{1}{2}$

quarks and squarks

leptons and sleptons

W boson and wino

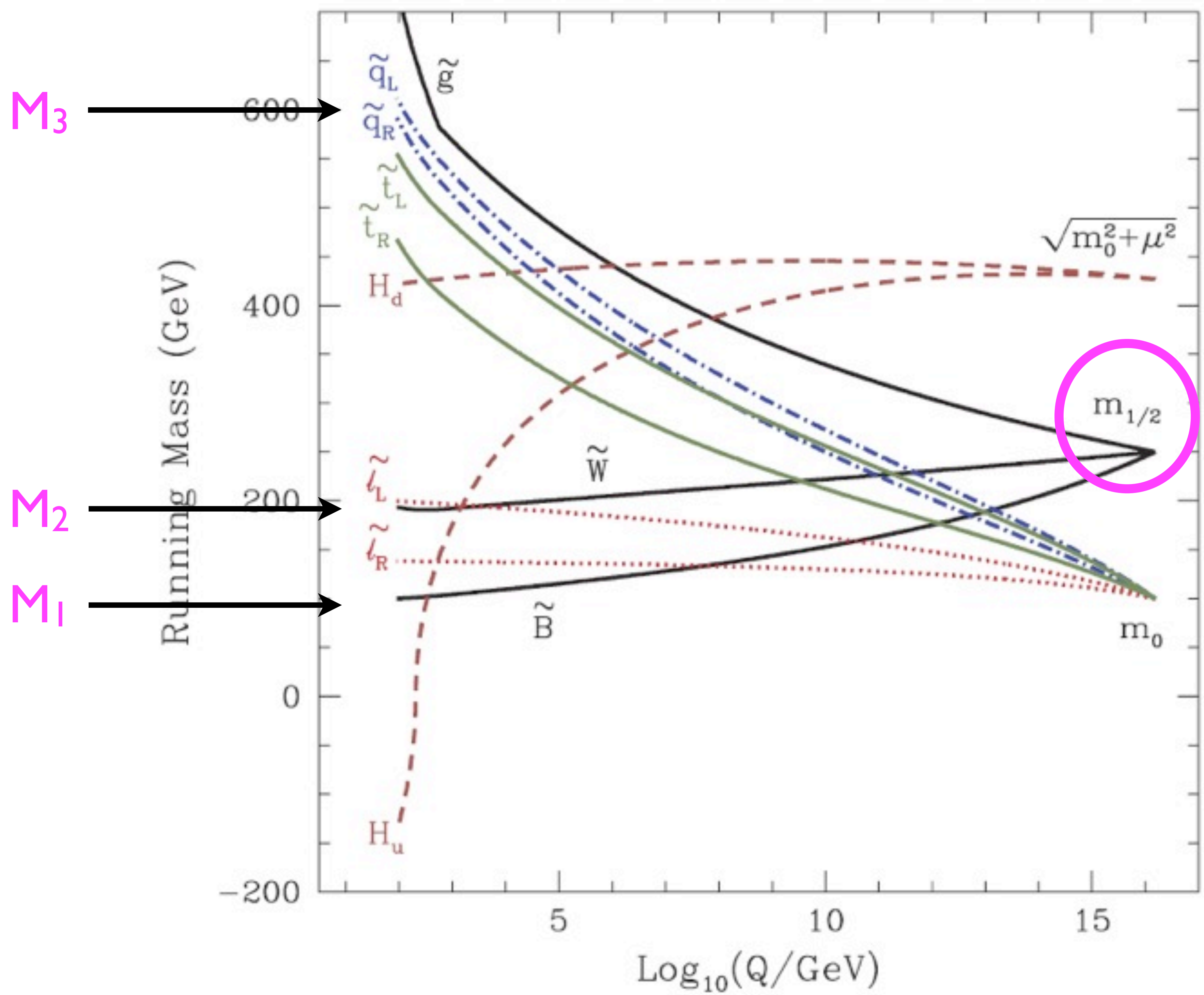
gluon and gluino

B boson and bino

Higgs bosons and higgsinos

neutralinos

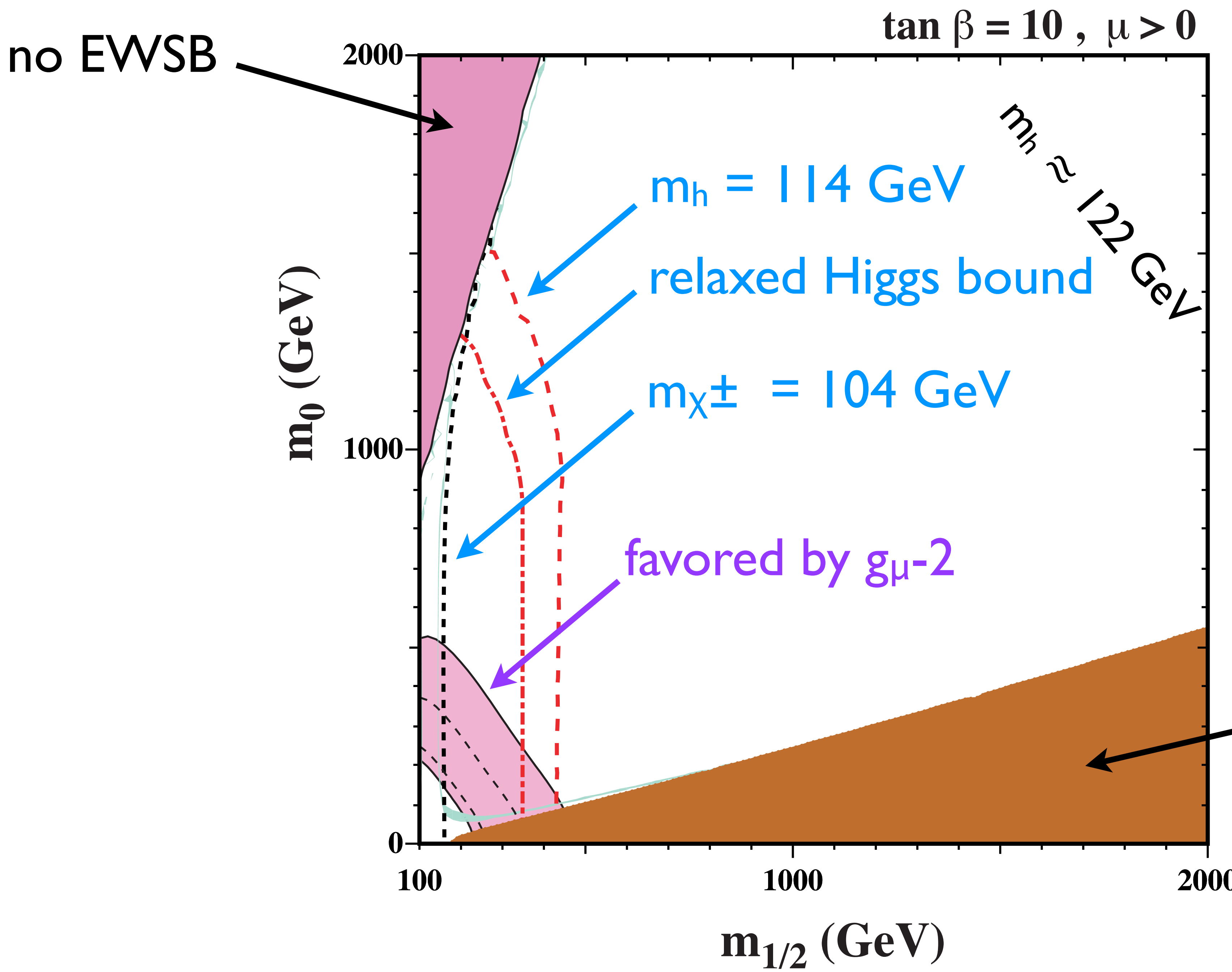
SUSY Breaking (pheno.)



Constraints

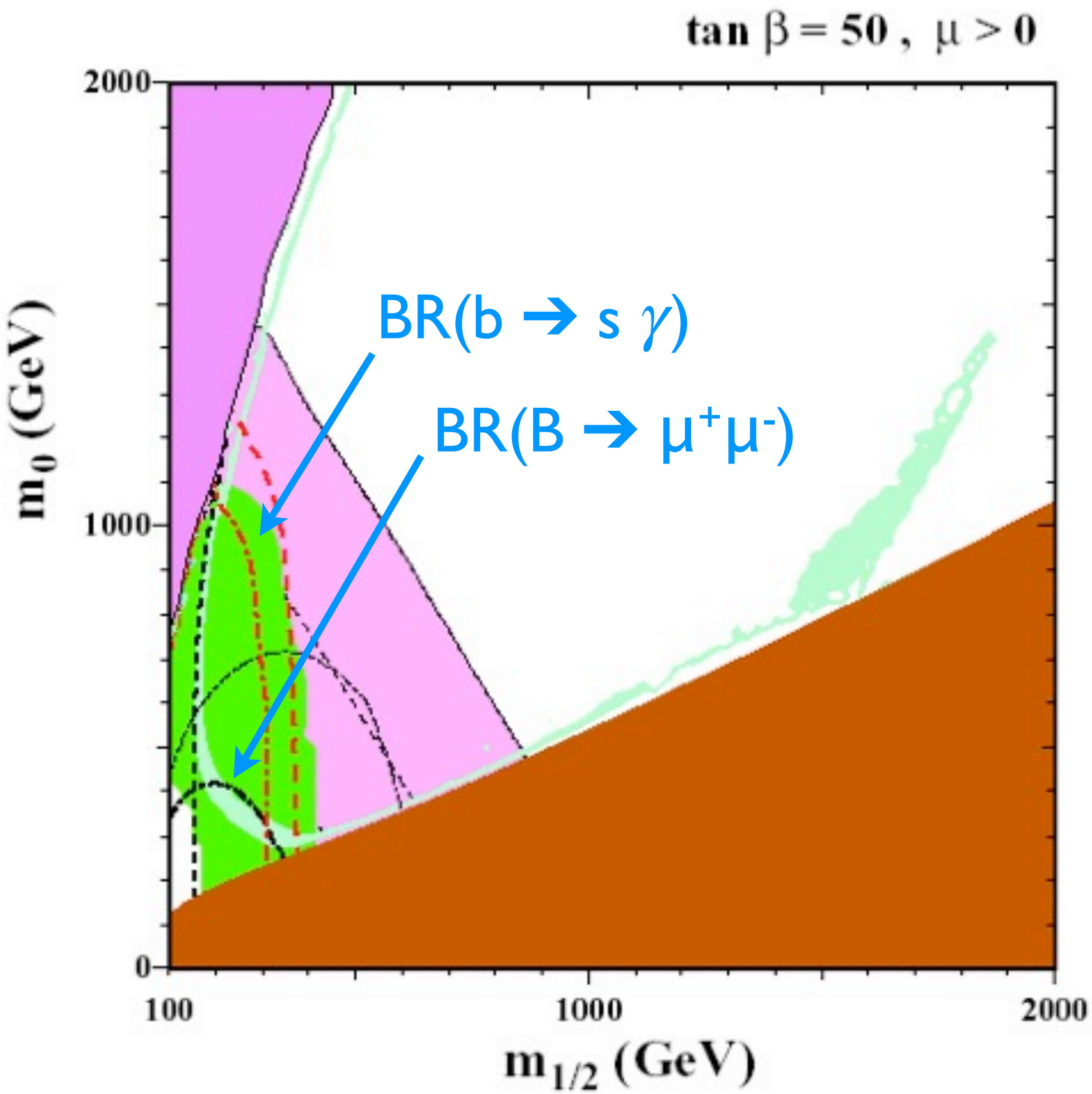
- Higgs mass
- Chargino mass > 104 GeV
- Stop and stau masses > 100 GeV
- BR($b \to s\gamma$)
- BR($B_s \to \mu^+\mu^-$)
- g_μ-2
- Dark matter abundance

CMSSM



Ellis, Olive, Sandick (2007)

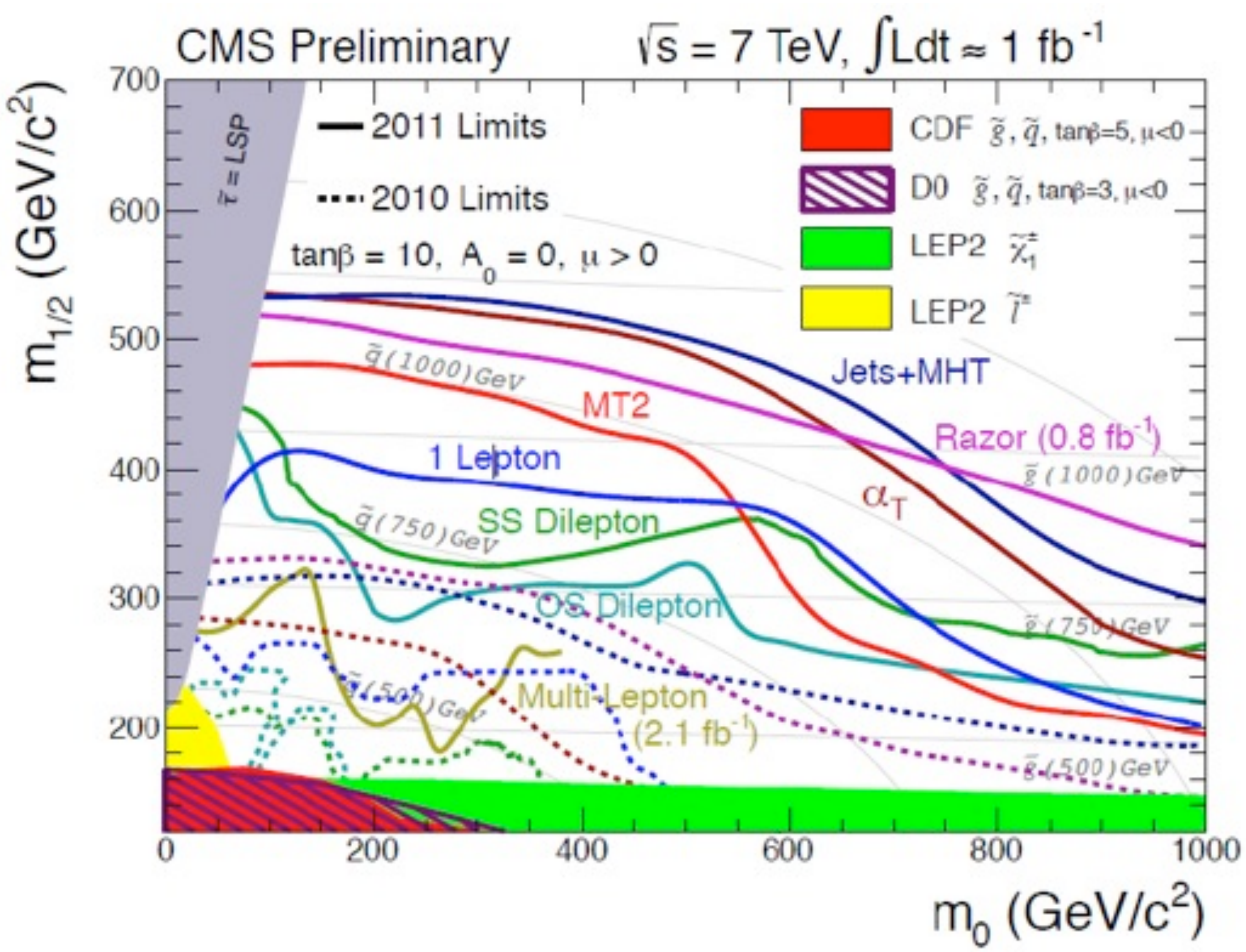
CMSSM



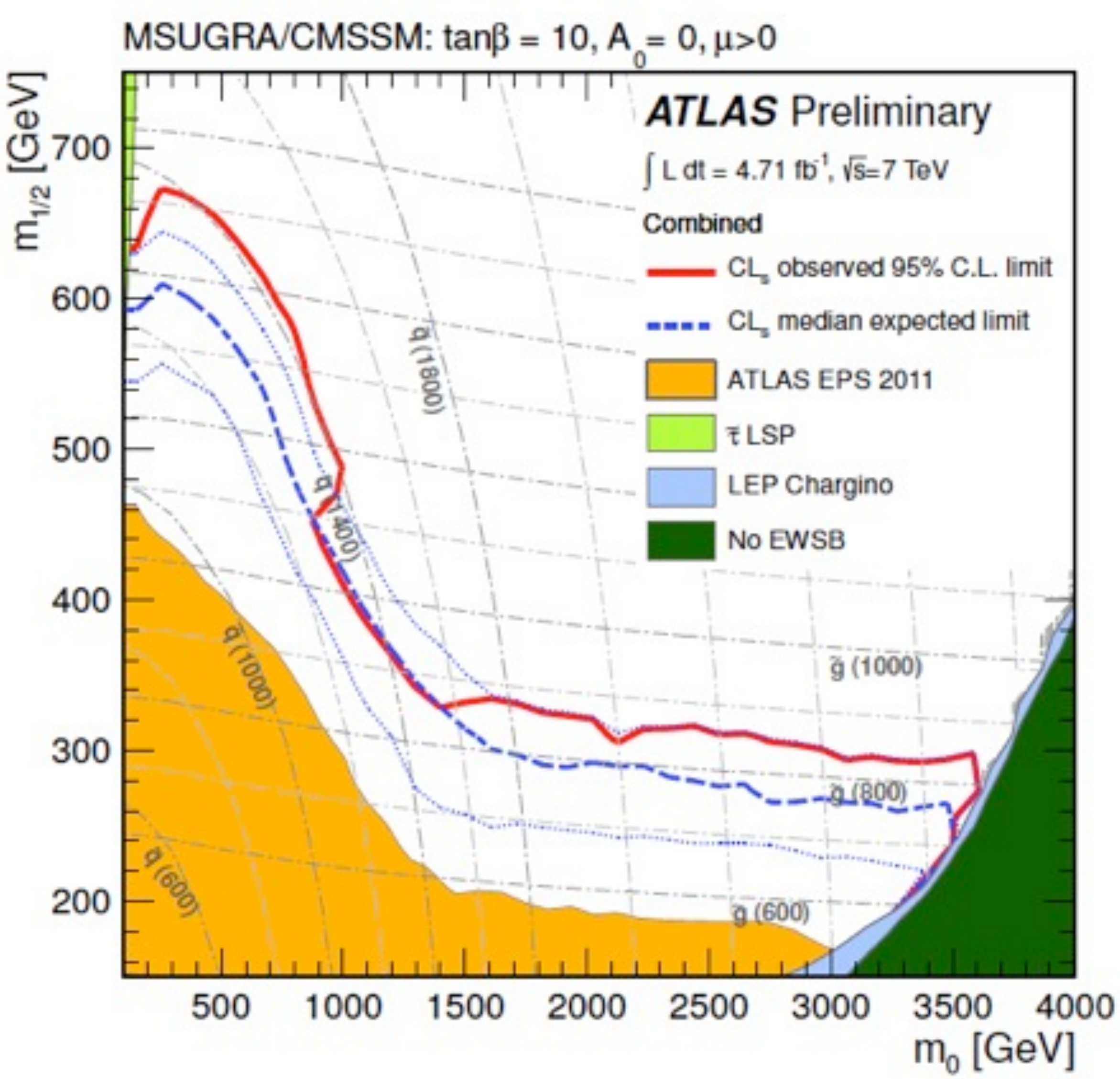
Ellis, Olive, Sandick (2007)

A note on LHC constraints

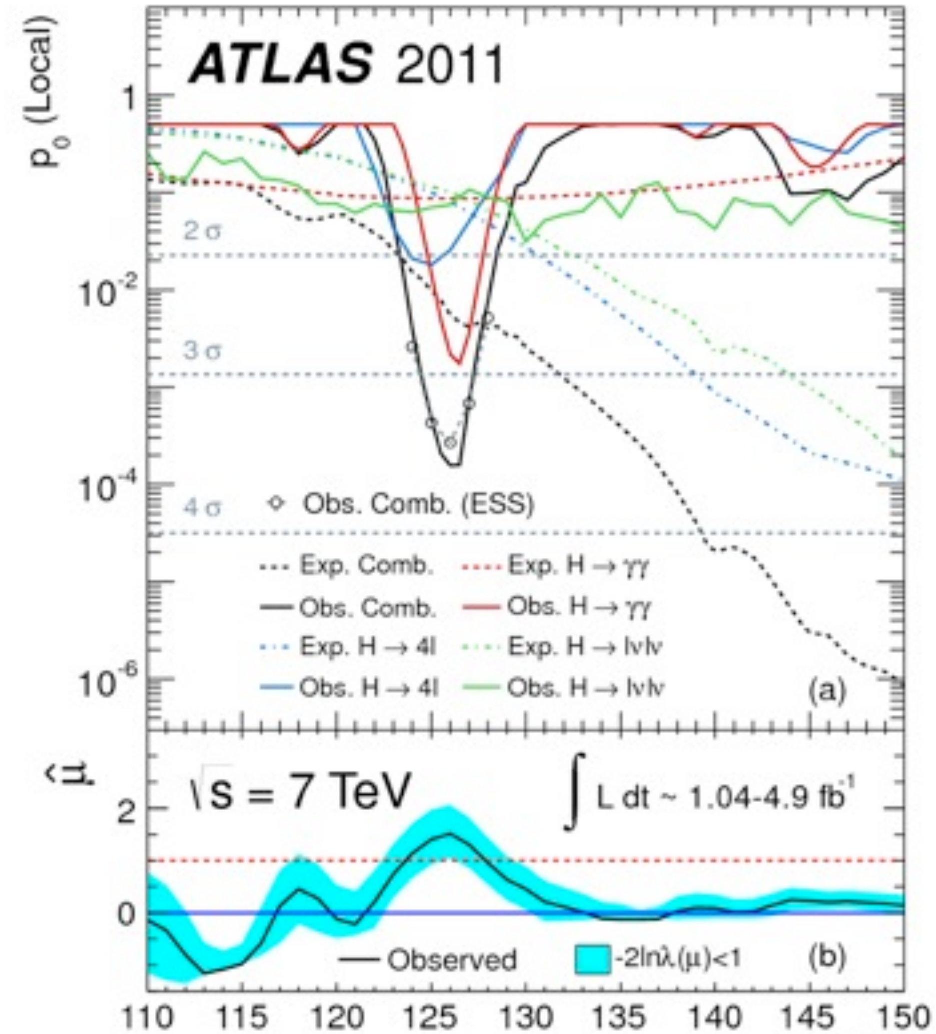
T. Dorigo for CMS (2012)

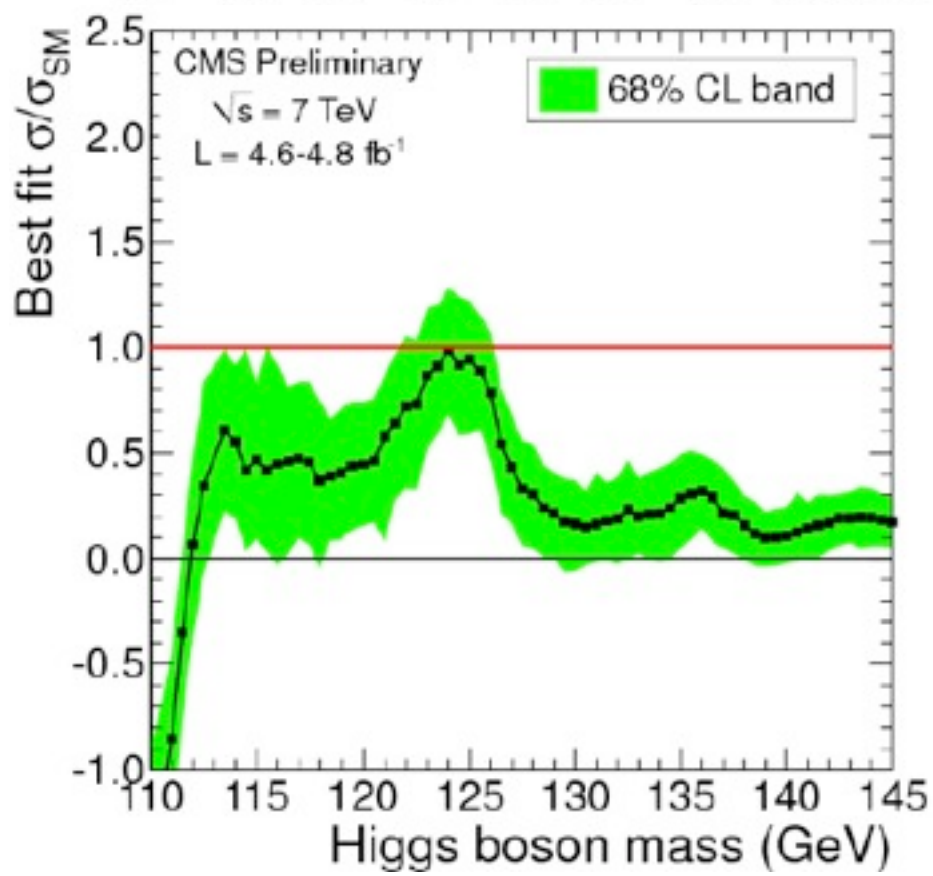


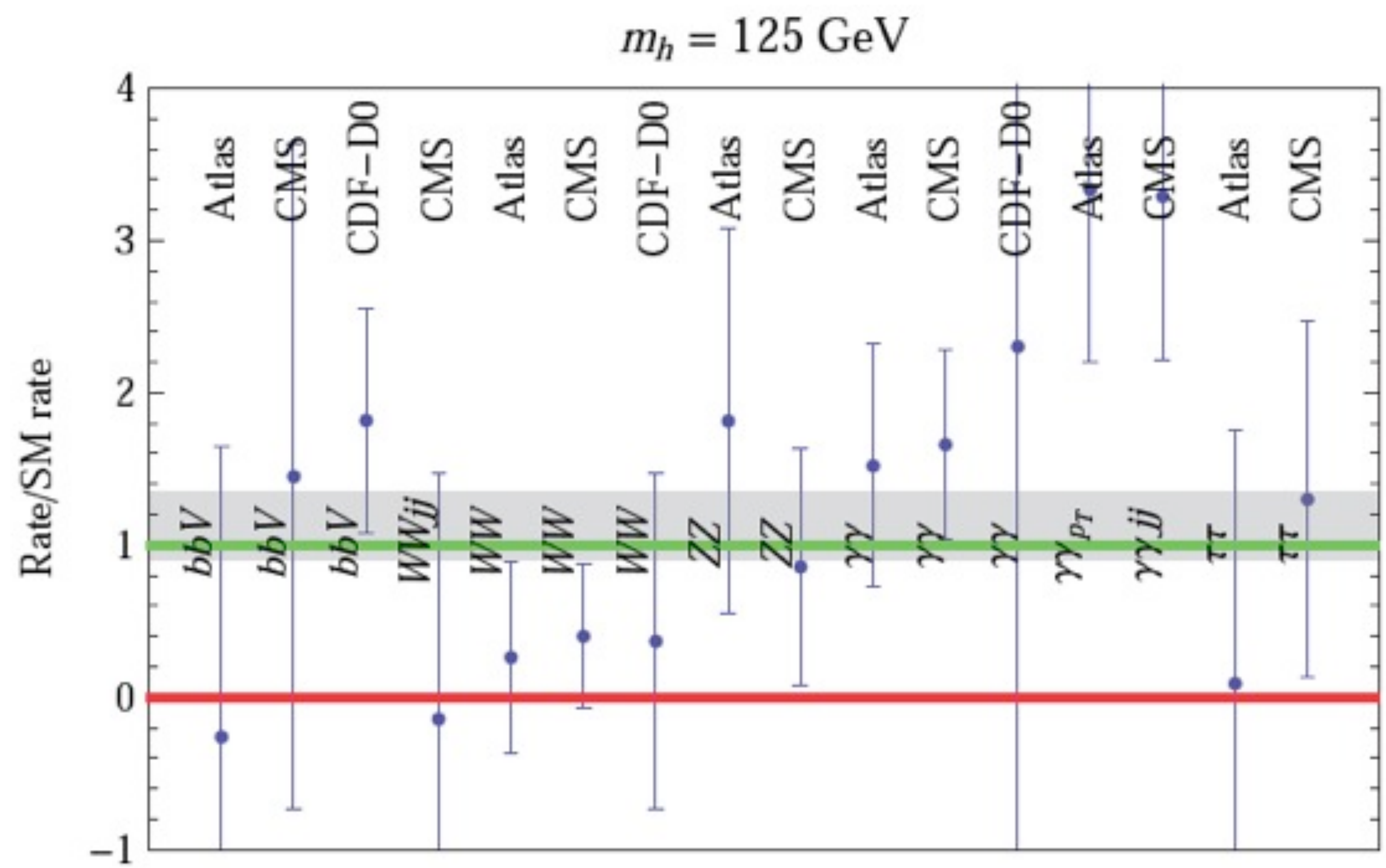
ATLAS-CONF-2012-033



Higgs at LHC?



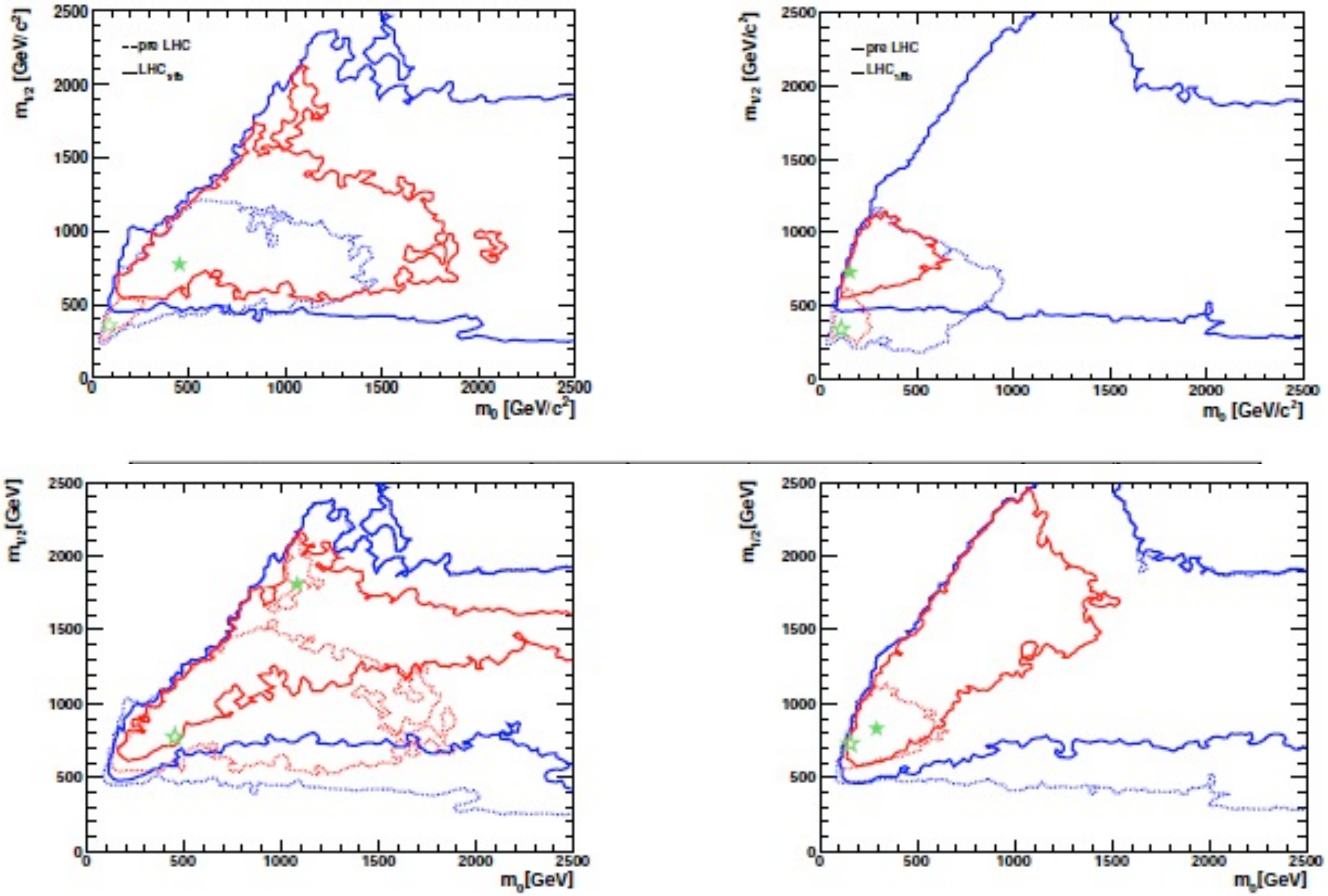




Giardino et al. (2012)

A note on LHC constraints

CMSSM NUHM1

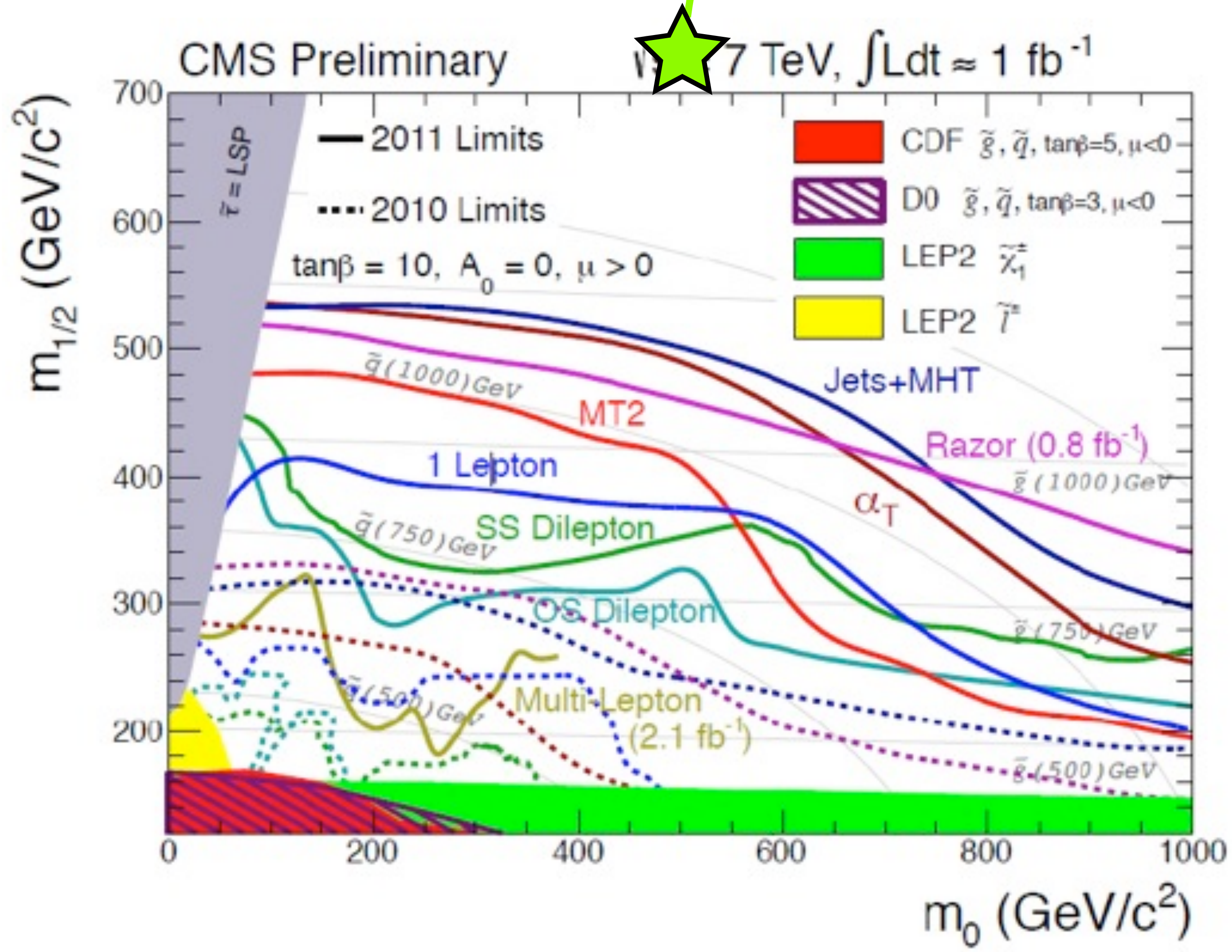


Buchmueller et al. (2012a,b)

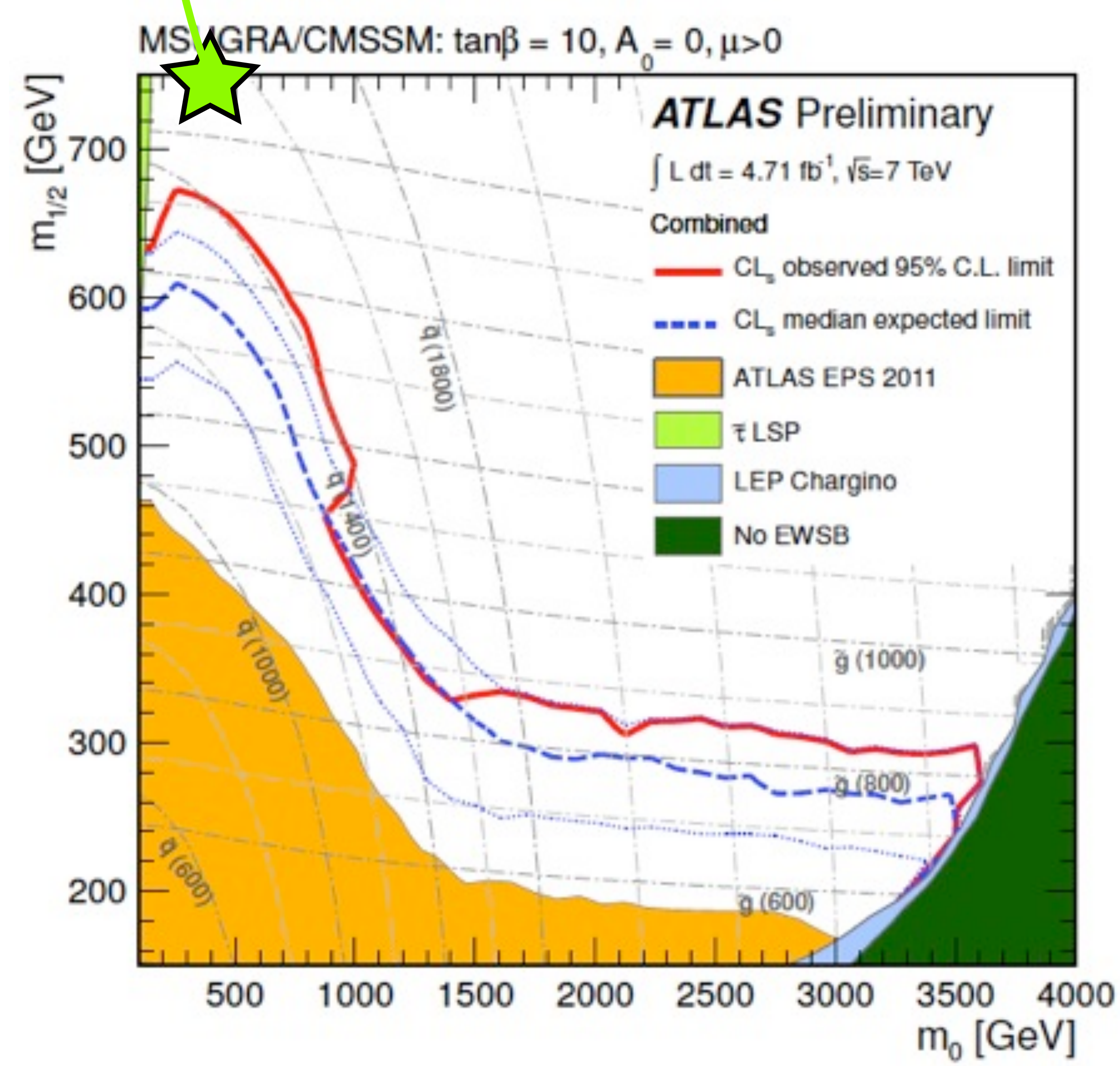
$(g-2)_\mu$ neglected	20.3/19	38%	2020^+_-	1410^+_-	2580^+_-	48^+_-	$126.6^{+0.7}_{-1.9}$
Both	19.5/19	43%	2020^+_-	1410^+_-	2580^+_-	48^+_-	$126.6^{+0.7}_{-1.9}$

A note on LHC constraints

T. Dorigo for CMS (2012)



ATLAS-CONF-2012-033



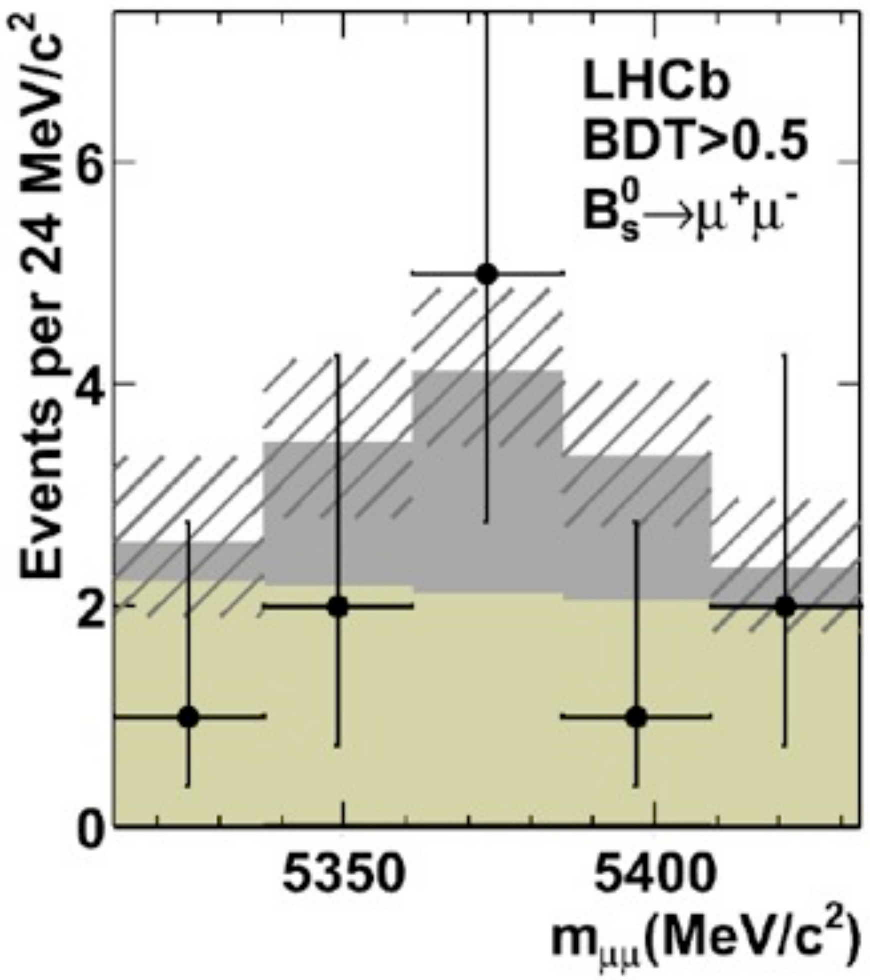
BR($B_s \rightarrow \mu^+\mu^-$)

- LHCb progress
- Current 95% CL limit:

$$BR(B_s^0 \rightarrow \mu^+\mu^-) < 4.5 \times 10^{-9}$$

Koji Ishiwata's talk on Wednesday

PRL (2012)



Back to Dark Matter

SUSY & Dark Matter

- Lightest Supersymmetric Particle (LSP)
- Stability: Conservation of R-Parity

Theory	Z_2 Parity	Dark Matter
SUSY	R-parity	LSP
UED	KK-parity	LKP
Little Higgs	T-parity	LTP

Why conserve R-parity?
Stability of proton
Neutron-antineutron oscillations
Neutrino mass

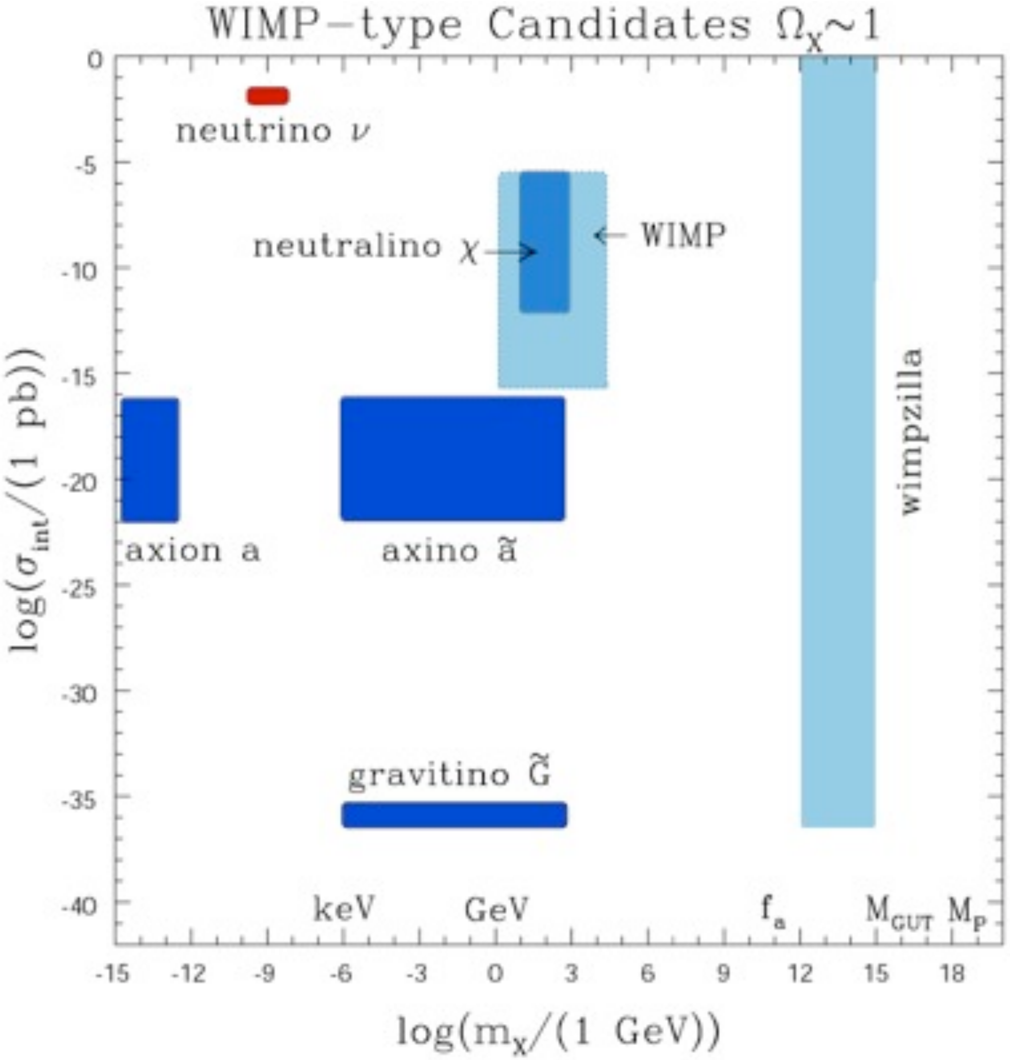
Ad hoc?
SO(10) GUTs
B and L numbers become
accidental symmetries of SUSY

SUSY DM Candidates

- neutralinos (our favorite WIMPs)
  - H. Goldberg, Phys. Rev. Lett. 50, 1419 (1983); J. Ellis, J. Hagelin, D.V. Nanopoulos, K. Olive, and M. Srednicki, Nucl. Phys. B 238, 453 (1984), etc.
- sneutrinos (also WIMPs)
  - T. Falk, K. A. Olive and M. Srednicki, Phys. Lett. B 339 (1994) 238; T. Asaka, K. Ishiwata, and T. Moroi, Phys. Rev. D 73, 051301 (2006); 75, 065001 (2007); F. Deppisch and A. Pilaftsis, J. High Energy Phys. 10 (2008) 080; J. McDonald, J. Cosmol. Astropart. Phys. 01 (2007) 001; H. S. Lee, K. T. Matchev, and S. Nasri, Phys. Rev. D 76, 041302 (2007); D. G. Cerdeno, C. Munoz, and O. Seto, Phys. Rev. D 79, 023510 (2009); D. G. Cerdeno and O. Seto, J. Cosmol. Astropart. Phys. 08 (2009) 032; etc.
- gravitinos (SuperWIMPs)
  - J.L. Feng, A. Rajaraman and F. Takayama, Phys. Rev. Lett. 91, 011302 (2003) [hep-ph/0302215], Phys. Rev. D 68, 063504 (2003) [hep-ph/0306024]; J.R. Ellis, K.A. Olive, Y. Santoso and V.C. Spanos, Phys. Lett. B 588, 7 (2004) [hep-ph/0312262]; J.L. Feng, S.f. Su and F. Takayama, Phys. Rev. D 70, 063514 (2004) [hep-ph/0404198]; etc.
- axinos (SuperWIMPs)
  - T. Goto and M. Yamaguchi, Phys. Lett. B 276, 103 (1992); L. Covi, H.B. Kim, J.E. Kim and L. Roszkowski, JHEP 0105, 033 (2001) [hep-ph/0101009]; L. Covi, L. Roszkowski, R. Ruiz de Austri and M. Small, JHEP 0406, 003 (2004) [hep-ph/0402240]; etc.

SuperWIMPs/E-WIMPs

- Interaction scale with ordinary matter suppressed by large mass scale:
- For axino, $f_{PQ} \approx 10^{11}$ GeV
  - $\sigma \approx (m_W / f_{PQ})^2 \sigma_{weak}$
    $\sigma \approx 10^{-18} \sigma_{weak}$
    $\sigma \approx 10^{-20}$ pb
- For gravitino, $m_{Pl} \approx 10^{19}$ GeV
  - $\sigma \approx 10^{-36}$ pb



Choi and Roszkowski (2005)

Axinos

- Strong CP Problem: QCD is observed to conserves CP, but CP violating operators are allowed. Why are they suppressed?
- $L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$ violates CP. Limit from neutron EDMs: $\theta < 10^{-9}$
- Peccei Quinn Mechanism (1977): Promote CP-violating operator to a field. Require new global (PQ) symmetry, spontaneously broken at some scale, f_{PQ}.
- Weinberg (1978) & Wilczek (1978): spontaneously broken symmetry means there must be a Goldstone boson! Axion.
- QCD vacuum effects: $m_a \simeq f_\pi m_\pi / f_{PQ}$
- SUSY: axion chiral multiplet w/ saxion, axino Tamvakis & Wyler; Nilles & Raby (1982)

$$\Phi_a = (s + ia)/\sqrt{2} + \vartheta \tilde{a} + (F \text{ term})$$

- $m_{\tilde{a}}$ ~ eV - GeV

Axino Dark Matter

- If the axino is the LSP,

(see, for example, Baer et al. (2010) & references therein)

$$\Omega_{a\tilde{a}}h^2 = \Omega_{\tilde{a}}^{NTP}h^2 + \Omega_{\tilde{a}}^{TP}h^2 + \Omega_a h^2$$

non-thermally produced axinos from neutralino NLSP decay (pre-BBN)

$$\tilde{\chi}_1^0 \to \tilde{a}\gamma$$

$$\Omega_{\tilde{a}}^{NTP} = \frac{m_{\tilde{a}}}{m_{\tilde{\chi}_1^0}}\Omega_{\tilde{\chi}_1^0}h^2$$

axion abundance (Leslie Rosenberg's talk on Wednesday)

thermally produced axinos from radiation off MSSM scattering processes

$$\Omega_{\tilde{a}}^{TP}h^2 \approx 5.5g^6 \ln\left(\frac{1.108}{g}\right)\left(\frac{m_{\tilde{a}}}{0.1\ \mathrm{GeV}}\right)\left(\frac{10^{11}\ \mathrm{GeV}}{f_{PQ}/N}\right)^2\left(\frac{T_R}{10^4\ \mathrm{GeV}}\right)$$

- TP axinos are CDM for $m_{\tilde{a}} \gtrsim 0.1\ \mathrm{MeV}$

Gravitinos

- Gravitino mass depends on how SUSY breaking is communicated to the observable sector.
  - Gravity (modulus) mediated ~~SUSY~~:
    - $m_{3/2} \approx$ 100 GeV - few TeV

    maybe LSP
  - Anomaly mediated ~~SUSY~~:
    - $m_{3/2} \approx$ 10 TeV - 100 TeV

    not LSP
  - Gauge mediated ~~SUSY~~:
    - $m_{3/2} \approx$ 1 eV - 1 GeV

    probably LSP
  - Gaugino mediated ~~SUSY~~:
    - $m_{3/2} \approx$ 10 GeV - TeV

    maybe LSP

Gravitino Dark Matter

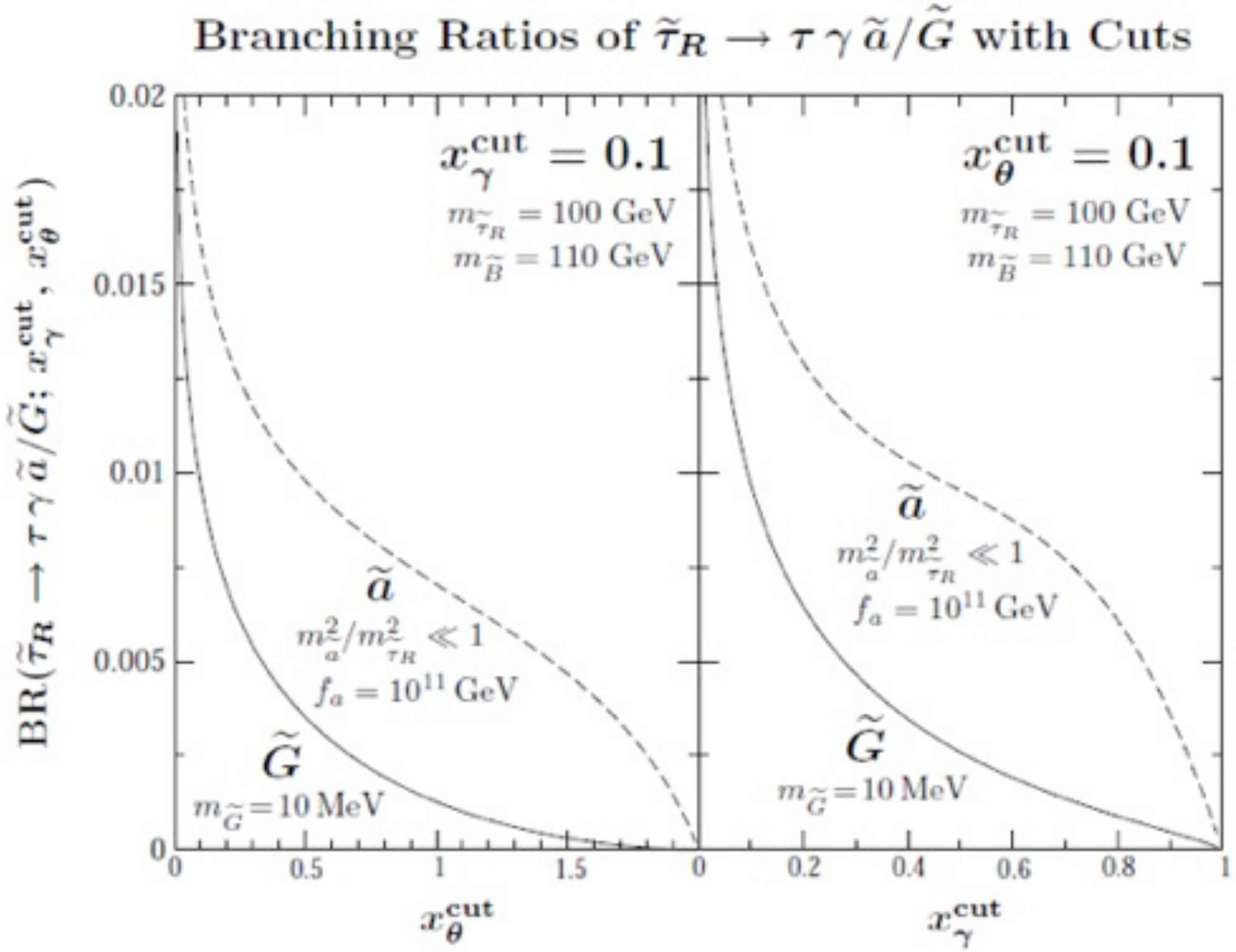
- Like axino, both thermal and non-thermal production mechanisms
  - NTP: $\Omega_{\tilde{G}}^{\rm NTP} h^2 = \frac{m_{\tilde{G}}}{m_{\rm NLSP}} \Omega_{\rm NLSP} h^2$
    - Late decays of NLSP can spoil BBN light element abundances.
    - $\Omega_G h^2 \sim 0.1$ for 1 GeV < m_G < 700 GeV (Steffen 2006)
  - TP: $\Omega_{\tilde{G}}^{\rm TP} h^2 \simeq 0.2 \left(\frac{T_{\rm R}}{10^{10}\,{\rm GeV}}\right) \left(\frac{100\,{\rm GeV}}{m_{\tilde{G}}}\right) \left(\frac{m_{\tilde{g}}(\mu)}{1\,{\rm TeV}}\right)^2$
    - $T_R \ll T_f$ to avoid overproduction of gravitinos
    - For natural ranges of gluino and gravitino masses, one can have TP $\Omega_G h^2 \sim 0.1$ at T_R as high as $10^{9\text{-}10}$ GeV. (M. Boltz et al. 1998, 2001 + subsequent work)

Gravitino vs. Axino

Can we tell them apart?

- Maybe! If long-lived staus are accumulated and observed (i.e. at the LHC), we might be able to determine if CDM is axino or gravitino based on stau decay event distributions or even just NLSP lifetime.

  Brandenburg et al. (2005)



opening angle

photon energy

WIMPs

WIMP “Coincidence”
Relic Abundance

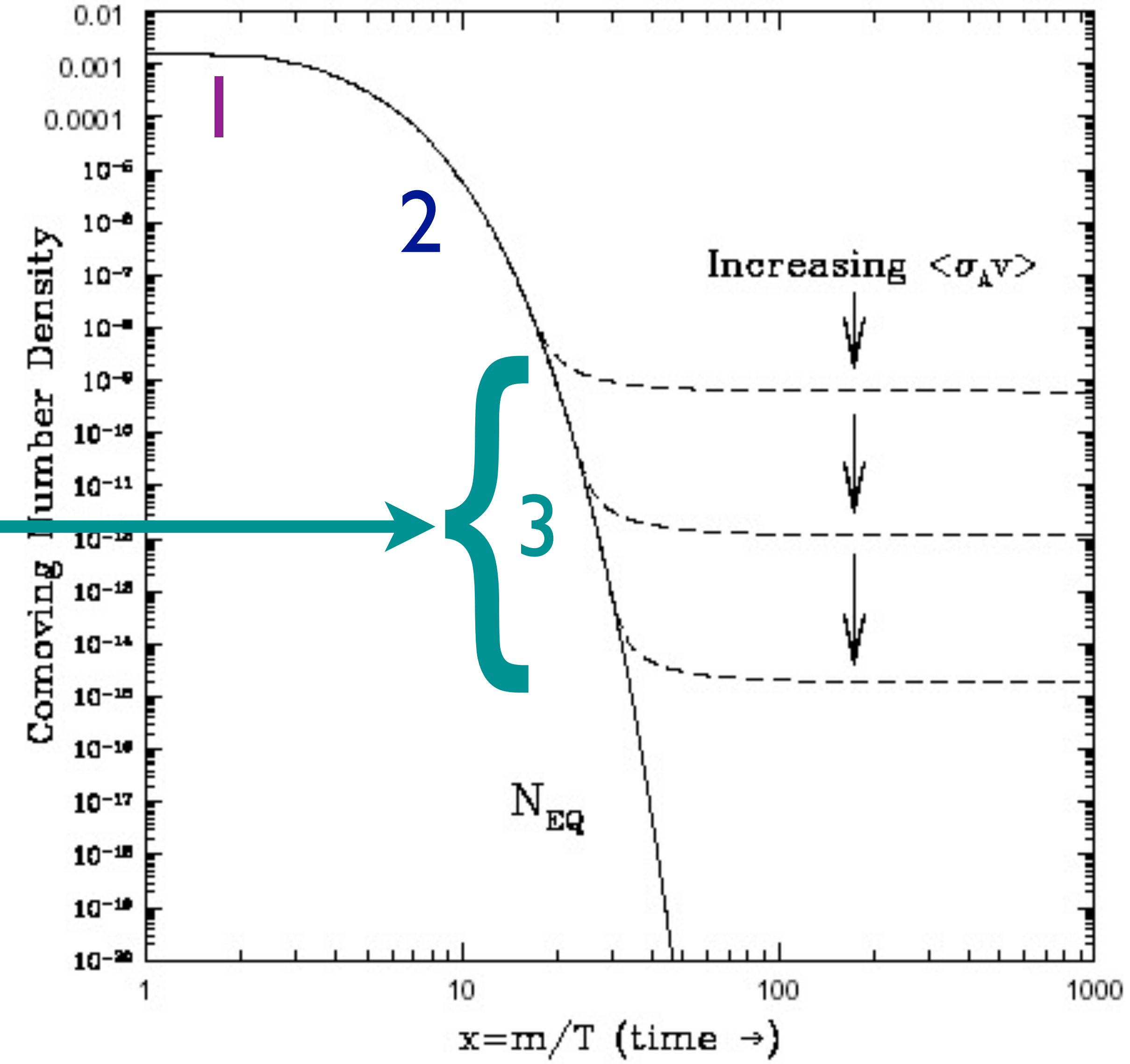
Expansion and annihilation compete to determine the number density:

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma v_{rel} \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

Stable matter with GeV-TeV mass and weak-scale annihilation cross section yield

$\Omega_\chi h^2 \approx 0.1$

Jungman, Kamionkowski & Griest, PR (1996)



Sneutrinos

- L-handed neutrinos have L-handed sneutrino superpartners in the MSSM
  - Large coupling to Z boson leads to low relic abundance and larger-than-observed scattering rates with nuclei. Falk, Olive, & Srednicki (1994)
  - Low mass window closed by limits from invisible Z decay at LEP. LEPEWWG (2003)
- R-handed neutrinos can be added to the SM to explain the origin of neutrino masses, so expect R-handed sneutrino partners.
  - L-R mixed sneutrinos have reduced coupling to Z, but a significant L-R mixing is only possible in certain SUSY-breaking scenarios.
  - Pure R-handed sneutrinos could be CDM, but can't be thermal relics due to tiny coupling to ordinary matter, unless the model has an extended gauge or Higgs sector. Arina & Fornengo (2007); Asaka, Ishiwata, & Moroi (2007); Cerdeno & Seto (2009); etc.

Sneutrino Dark Matter

- Example: MSSM + gauged U(1)B-L   Allahverdi et al. (2007,2009)
  - DM could be R-sneutrino if U(1)B-L is broken at ~TeV scale

- Example: MSSM + singlet superfield *S* for mu problem + singlet superfield *N* for R-(s)neutrino states   Cerdeno & Seto (2009)
  - DM is pure R-sneutrino, *SNN* for neutrino mass and *S* couples to Higgs sector, so thermally-produced WIMP

- Example: MSSM + RH neutrinos w/ only Dirac masses   Arkani-Hamed et al. (2001), Borzumati & Nomura (2001), Dumont et al. (2012)
  - DM is L-R mixed sneutrino, light sneutrino DM excluded if m_h =125 GeV

Take-home:

Sneutrino DM must be substantially R-handed to suppress coupling to Z, so need extended versions of the MSSM.

Variety of viable MSSM extensions

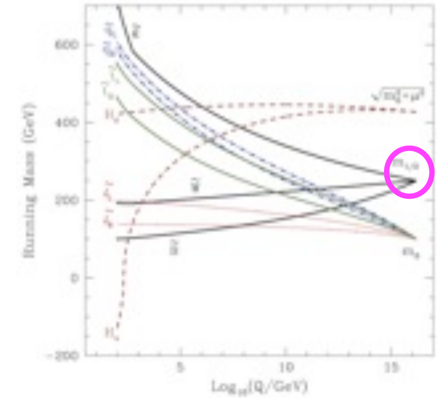
→ **many possibilities for sneutrino DM phenomenology**

Neutralino Dark Matter

$$\tilde{\chi}_i^0 = \alpha_i \tilde{B} + \beta_i \tilde{W}^3 + \gamma_i \tilde{H}_1^0 + \delta_i \tilde{H}_2^0$$

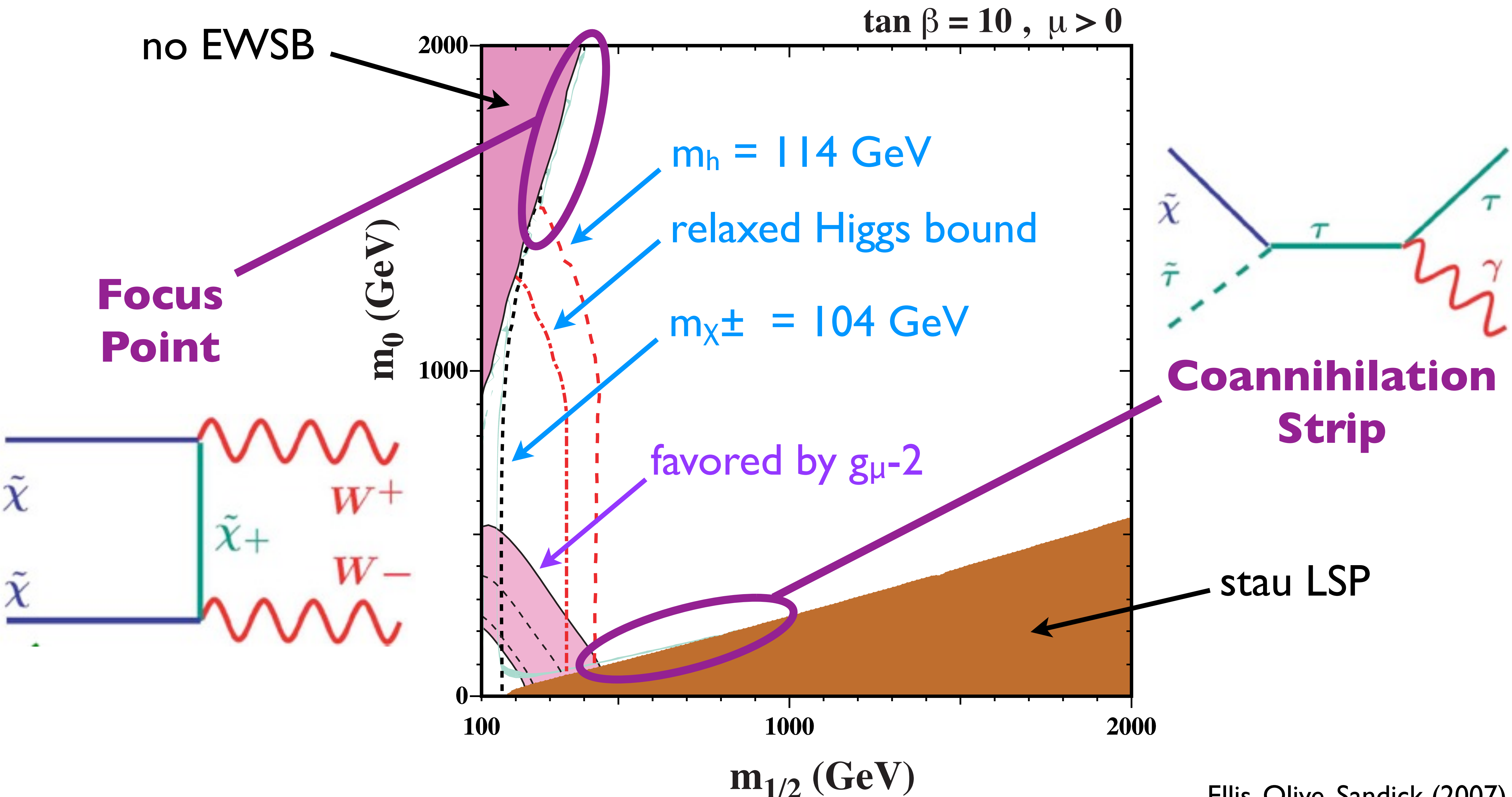
- Composition of each neutralino is determined by the mixing matrix:

$$(\tilde{W}^3, \tilde{B}, \tilde{H}_1^0, \tilde{H}_2^0) \begin{pmatrix} M_2 & 0 & \frac{-g_2 v_1}{\sqrt{2}} & \frac{g_2 v_2}{\sqrt{2}} \\ 0 & M_1 & \frac{g_1 v_1}{\sqrt{2}} & \frac{-g_1 v_2}{\sqrt{2}} \\ \frac{-g_2 v_1}{\sqrt{2}} & \frac{g_1 v_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g_2 v_2}{\sqrt{2}} & \frac{-g_1 v_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{W}^3 \\ \tilde{B} \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$



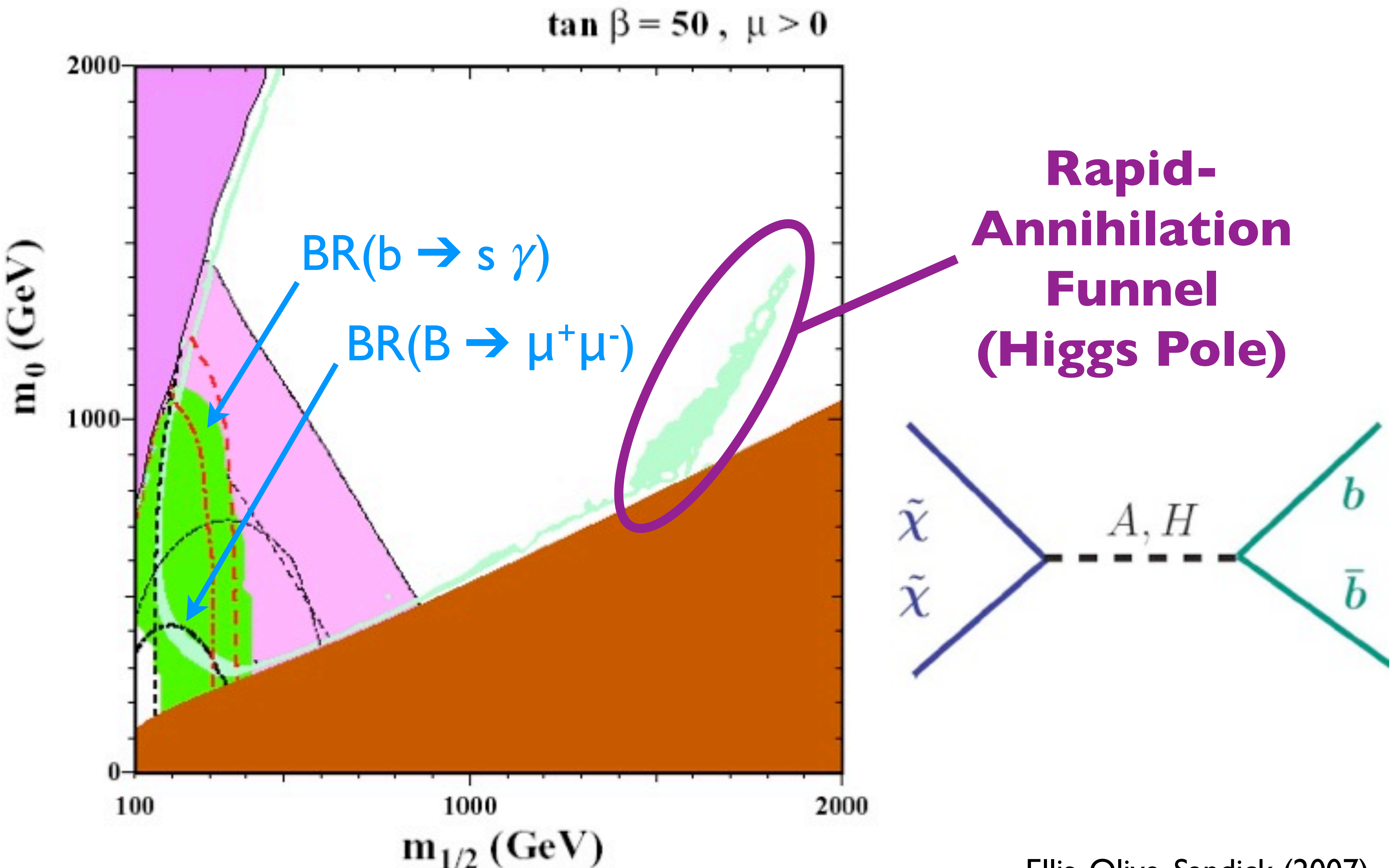
- Properties of neutralino depend on composition
  - gaugino universality ➞ bino/higgsino
  - non-universal gaugino masses ➞ any (wino/higgsino in AMSB)

CMSSM



Ellis, Olive, Sandick (2007)

CMSSM



Ellis, Olive, Sandick (2007)

Beyond the CMSSM

- Relax some assumptions.
- Should the effective Higgs masses be related to $m_0(m_{GUT})$?
  - scalar mass universality motivated by suppression of flavor-changing processes
  - Full universality only in mSUGRA!
  - $m_{Hd}(m_{GUT}) = m_{Hu}(m_{GUT})$ from SO(10) GUTs
  - Otherwise, $m_{Hd}(m_{GUT})$, $m_{Hu}(m_{GUT})$, and $m_0(m_{GUT})$ all independent.

NUHM

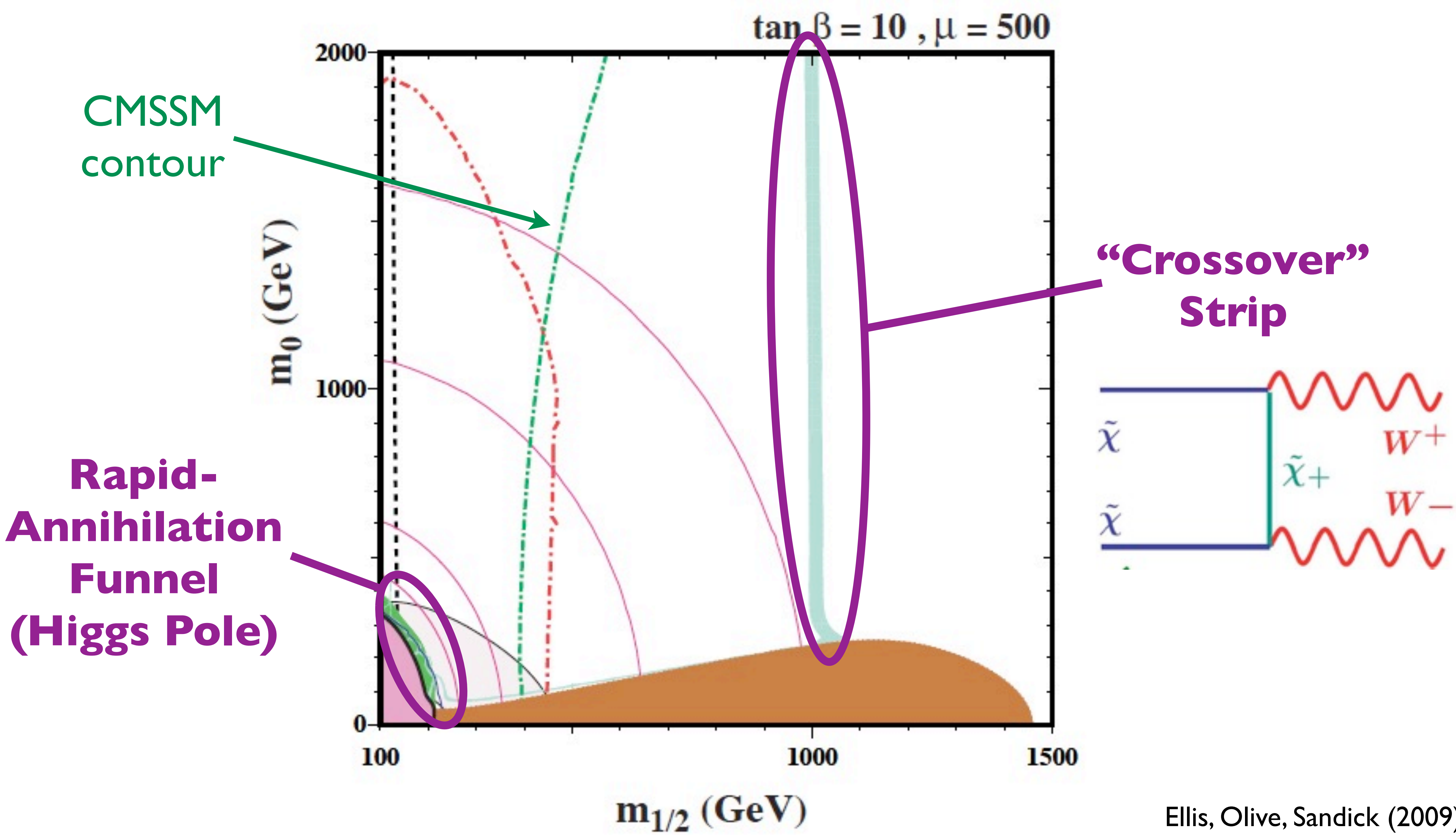
- Require EW symmetry to be broken radiatively
- Input at GUT scale ($m_{Hd} = m_{Hu} = m_0$ in CMSSM)

$$m_A^2(Q) = m_{H_d}^2(Q) + m_{H_u}^2(Q) + 2\mu^2(Q) + \Delta_A(Q)$$

$$\mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta + \frac{1}{2}m_Z^2(1 - \tan^2\beta) + \Delta_\mu^{(1)}}{\tan^2\beta - 1 + \Delta_\mu^{(2)}}$$

- NUHM1: 1 additional parameter ($m_{Hd} = m_{Hu}$, or mu, or mA)
- NUHM2: 2 additional parameters (m_{Hd} and m_{Hu}, or mu and mA)

NUHM1



Ellis, Olive, Sandick (2009)

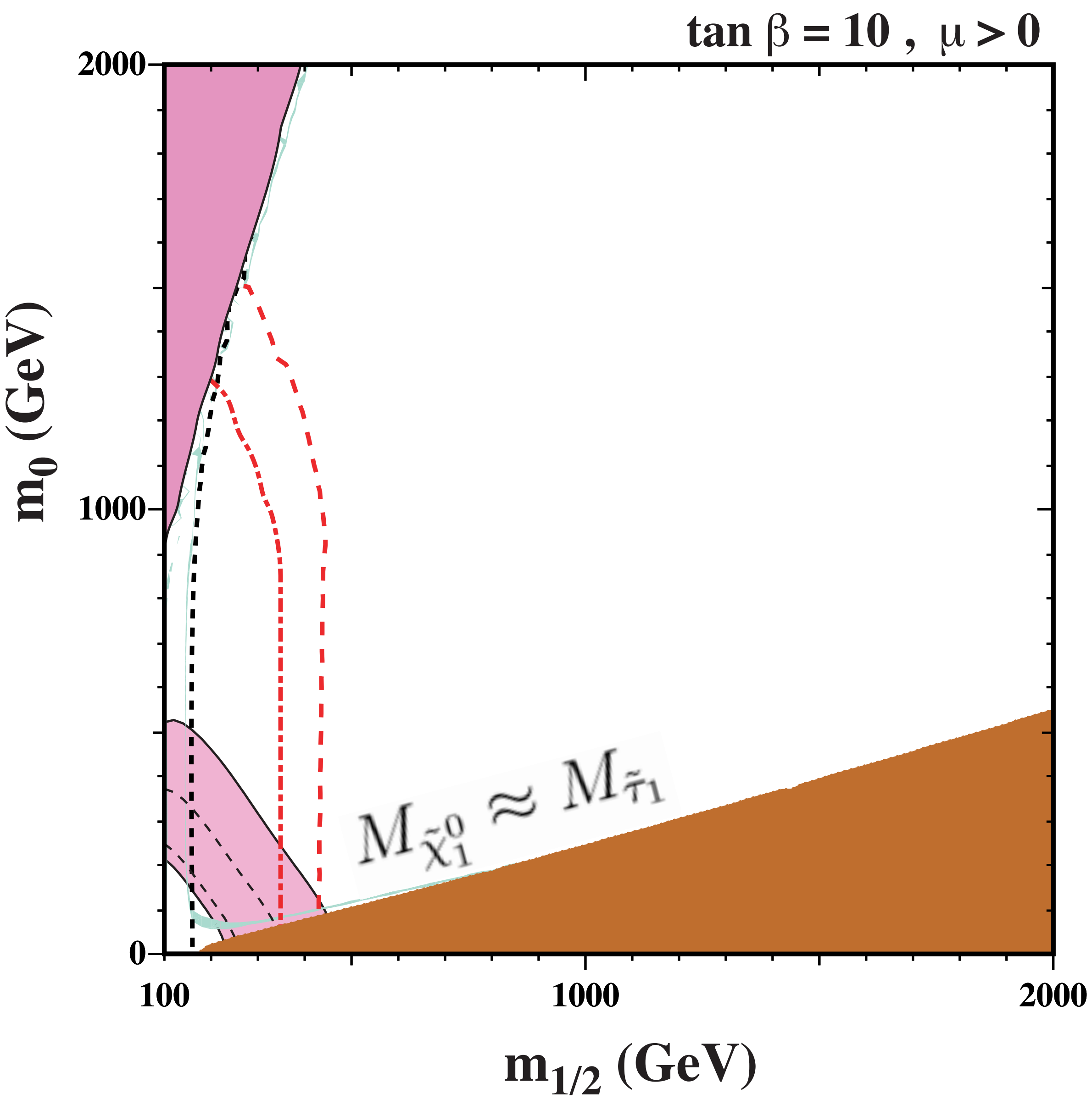
Relic Abundance

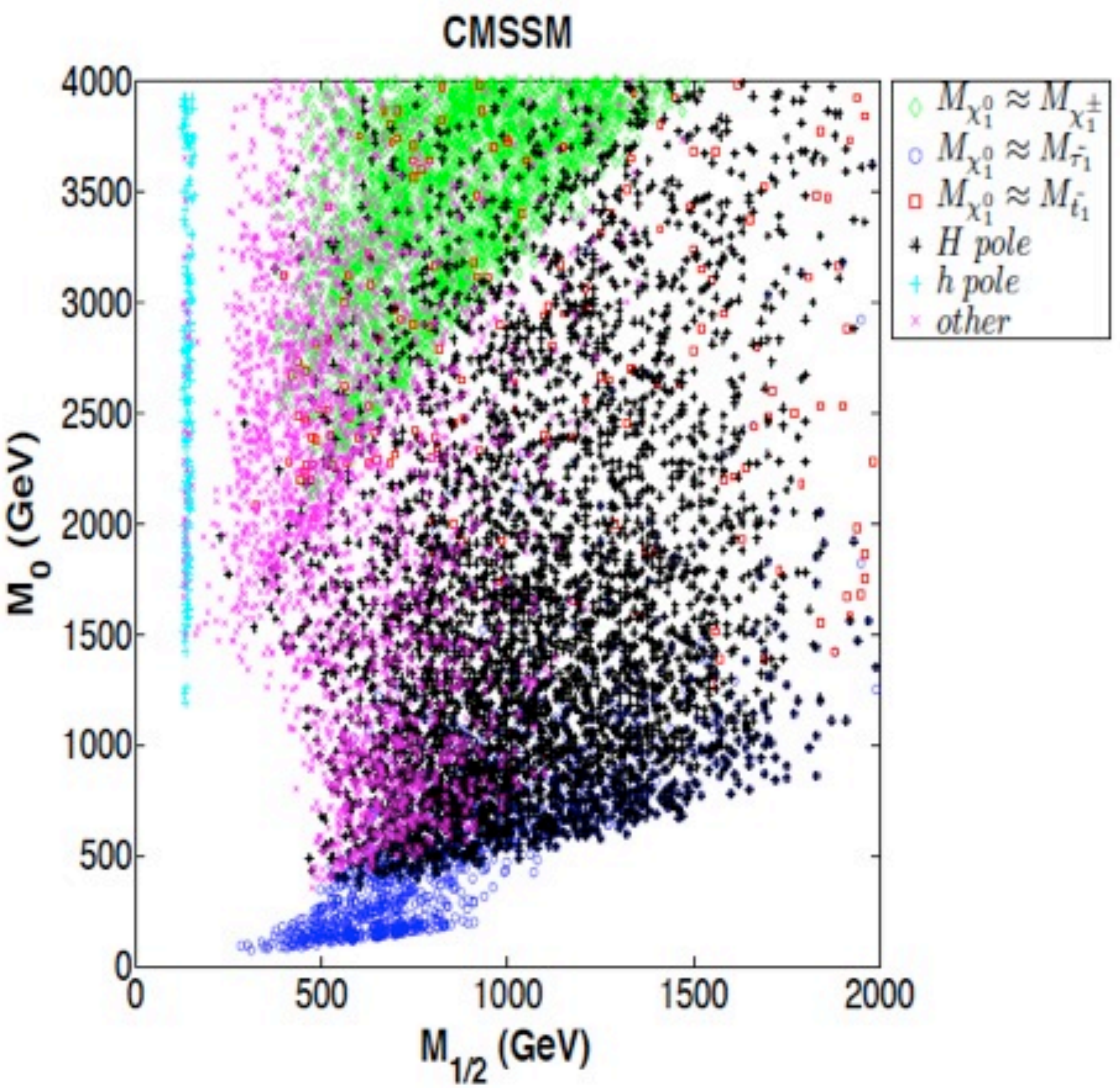
- Especially in the CMSSM, it is typical that $\Omega_{\chi} > \Omega_{CDM}$.
- Some mechanism(s) necessary for $\Omega_{\chi} \approx \Omega_{CDM}$.
  - Coannihilations with staus, stops, charginos, etc.

    ✓ $m_{\tilde{\chi}_1^0} \approx m_{\tilde{\tau}_1, \tilde{t}_1, \tilde{\chi}_1^{\pm}}$
  - Pole annihilations (Rapid Annihilation Funnel)

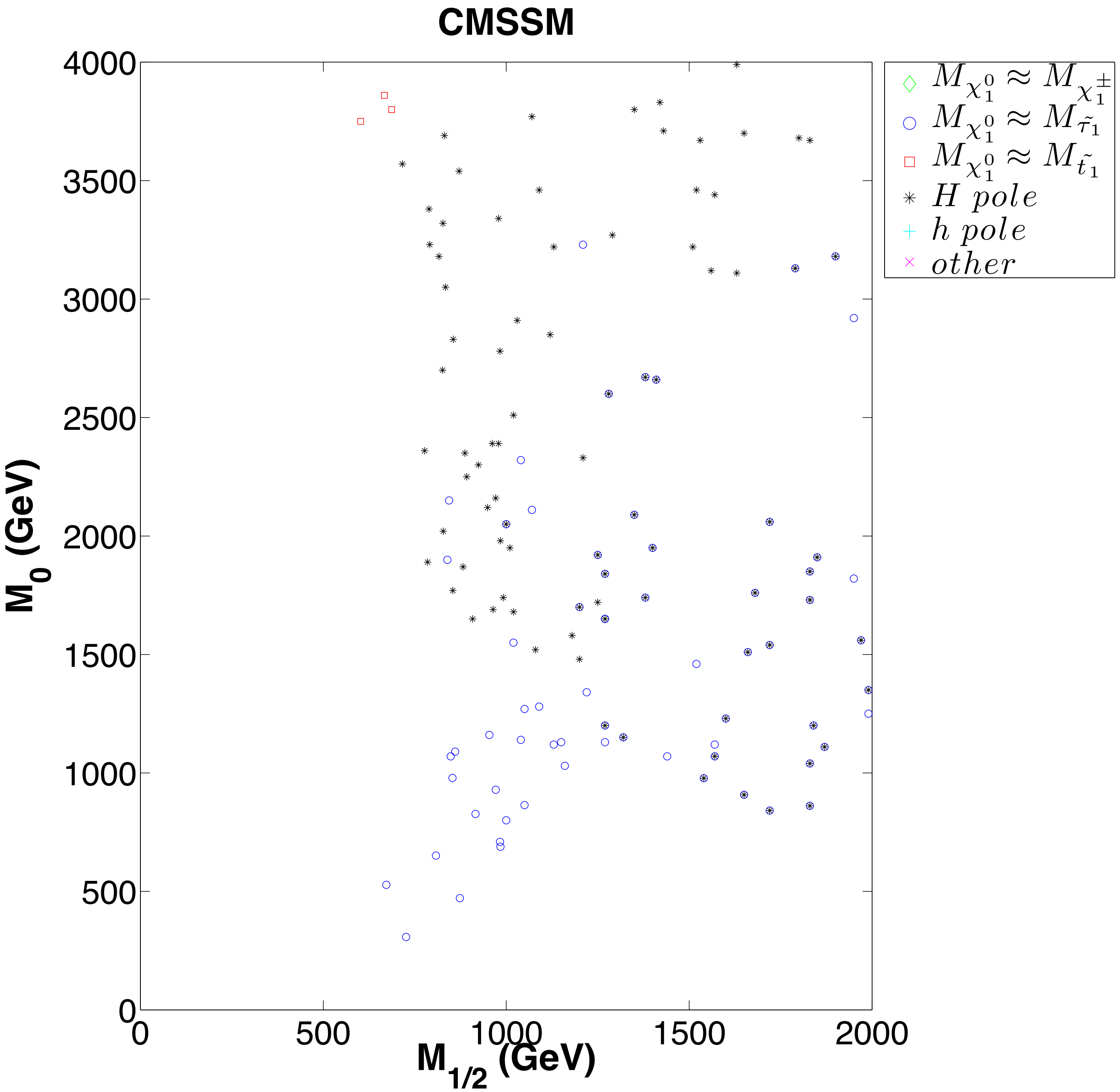
    ✓ $2m_{\tilde{\chi}_1^0} \approx m_{h,A}$
  - Substantial Higgsino fraction (CMSSM Focus Point)

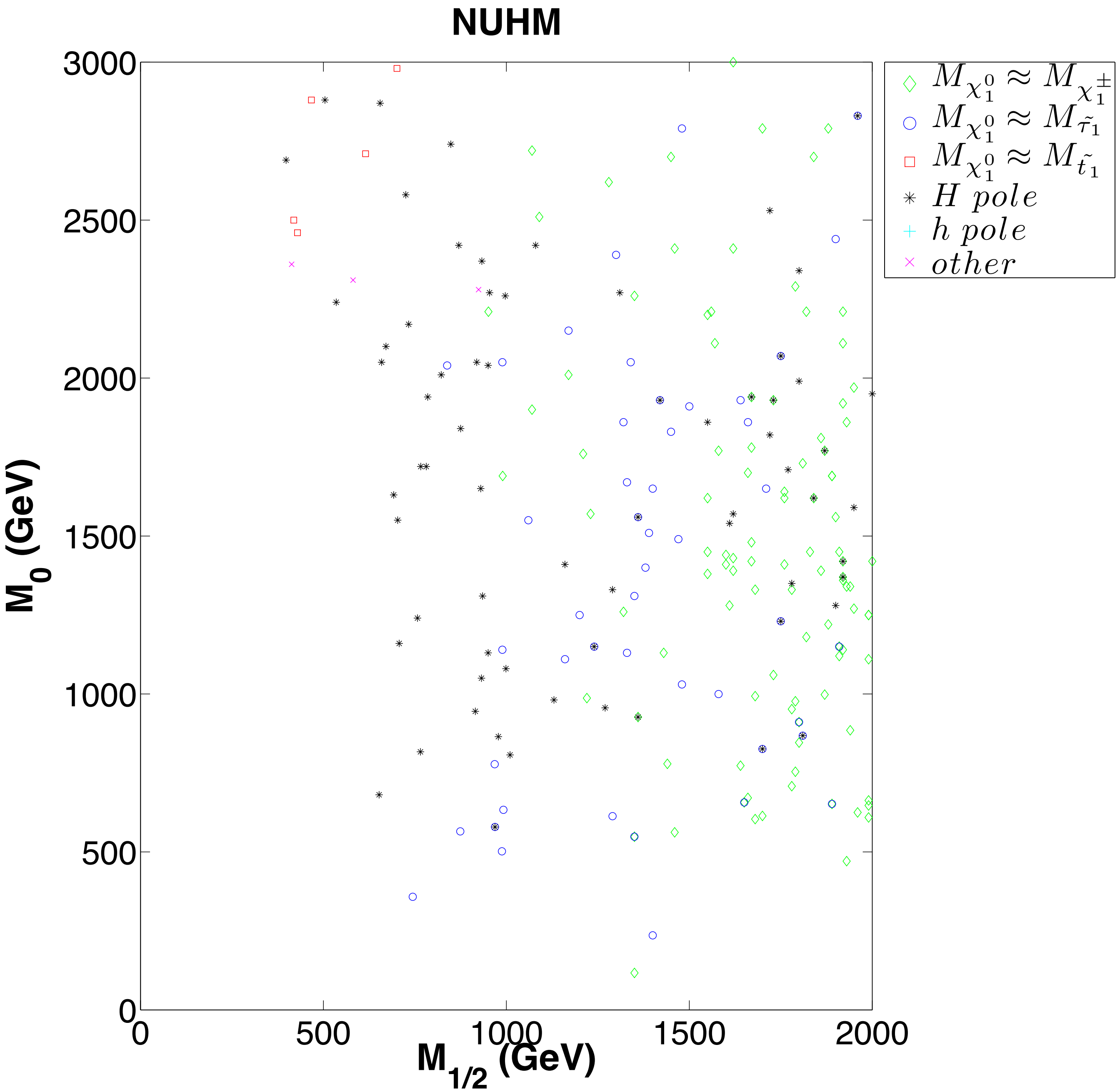
More than one slice...



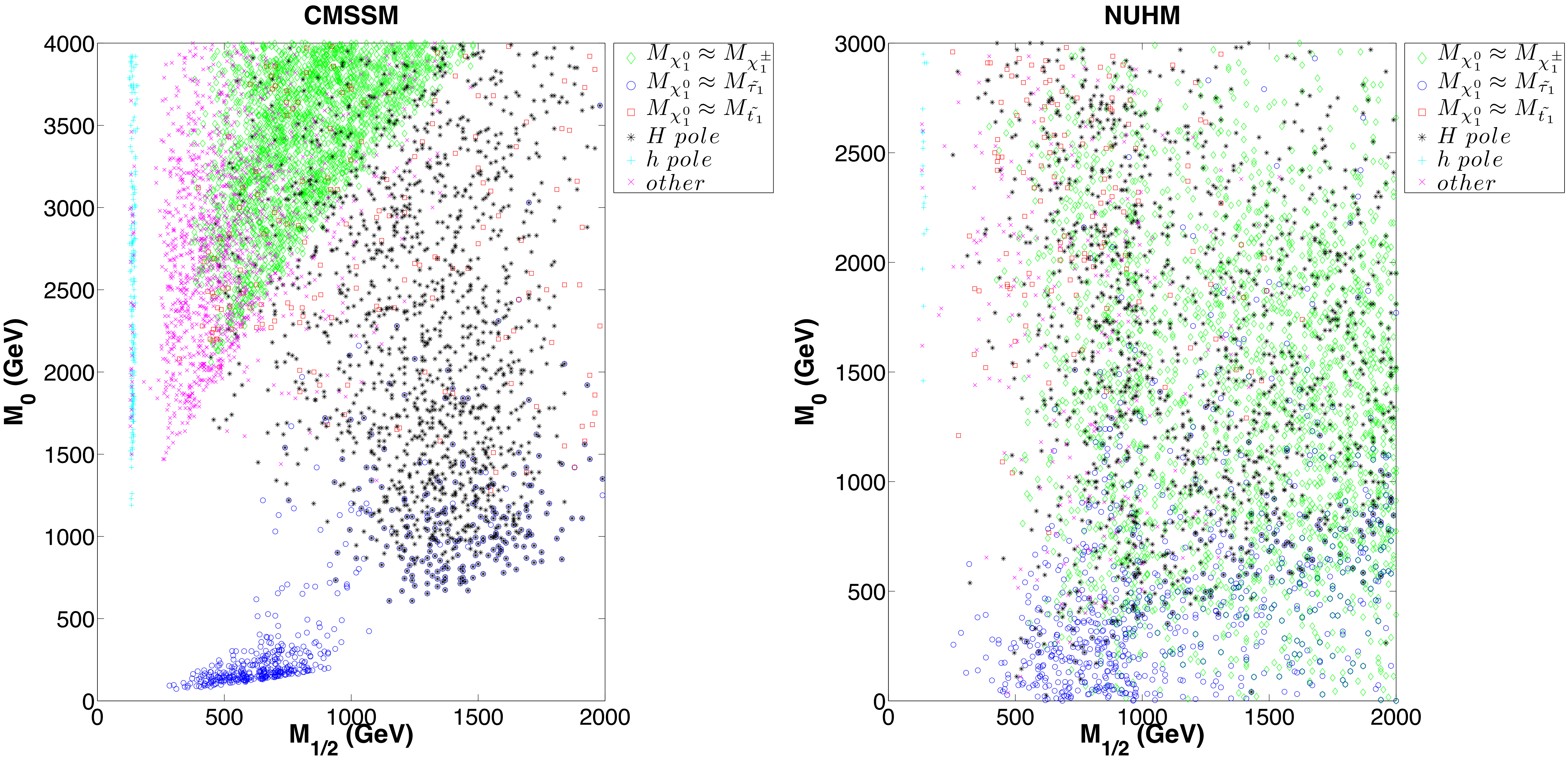


Higgs Mass

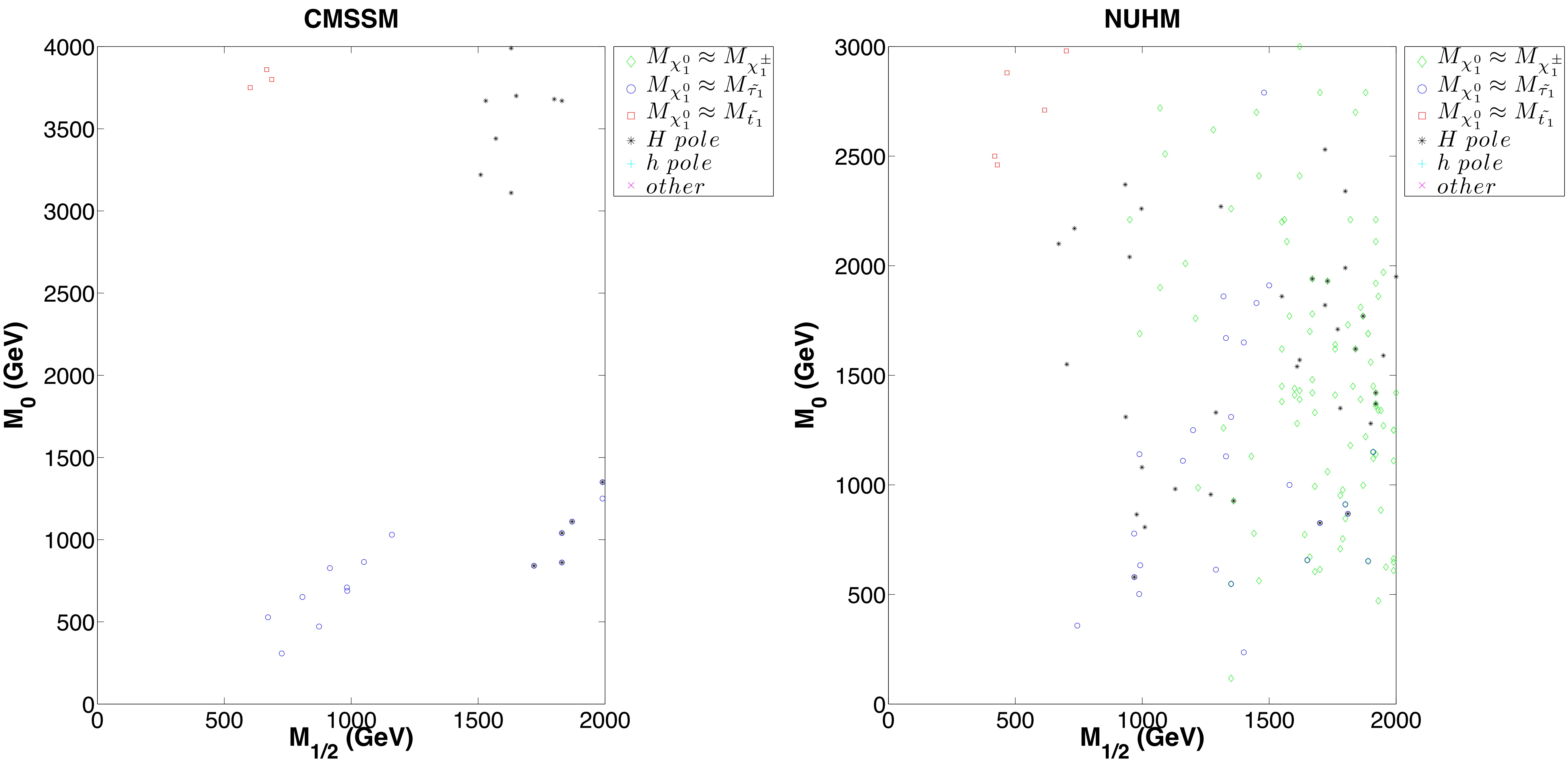

CMSSM
M_0 (GeV)
$M_{1/2}$ (GeV)
0
500
1000
1500
2000
2500
3000
3500
4000
$M_{\chi_1^0} \approx M_{\chi_1^\pm}$
$M_{\chi_1^0} \approx M_{\tilde{\tau}_1}$
$M_{\chi_1^0} \approx M_{\tilde{t}_1}$
H pole
h pole
other


NUHM
M_0 (GeV)
$M_{1/2}$ (GeV)
0
500
1000
1500
2000
2500
3000
$M_{\chi_1^0} \approx M_{\chi_1^\pm}$
$M_{\chi_1^0} \approx M_{\tilde{\tau}_1}$
$M_{\chi_1^0} \approx M_{\tilde{t}_1}$
H pole
h pole
other

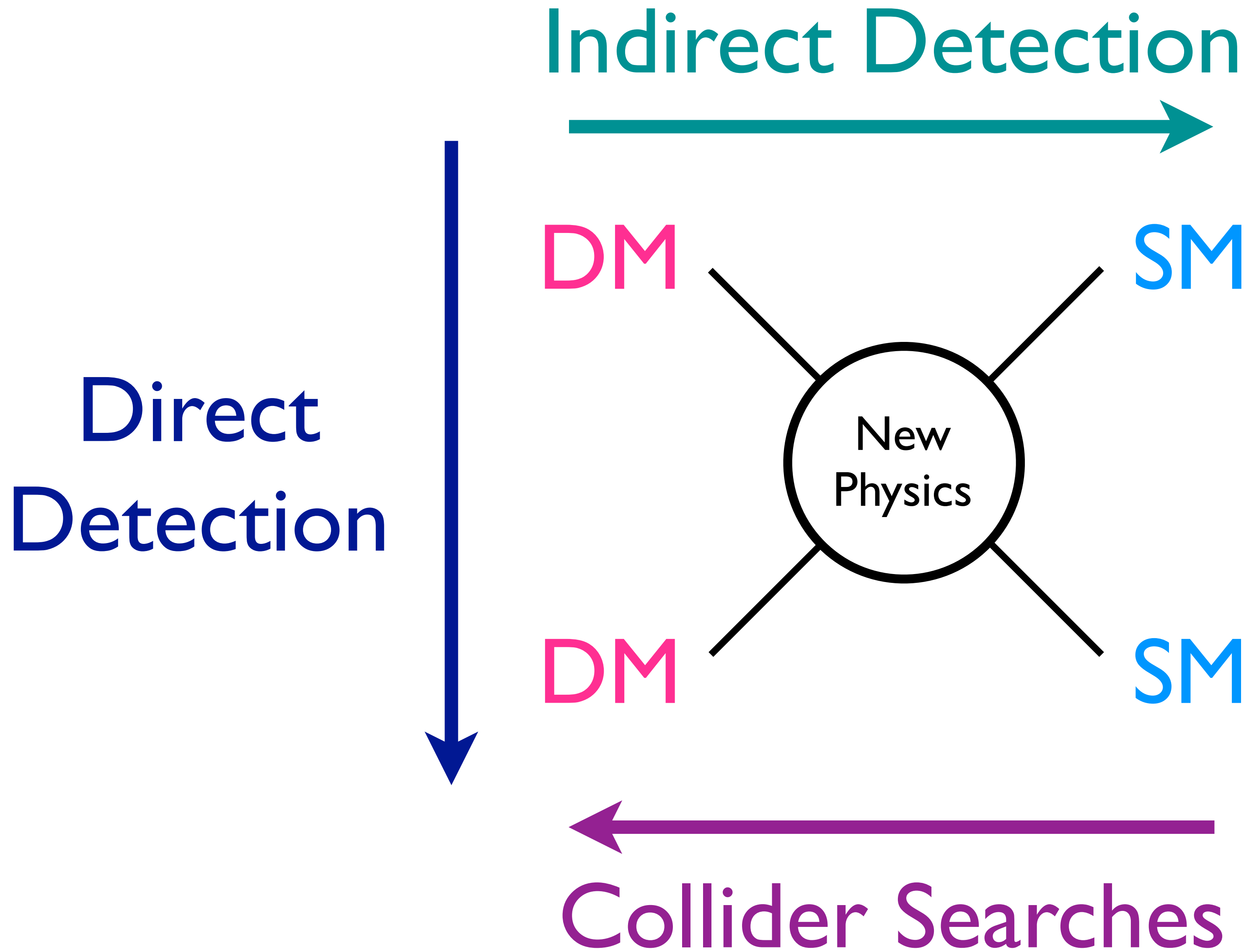
$BR(B_s \to \mu^+\mu^-)$



BR($B_s \rightarrow \mu^+\mu^-$) + m_H

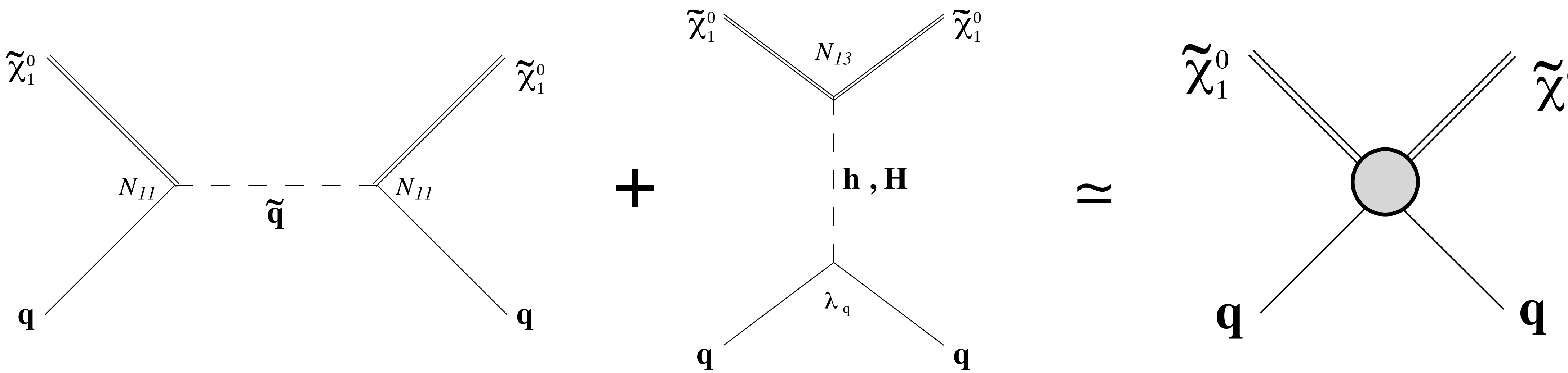


To Catch a WIMP...



Not so simple, but well-defined.

Neutralino-Nucleon Scattering

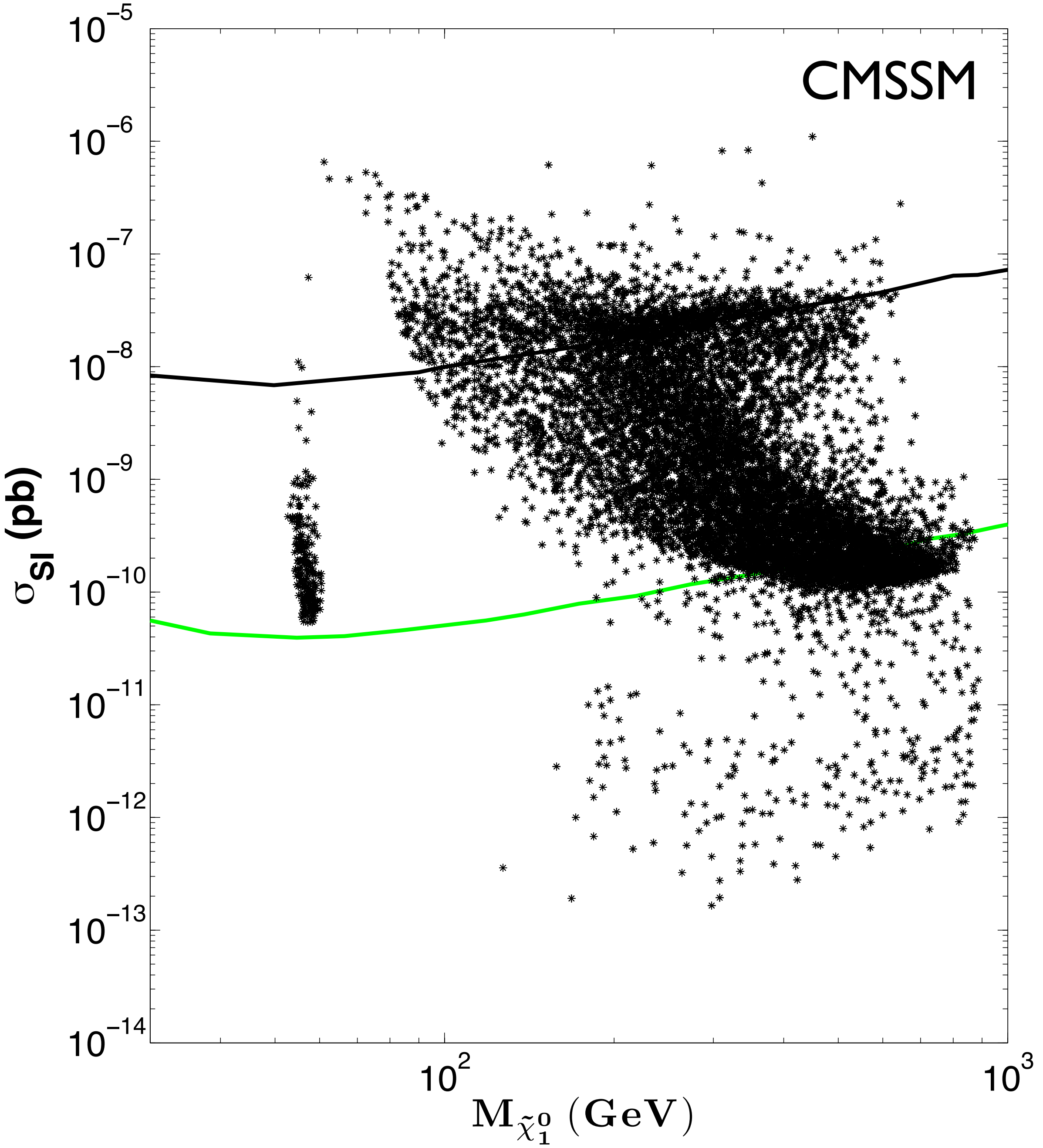


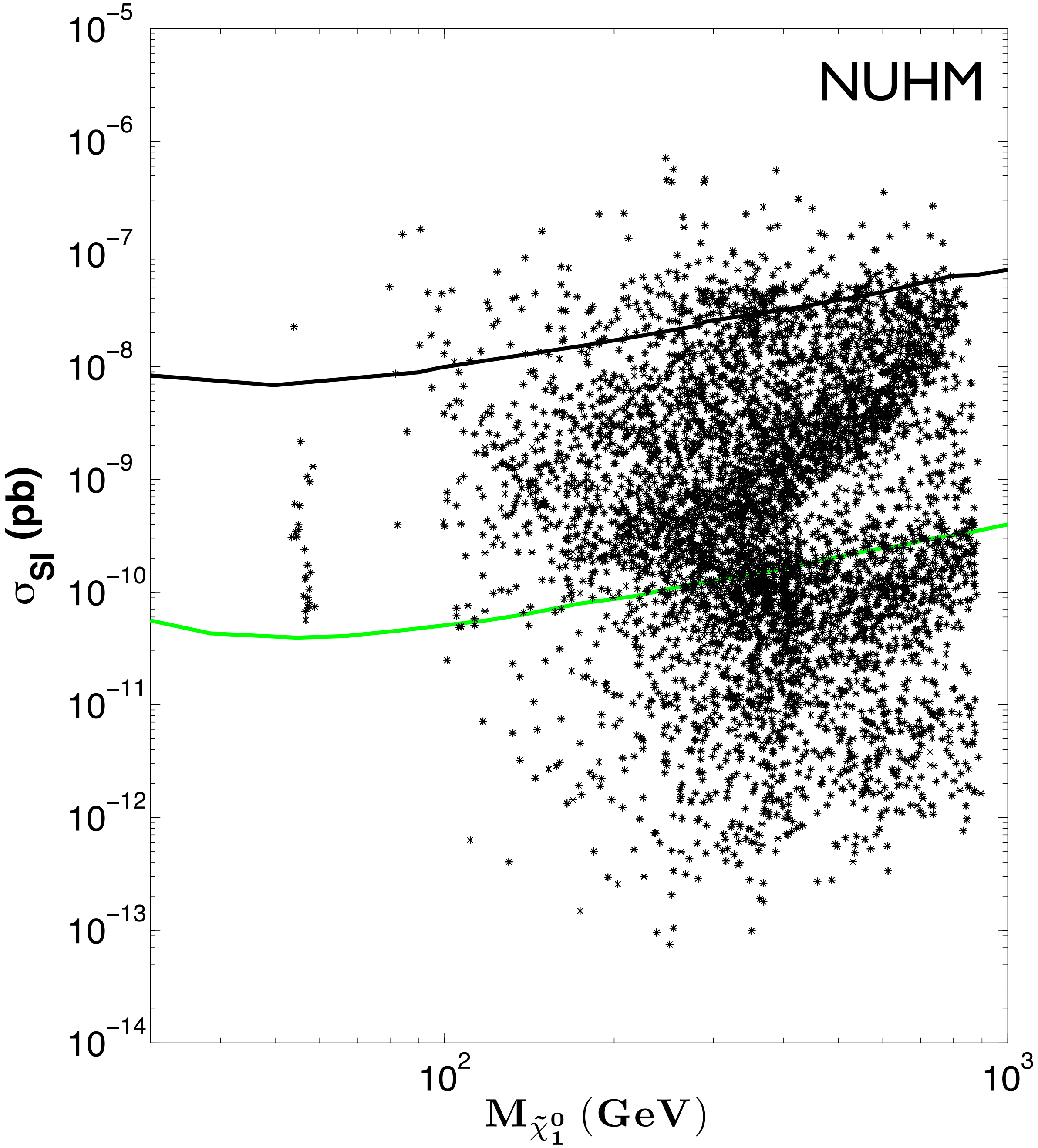
$$\mathcal{L}_{SI} = \alpha_q \bar{\chi}\chi\bar{q}q$$

$$\sigma_{SI} = \frac{4m_r^2}{\pi}\left(Zf_p + (A-Z)f_n\right)^2$$

$$\frac{f_N}{m_N} = \sum_{q=u,d,s} f_q^{(N)} \frac{\alpha_q}{m_q} + \frac{2}{27} f_G^{(N)} \sum_{q=c,b,t} \frac{\alpha_q}{m_q}$$

Direct Detection





Summary

- MSSM: neutralino - good prospects for direct detection
- (Slightly) beyond MSSM: gravitino, axino, mixed sneutrino
- Supersymmetry is alive and well...
  - ...and being tested!