Dark Matter and EWSB Naturalness in Unified SUSY Models

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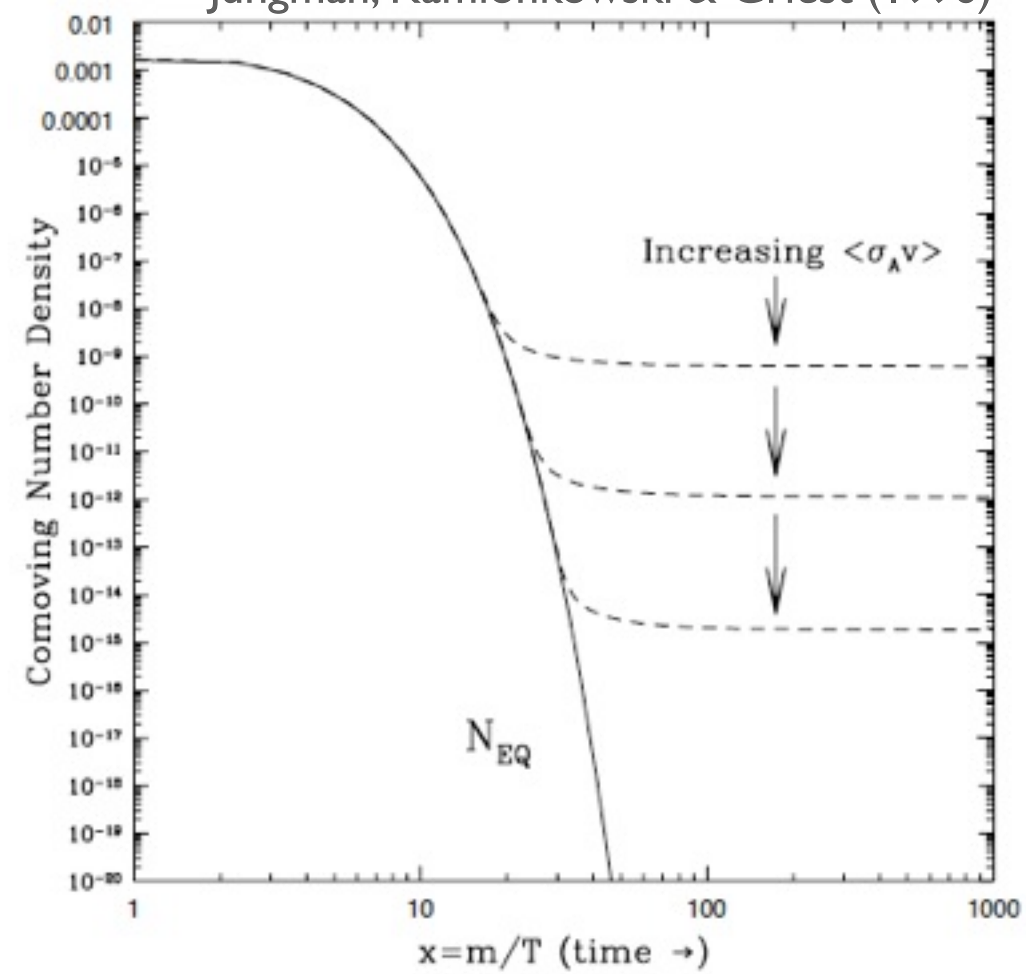
Amsel, Freese, & Sandick, JHEP (2011)

Motivation

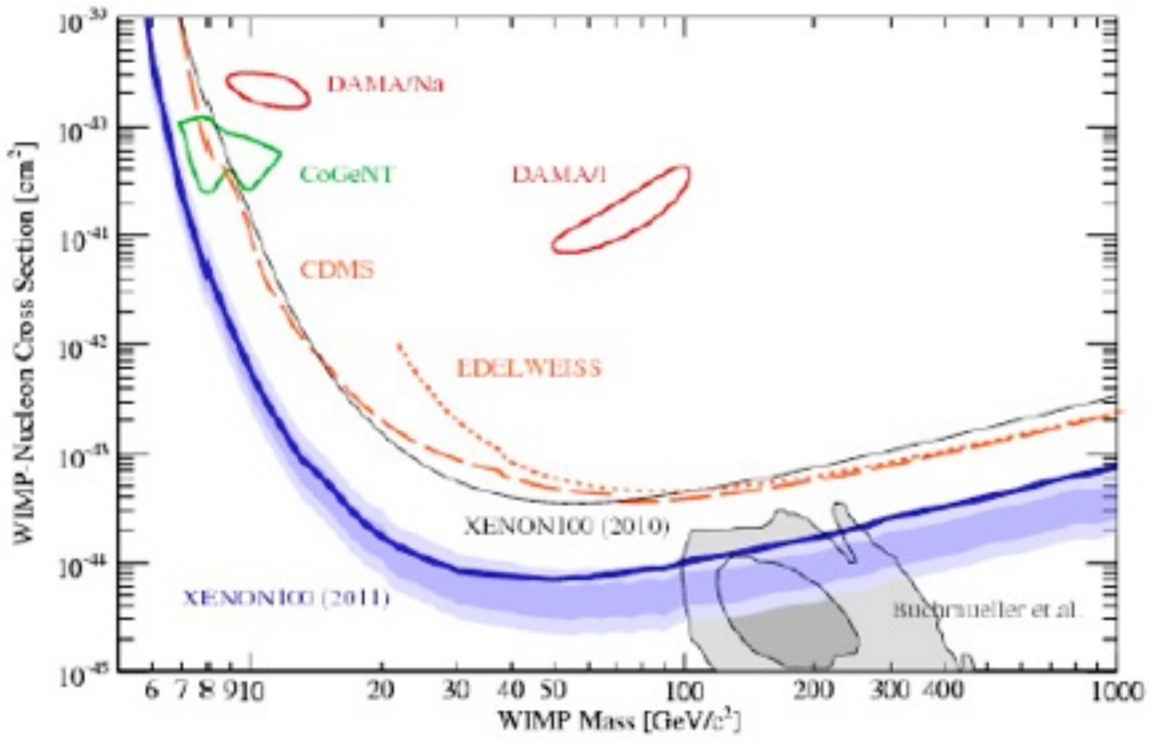
- Existence of DM firmly established
- Evidence for BSM physics
- Many theories contain dark matter candidates
- WIMP coincidence..? Or is the weak scale important in cosmology?

Jungman, Kamionkowski & Griest (1996)



Dark Matter Searches

- Direct searches are improving dramatically these days



XENON-100,
PRL 107 (2011) 131302

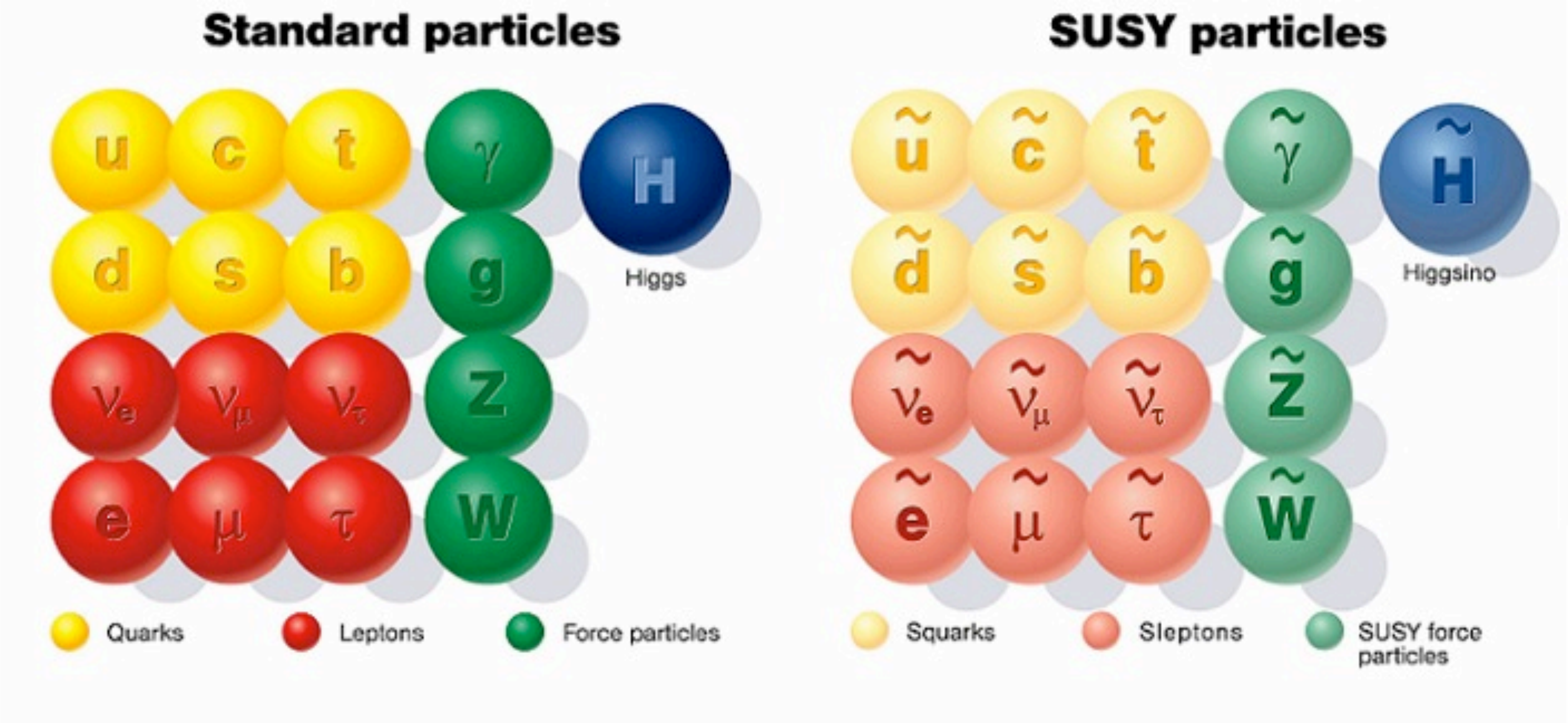
- Comparison to theoretical predictions becoming interesting
    - Null results ➔ limits on parameters

This Talk

- Most-studied BSM theories is Supersymmetry.
  - Problem: SUSY is too big.
  - Solution: well-motivated simplifying recipes
- What can direct DM searches tell us about our favorite SUSY models?
  - More specific: What is the relationship between ease-of-discovery and naturalness?

Why Study SUSY

- Aesthetically pleasing extension



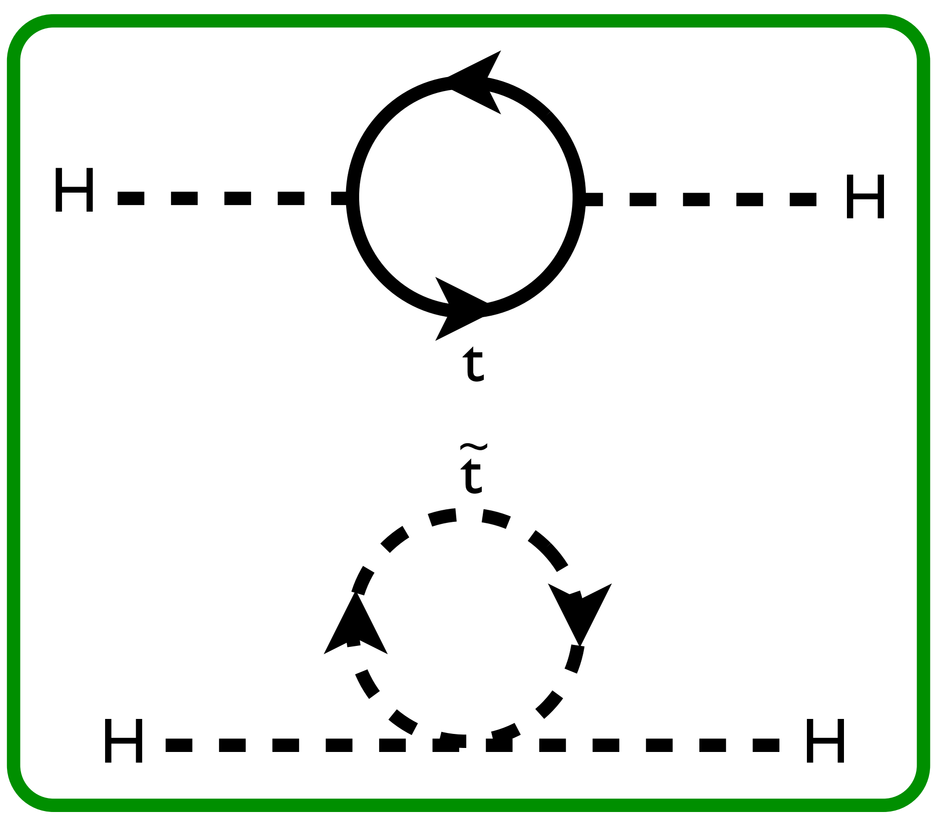
Supersymmetry is the only non-trivial extension of the space-time symmetries in a consistent 4-dimensional QFT.

Why Study SUSY

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

SM:

SUSY:



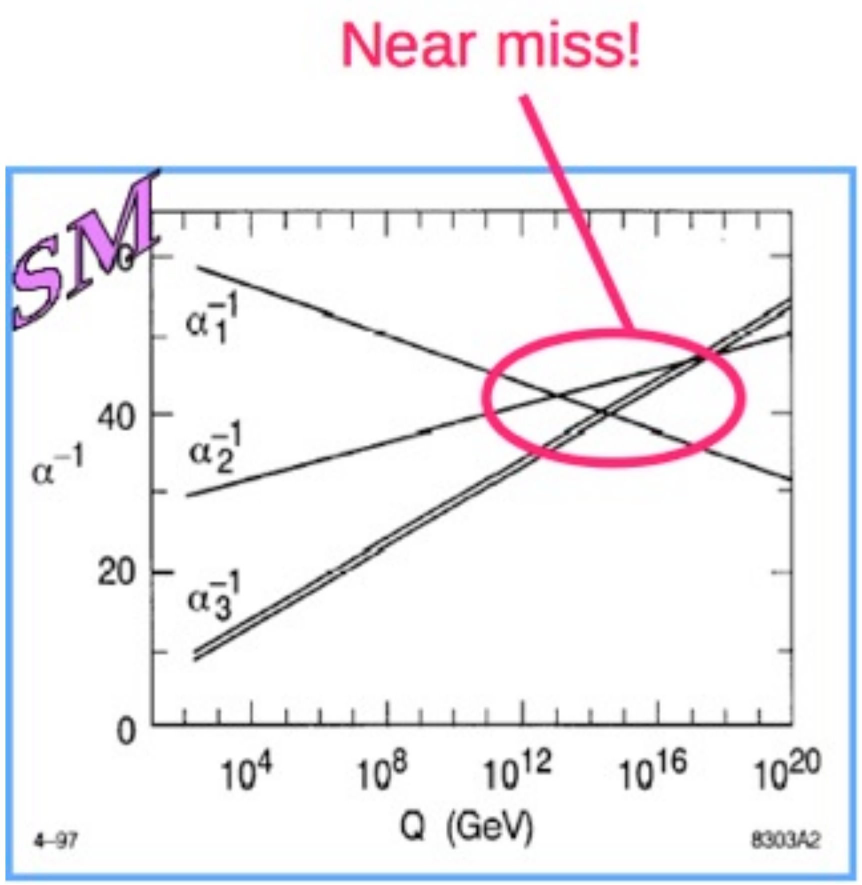
$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots$$

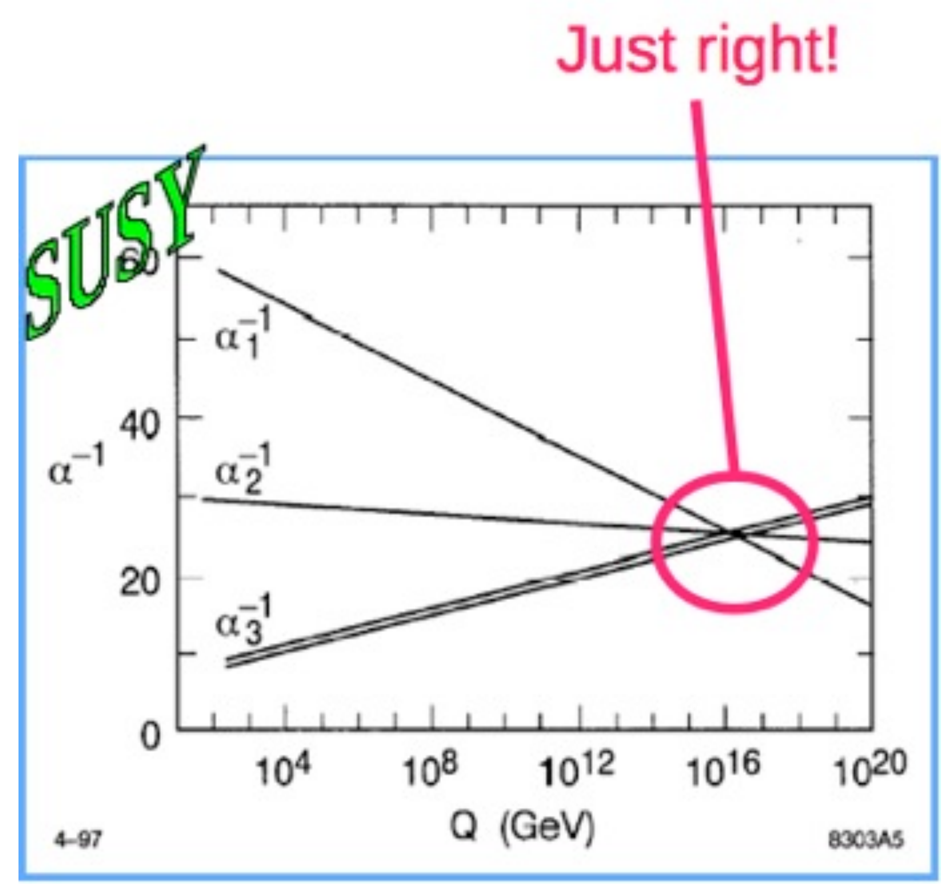
$$m_h^2 = (m_h^2)_0 \cancel{- \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2} + \frac{1}{16\pi^2}\left(m_{\tilde{f}}^2 - m_f^2\right)\ln\left(\Lambda/m_{\tilde{f}}\right) + \ldots$$

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

$105 \text{ GeV} \lesssim m_h \lesssim 135 \text{ GeV}$

The MSSM

	particle	sparticle	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
quarks and squarks	$\begin{pmatrix} u \\ d \end{pmatrix}_i$	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_i$	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	$\frac{1}{3}$
leptons and sleptons	$\begin{pmatrix} \nu \\ e \end{pmatrix}_i$	$\begin{pmatrix} \tilde{\nu} \\ \tilde{e} \end{pmatrix}_i$	1	2	$-\frac{1}{2}$
	e_i^c	$\tilde{e}_i^c$	1	1	1
W boson and wino	W	$\tilde{W}$	1	3	0
gluon and gluino	g	$\tilde{g}$	8	1	0
B boson and bino	B	$\tilde{B}$	1	1	0
Higgs bosons and higgsinos	$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$	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	$-\frac{1}{2}$

neutralinos
(and charginos)

SUSY & Dark Matter

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

$$R = (-1)^{3B + L + 2S} = \begin{cases} +1 \text{ for SM particles} \\ -1 \text{ for SUSY particles} \end{cases}$$

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

Neutralino Dark Matter

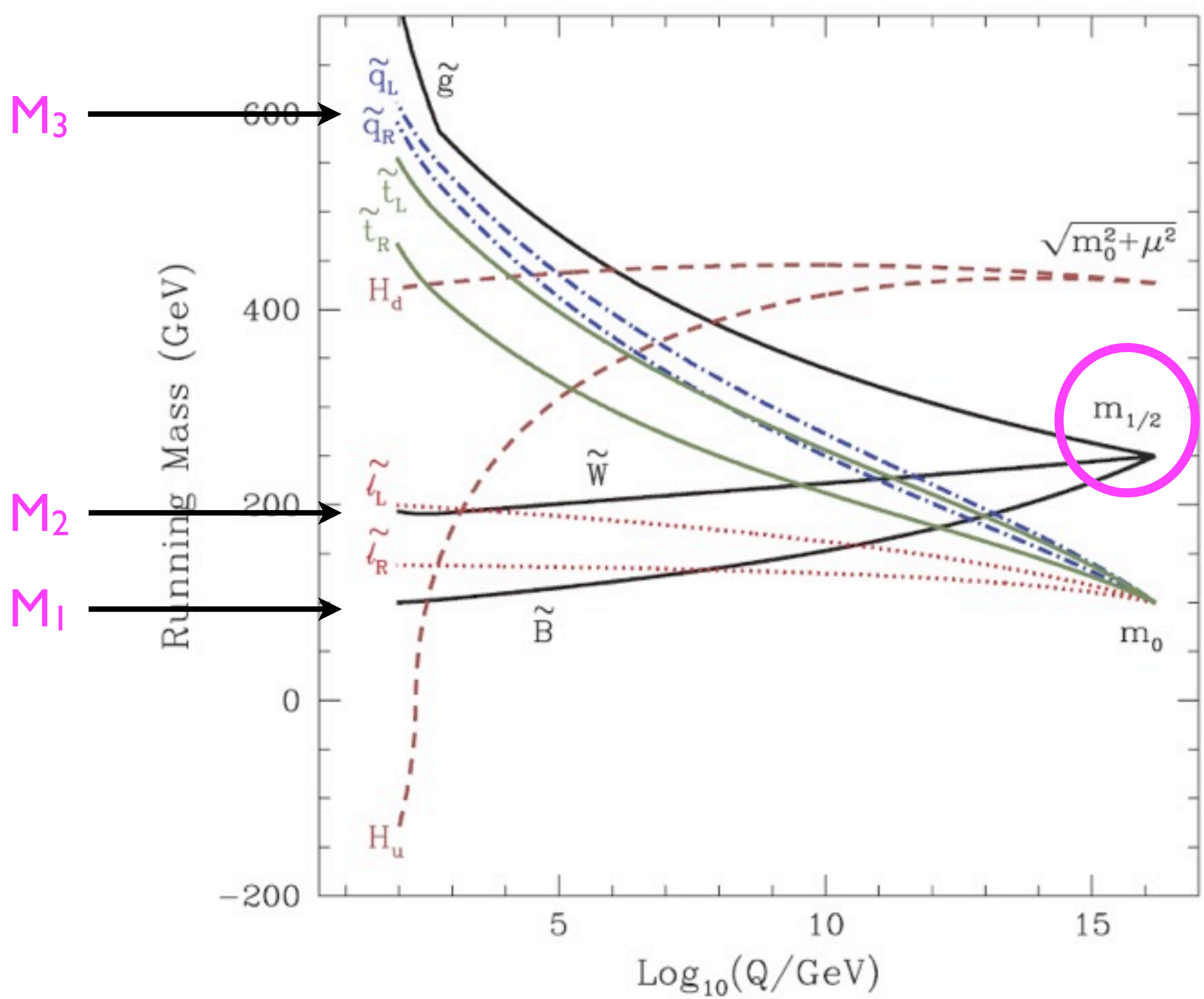
$$\tilde{\chi}_i^0 = \alpha_i \tilde{B} + \beta_i \tilde{W}^3 + \gamma_i \tilde{H}_1^0 + \delta_i \tilde{H}_2^0$$

- 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

Our Favorite SUSYs



Interlude: mSUGRA

- CMSSM ≠ mSUGRA
- Strict Minimal Supergravity (mSUGRA) is defined by the form of the Kahler potential that leads to *minimal* (canonical) kinetic terms in the supergravity Lagrangian.
    - $B_0 = A_0 - m_0$
    - Gravitino mass: $m_{3/2} = m_0$

Nilles, Srednicki, & Wyler (1983)
Hall, Lykken, & Weinberg (1983)

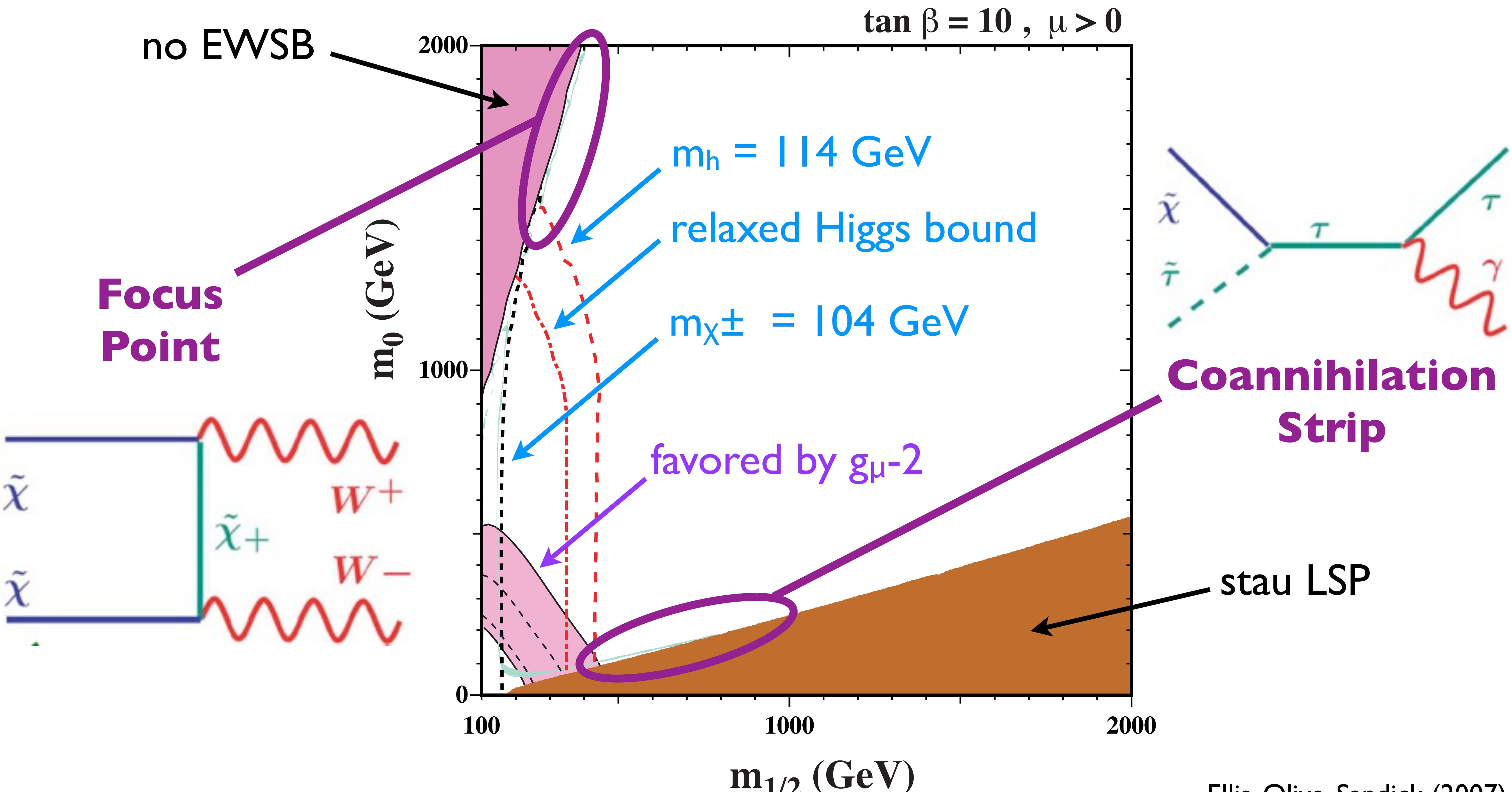
- Restriction on B_0 means you can calculate $\tan\beta$
- Neutralino dark matter → restriction on gravitino mass → restriction on m_0

Constraints

- Higgs mass > 114 GeV
- Chargino mass > 104 GeV
- Stop and stau masses > 100 GeV
- 3-sigma range for BR($b \to s\gamma$)
- BR($B_s \to \mu^+\mu^-$) < 10^{-7}
- g_μ-2
- Neutralino abundance consistent with dark matter

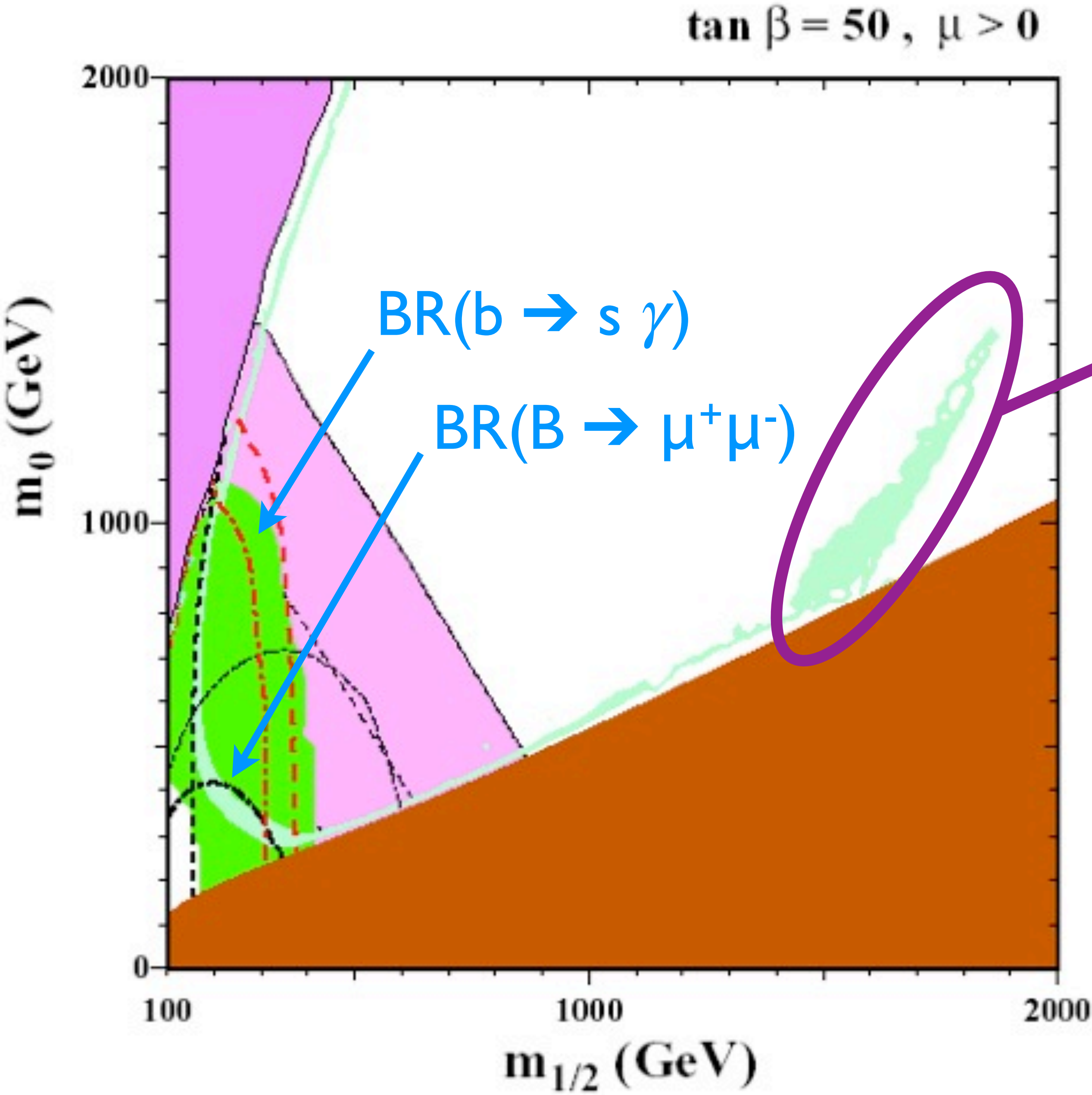
See Amsel, Freese, & Sandick (2011), and references therein.

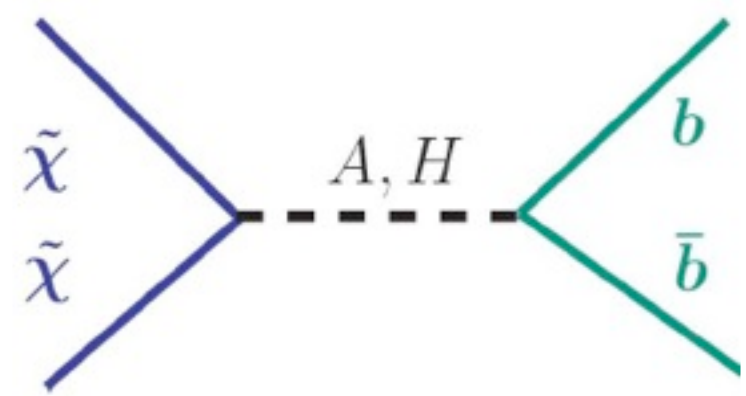
CMSSM Slice



Ellis, Olive, Sandick (2007)

Large tanβ





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

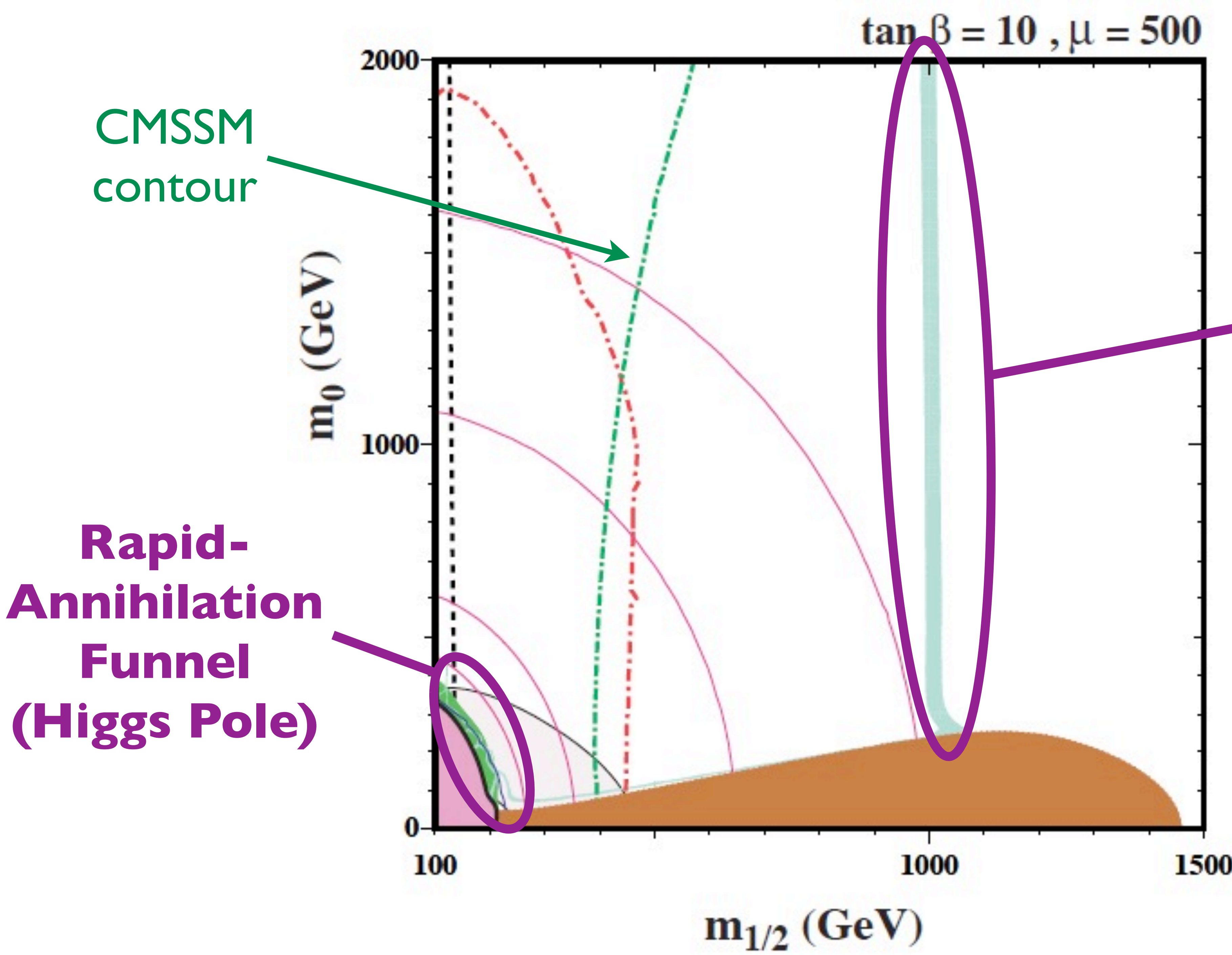
- Require EW symmetry to be broken radiatively
- Input at GUT scale ($m_{Hd} = m_{Hu} = m_0$ in CMSSM)

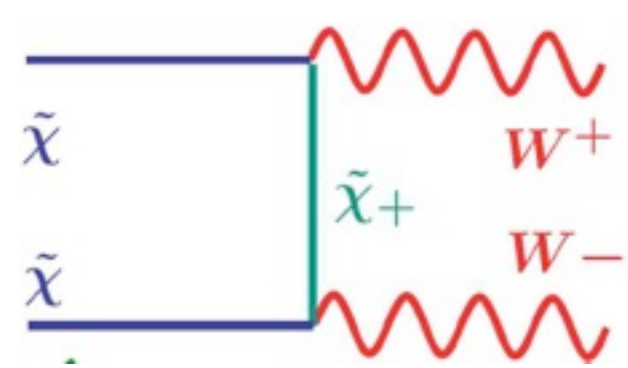
$$m_A^2(Q) = m_{H_d}^2(Q) + m_{H_u}^2(Q) + 2\mu^2(Q) + \Delta_A(Q)$$

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

- 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 (and mSUGRA), 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)

Mass Hierarchies

- What mechanism is responsible for generating the correct relic abundance?
  - look at a few relevant masses:

$$m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} < 0.2\, m_{\tilde{\chi}_1^0}$$

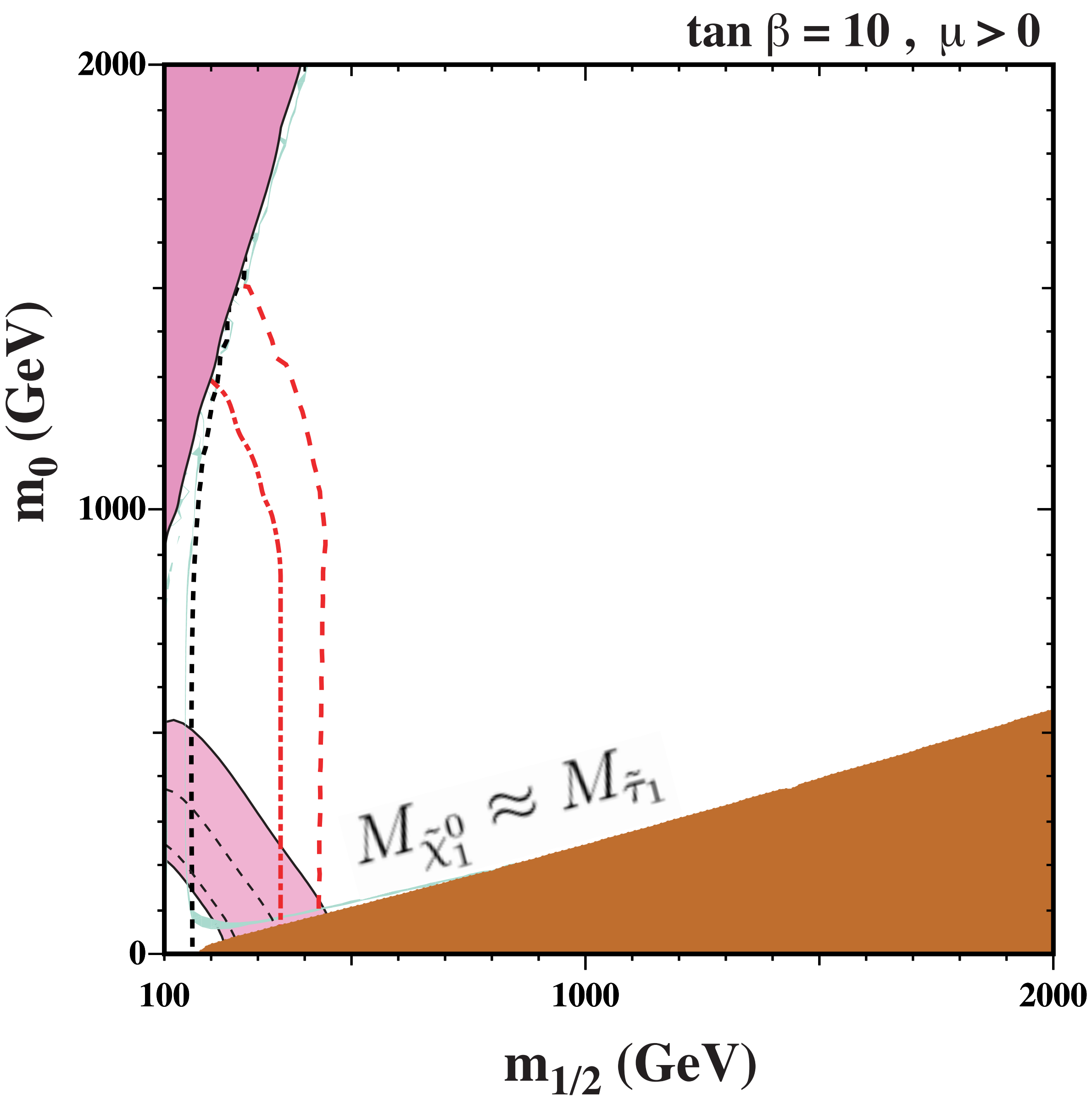
$$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} < 0.15\, m_{\tilde{\chi}_1^0}$$

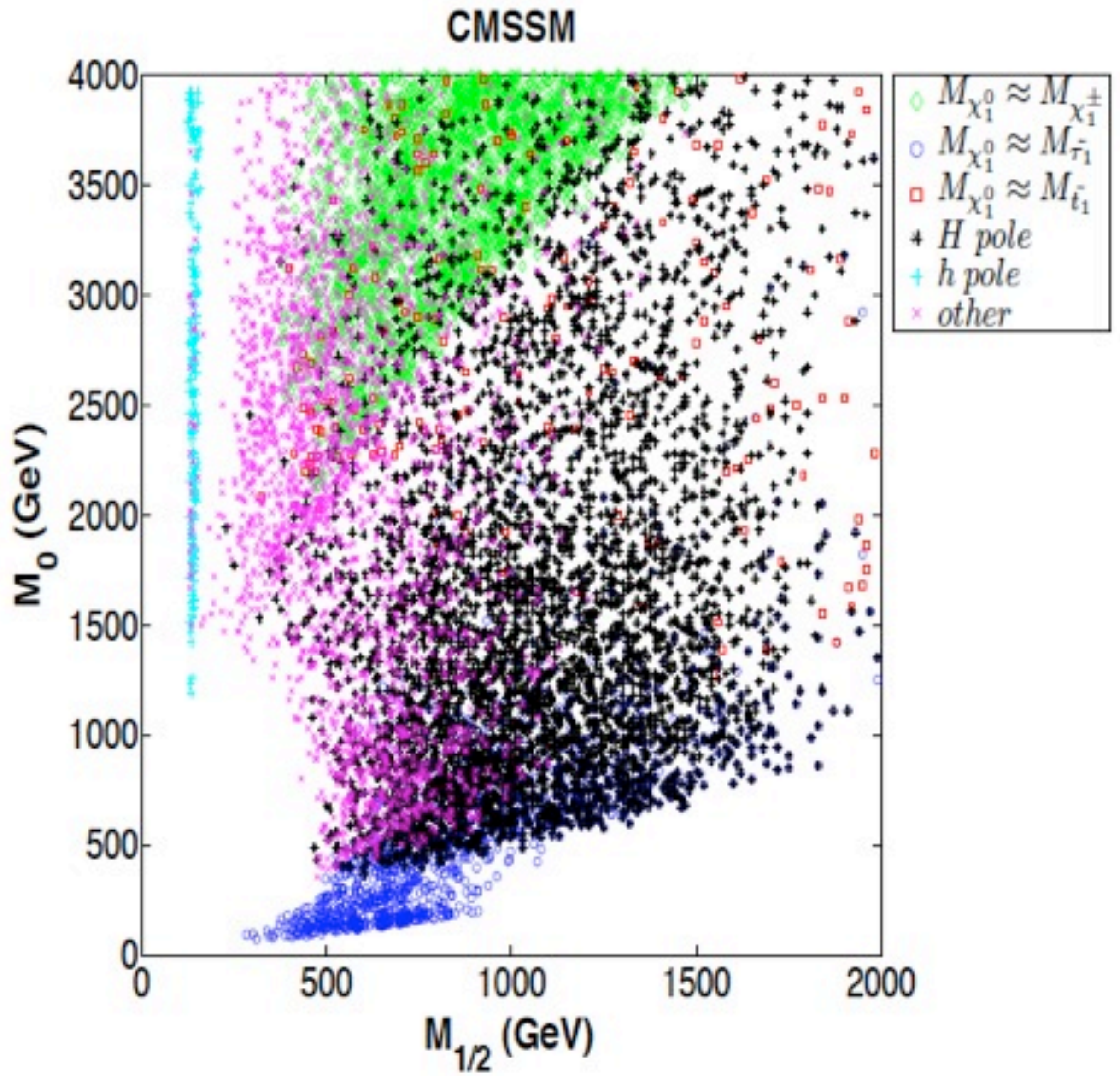
$$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} < 0.2\, m_{\tilde{\chi}_1^0}$$

$$\frac{m_A}{2} - m_{\tilde{\chi}_1^0} < 0.1\, m_{\tilde{\chi}_1^0}$$

$$\frac{m_h}{2} - m_{\tilde{\chi}_1^0} < 0.1\, m_{\tilde{\chi}_1^0}$$

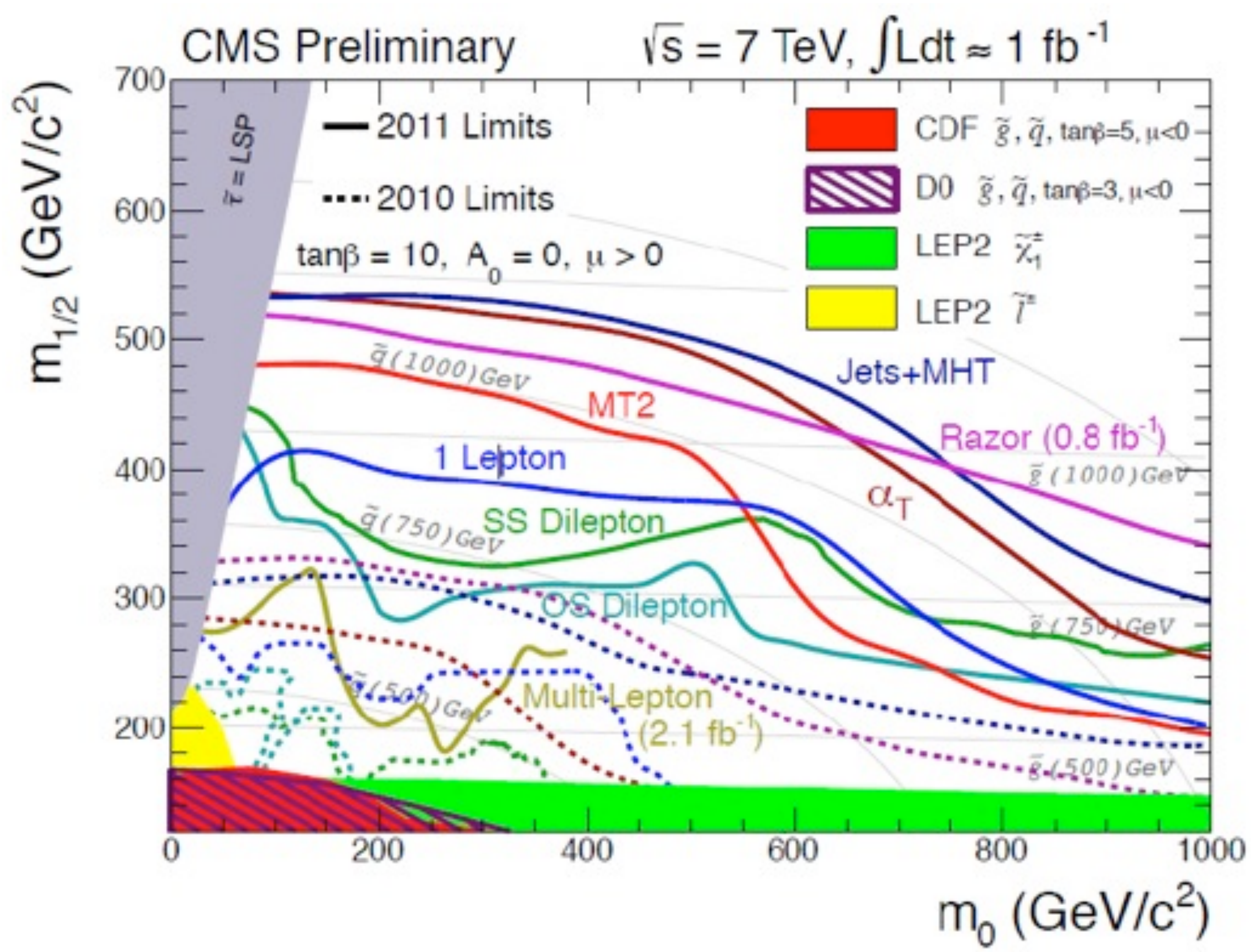
Big Scans


tan β = 10 , μ > 0
2000
1000
0
100
1000
2000
m_0 (GeV)
$m_{1/2}$ (GeV)
$M_{\tilde{\chi}_1^0} \approx M_{\tilde{\tau}_1}$


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

A note on LHC constraints

T. Dorigo for CMS (2012)



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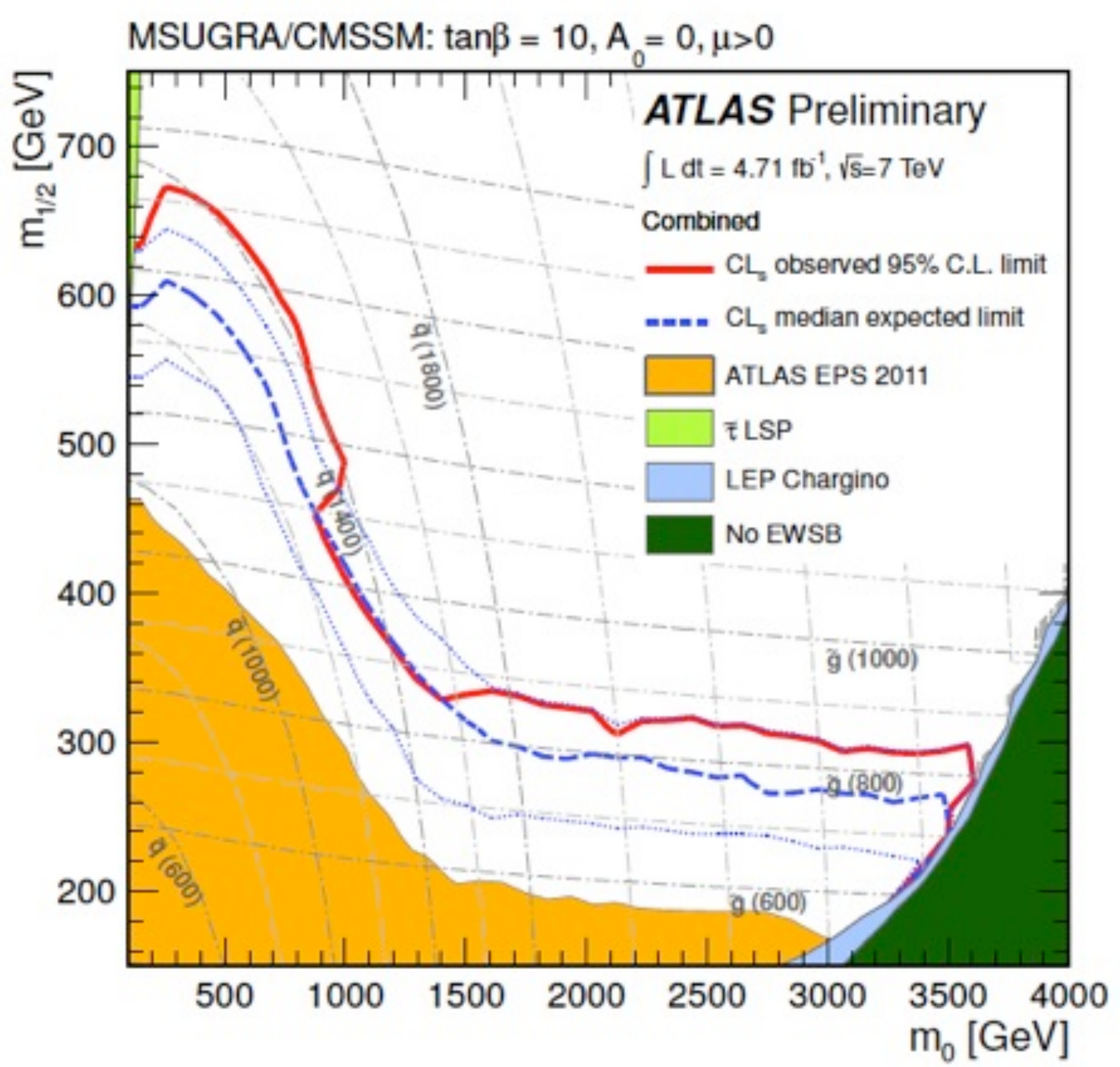
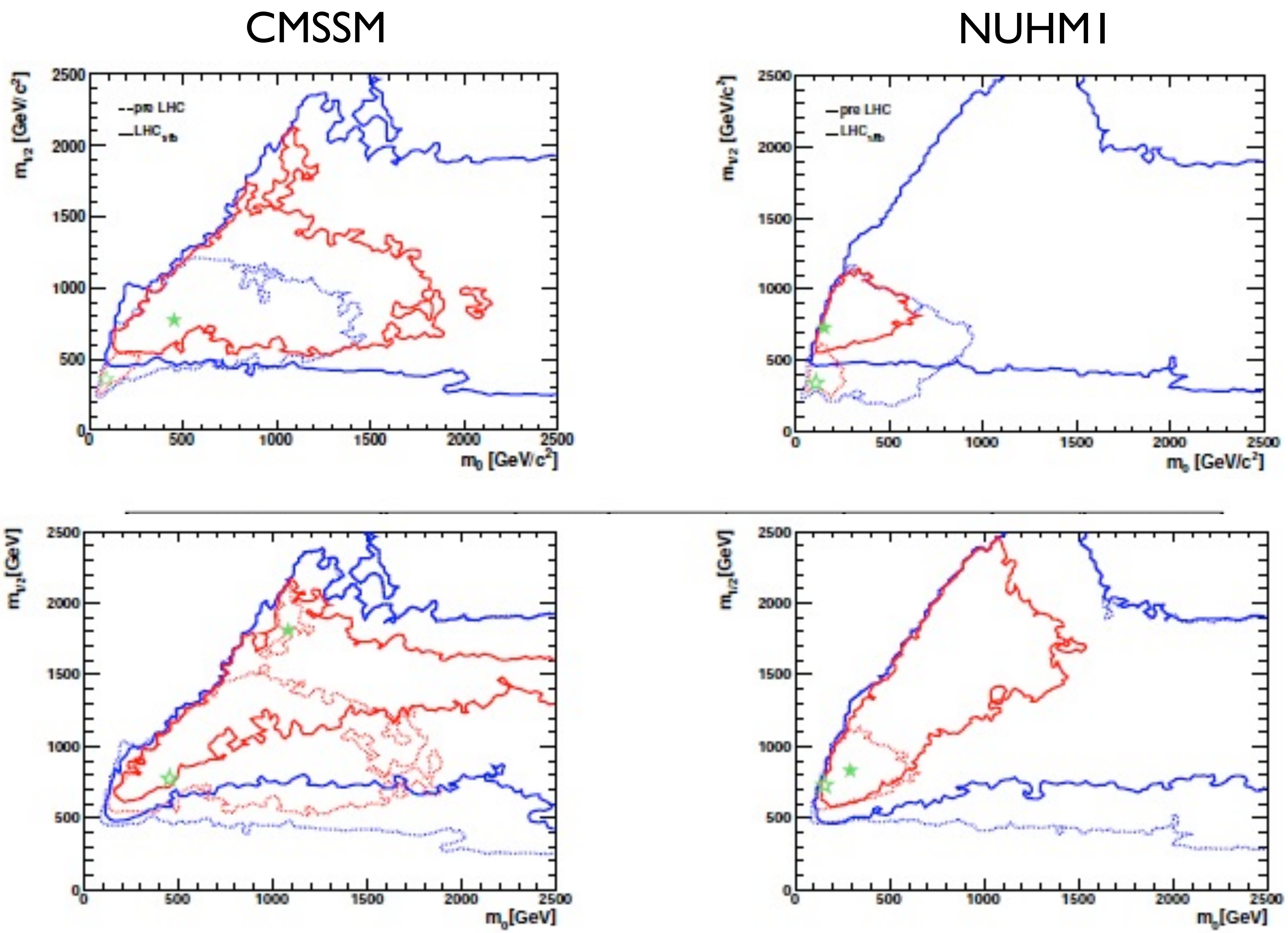


A note on LHC constraints

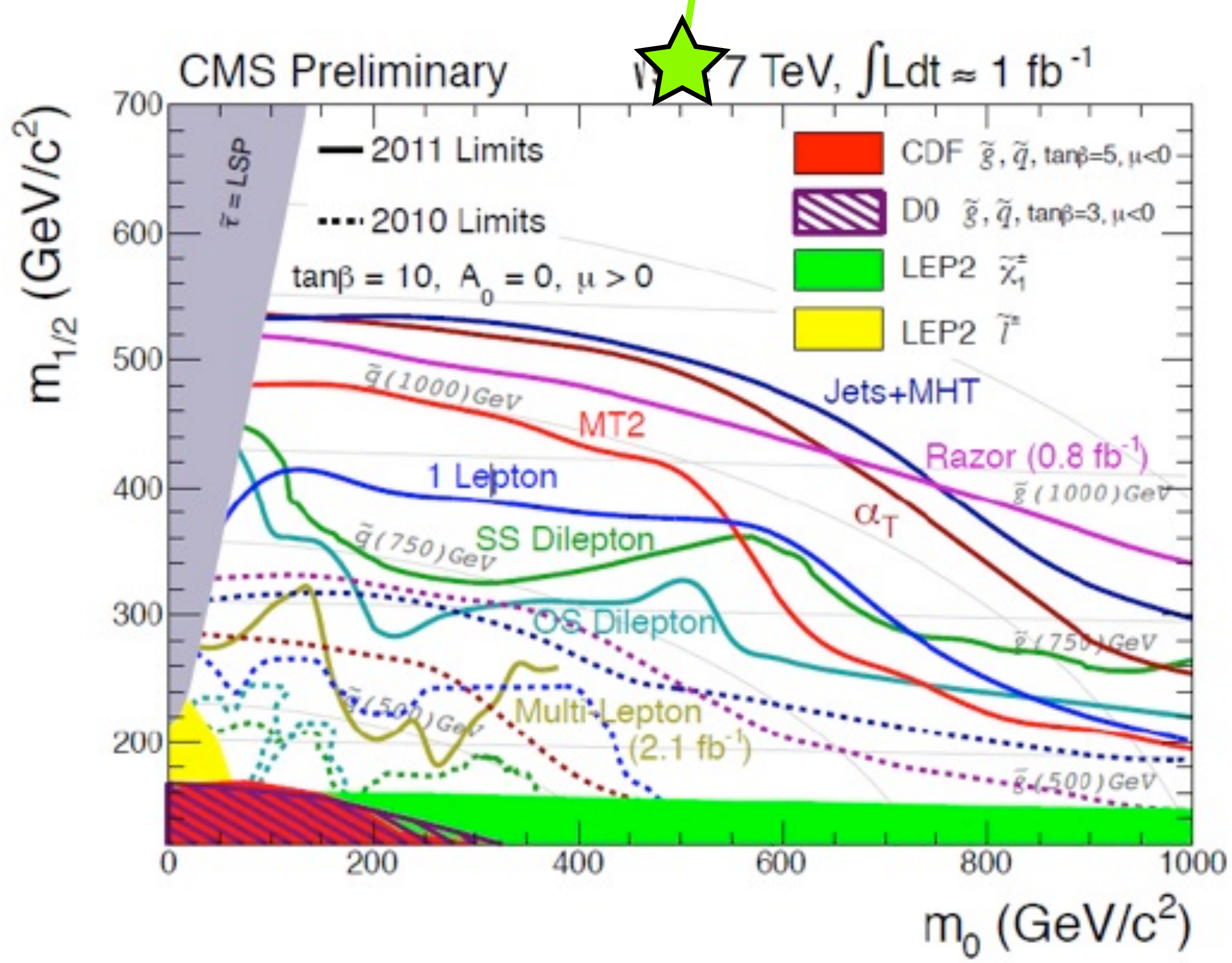


Buchmueller et al. (2012a,b)

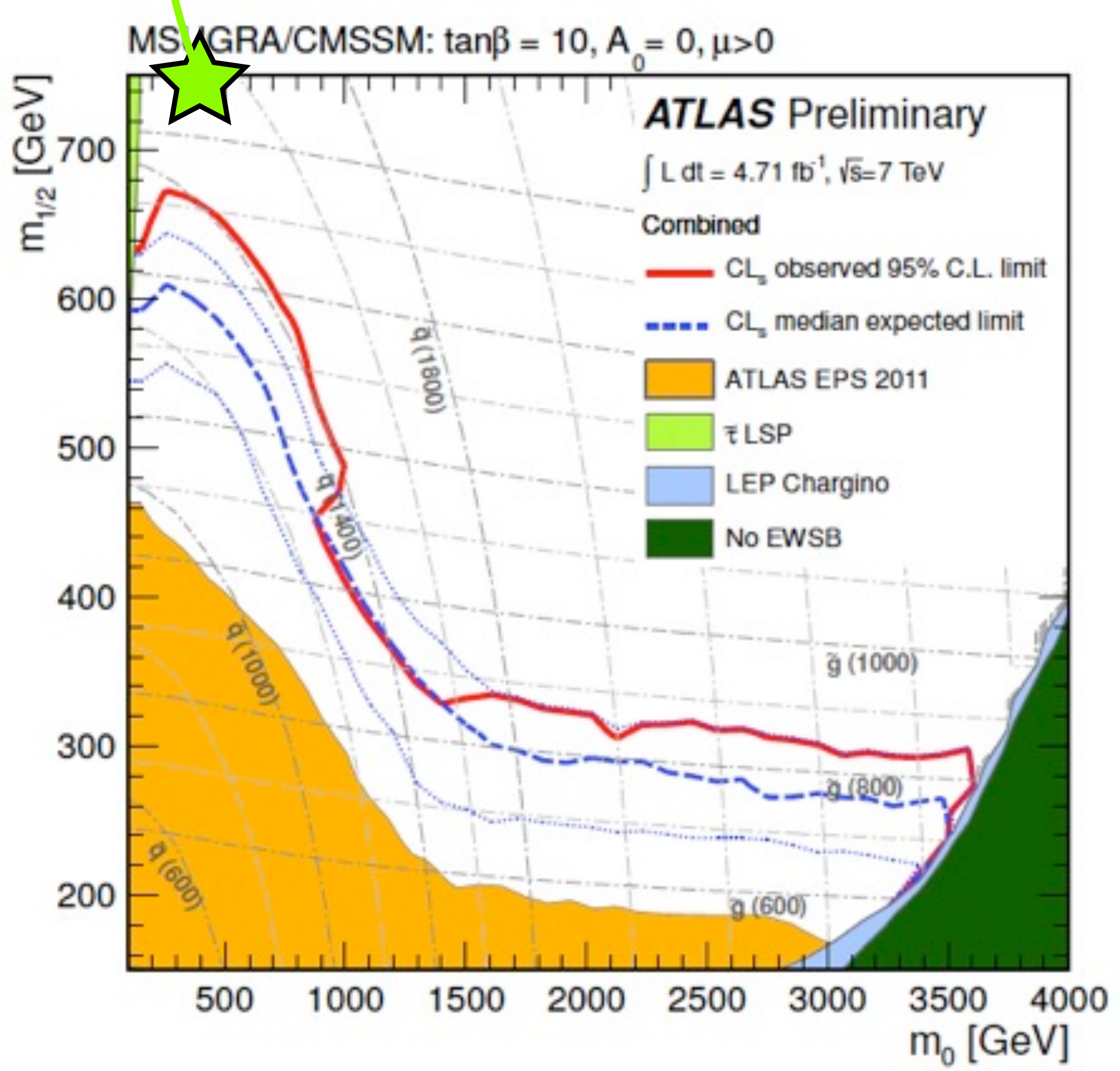
$(g-2)_\mu$ neglected	20.3/19	38%	2020$^+_-$	1410$^+_-$	2580$^+_-$	48$^+_-$	$126.6^{+0.7}_{-1.9}$
Both	19.5/19	43%	2020$^+_-$	1410$^+_-$	2580$^+_-$	48$^+_-$	$126.6^{+0.7}_{-1.9}$

A note on LHC constraints

T. Dorigo for CMS (2012)

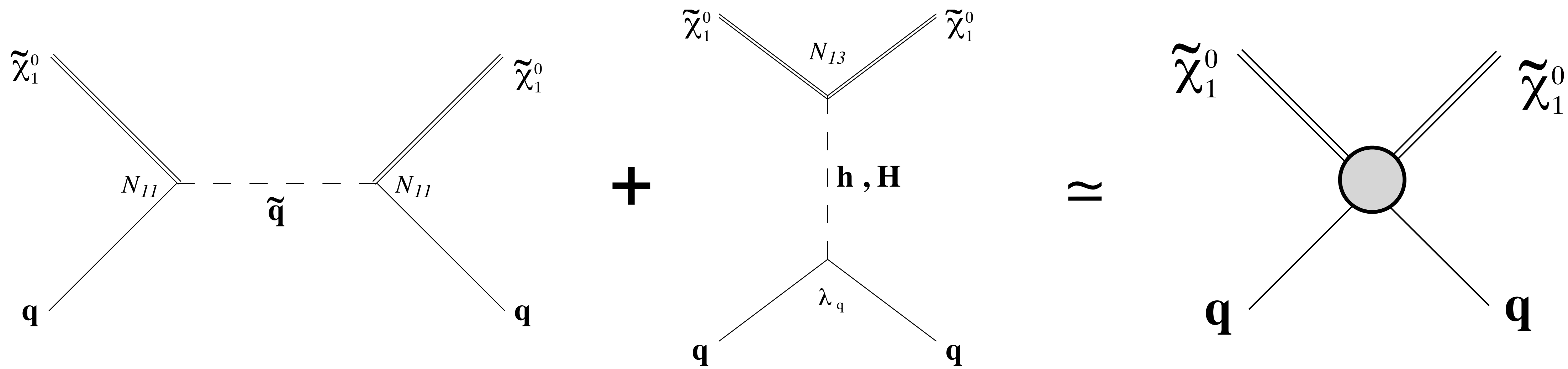


ATLAS-CONF-2012-033



Back to Dark Matter

Neutralino-Nucleon Scattering



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

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

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

Neutralino-Nucleon Scattering

$$f_u^{(N)} = \frac{m_u B_u^{(N)}}{m_N} = \frac{2\,\sigma_{\pi N}}{m_N\left(1+\frac{m_d}{m_u}\right)\left(1+\frac{B_d^{(N)}}{B_u^{(N)}}\right)},$$

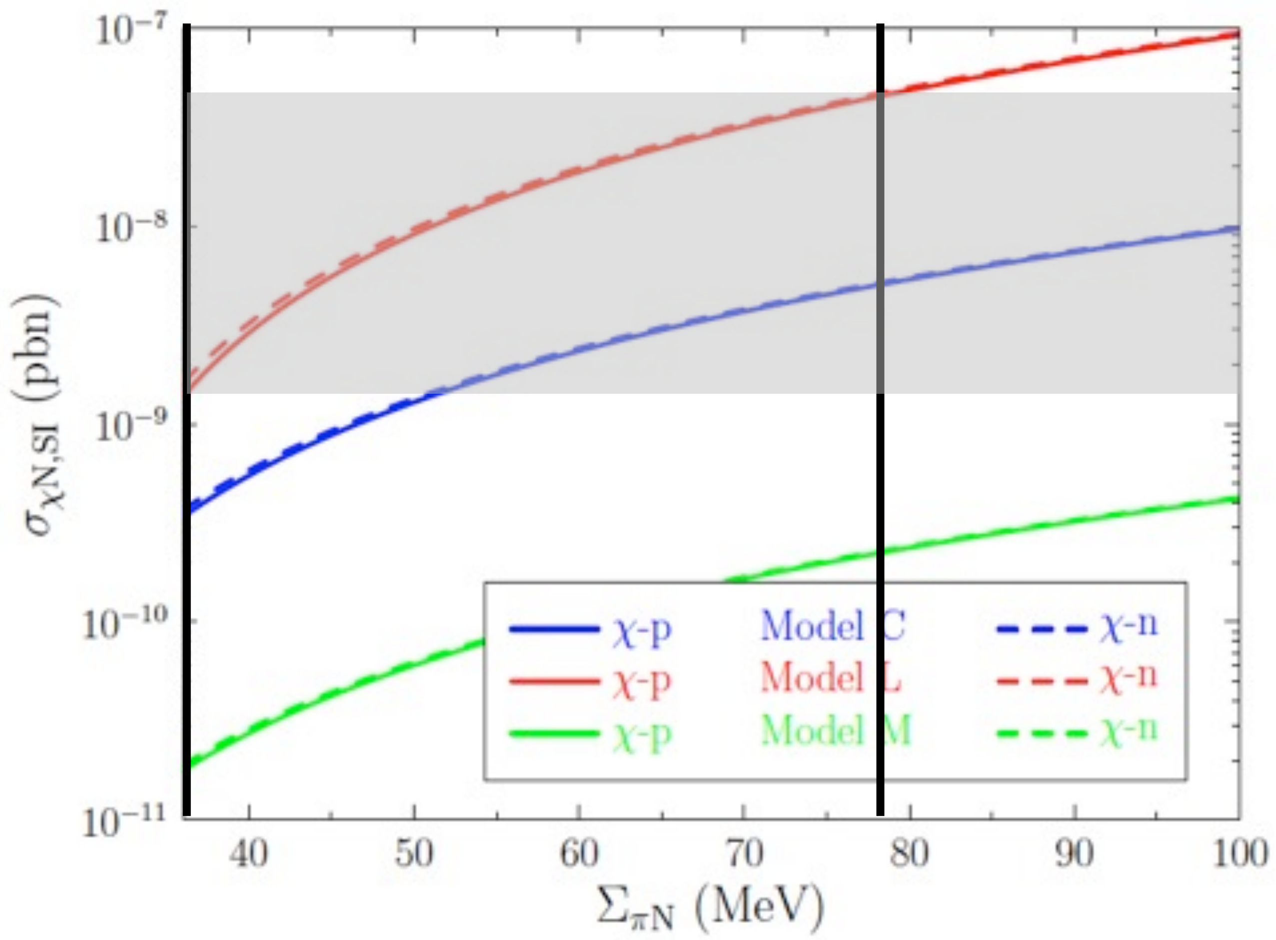
$$f_d^{(N)} = \frac{m_d B_d^{(N)}}{m_N} = \frac{2\,\sigma_{\pi N}}{m_N\left(1+\frac{m_u}{m_d}\right)\left(1+\frac{B_u^{(N)}}{B_d^{(N)}}\right)},$$

$$f_s^{(N)} = \frac{m_s B_s^{(N)}}{m_N} = \frac{\frac{m_s}{m_d}\,y\,\sigma_{\pi N}}{m_N\left(1+\frac{m_u}{m_d}\right)}.$$

$\sigma_{\pi N} = 55$ MeV and $\sigma_0 = 35$ MeV

$$f_u^{(p)} = 0.023,\quad f_d^{(p)} = 0.033,\quad f_s^{(p)} = 0.26$$
$$f_u^{(n)} = 0.018,\quad f_d^{(n)} = 0.042,\quad f_s^{(n)} = 0.26$$

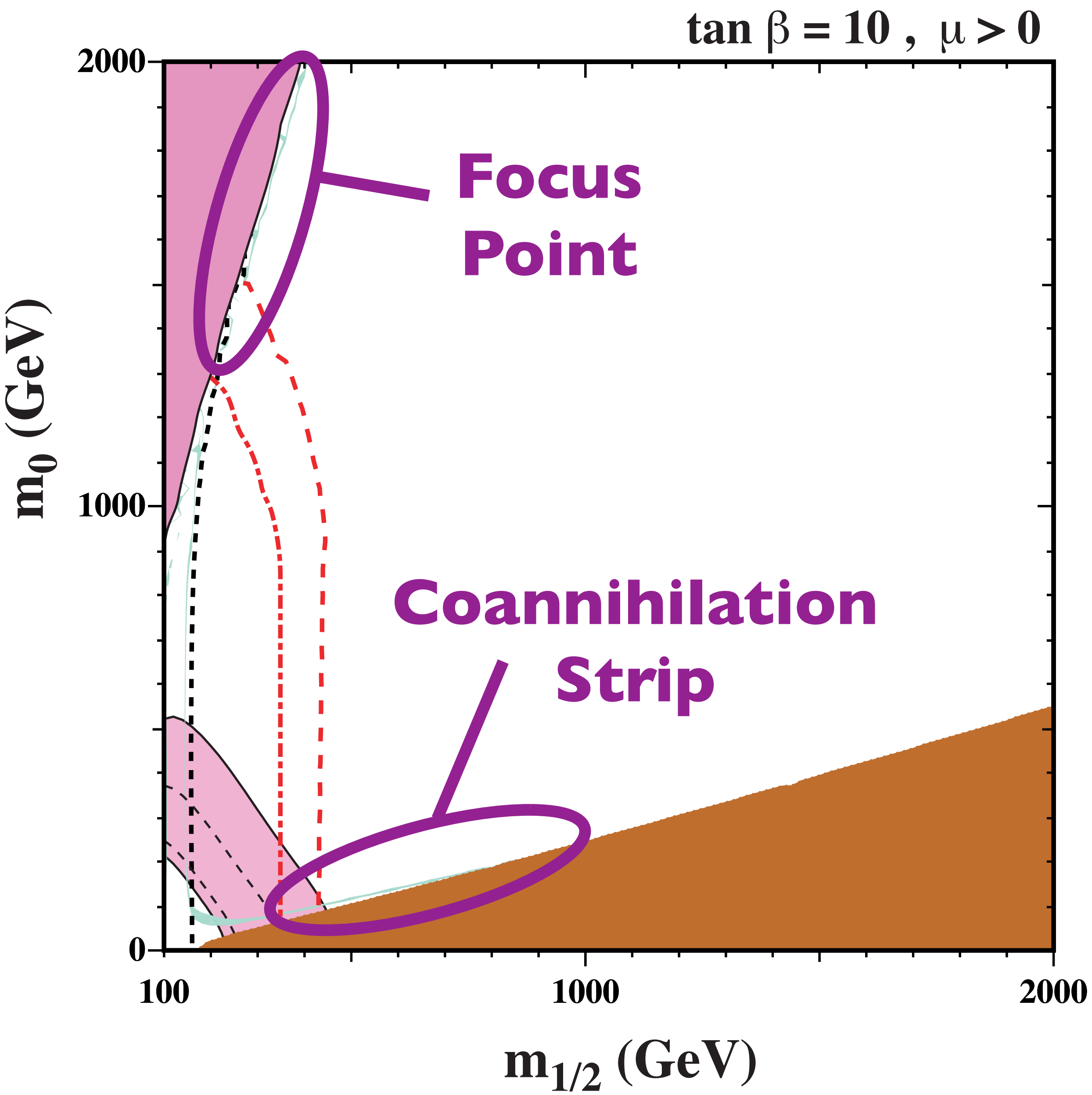
Ellis, Olive & Savage (2008)



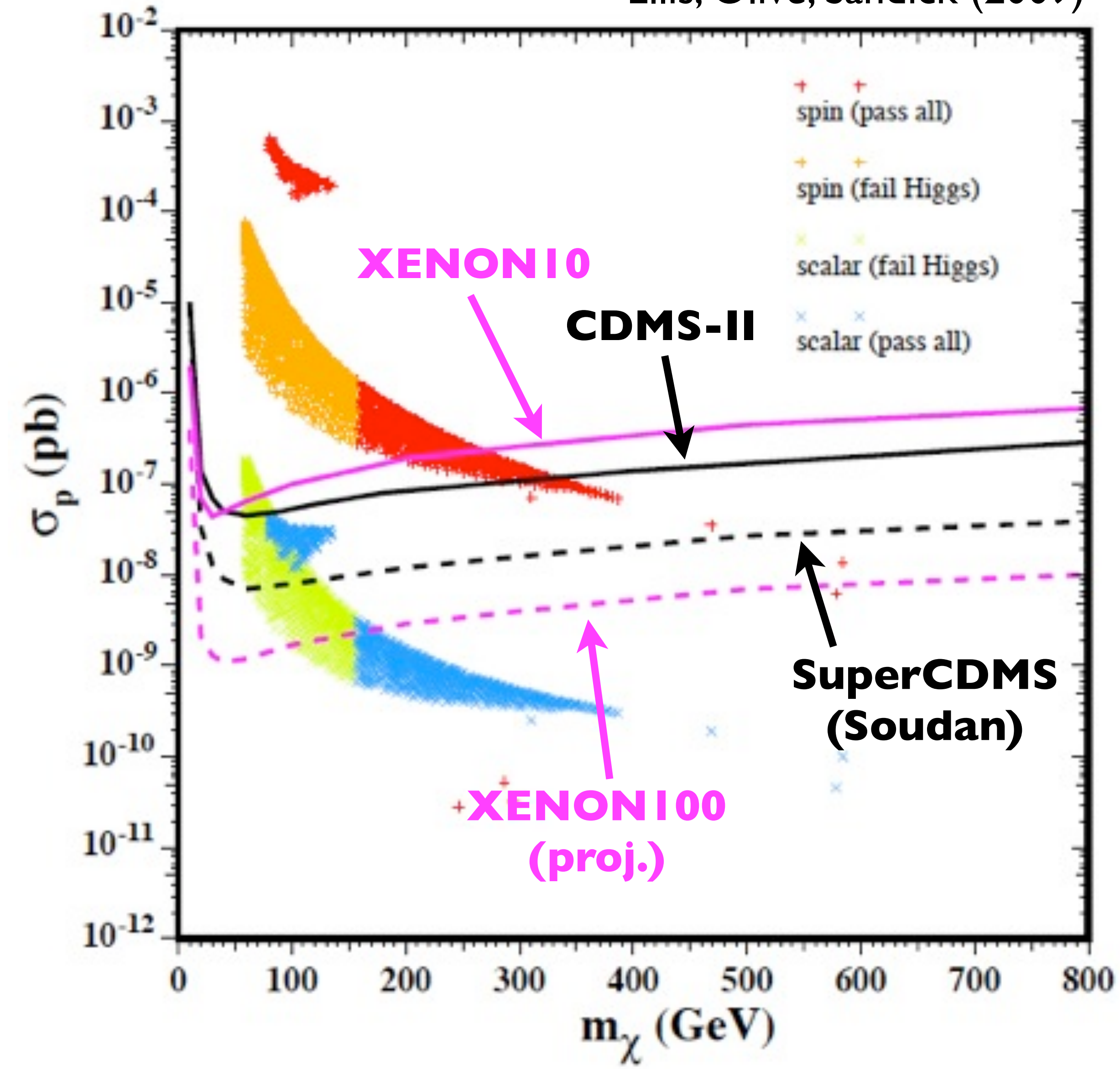
$$\sigma_{\pi N} = (50 \pm 14)\ \text{MeV}$$

Buchmueller *et al.* (2011)

CMSSM Example



Ellis, Olive, Sandick (2009)



Fine-Tuning

- What is the relationship between ease-of-discovery and electroweak naturalness?
- Define fine-tuning: sensitivity of m_Z to Lagrangian params.

$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2 2\beta}} - m_{H_d}^2 - m_{H_u}^2 - 2|\mu|^2 \qquad \sin 2\beta = \frac{2b}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2}$$

  - Terms on the RHS must cancel for m_Z = 91.19 GeV
  - If all RHS masses are $\gg m_Z$, the model is considered to be "fine-tuned."

Fine-Tuning

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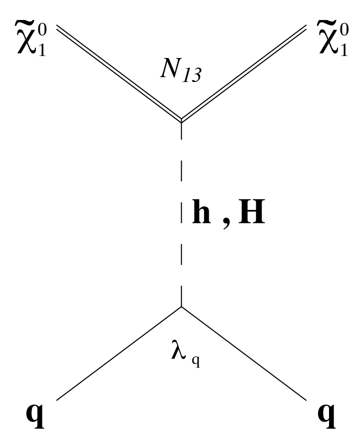
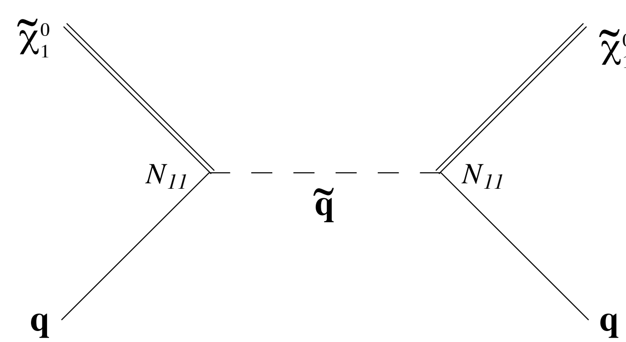
$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2 2\beta}} - m_{H_d}^2 - m_{H_u}^2 - 2|\mu|^2 \qquad \sin 2\beta = \frac{2b}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2}$$

- Depends on $\mu,\ m_{H_d},\ m_{H_u},\ \text{and } b \Longleftrightarrow \mu,\ m_A,\ m_Z,\ \tan\beta$

$\mathrm{M}_1,\ M_2,$
$\mu,\ \tan\beta,\ m_A$





$\mathrm{M}_1,\ M_2,\ \mu,\ \tan\beta,$
$\mathrm{m}_{\tilde{q}L}^2,\ m_{\tilde{q}R}^2,\ A_q$

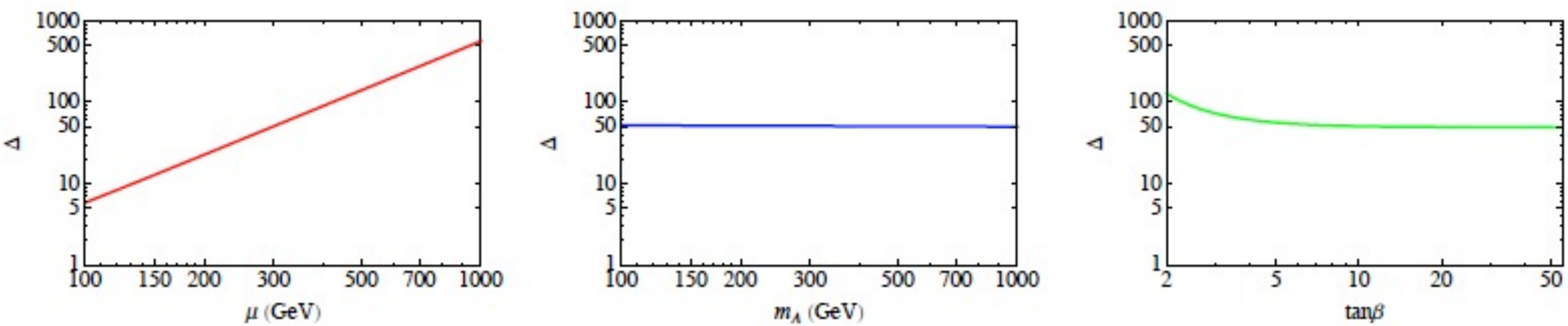
Fine-Tuning

- Quantify fine-tuning:

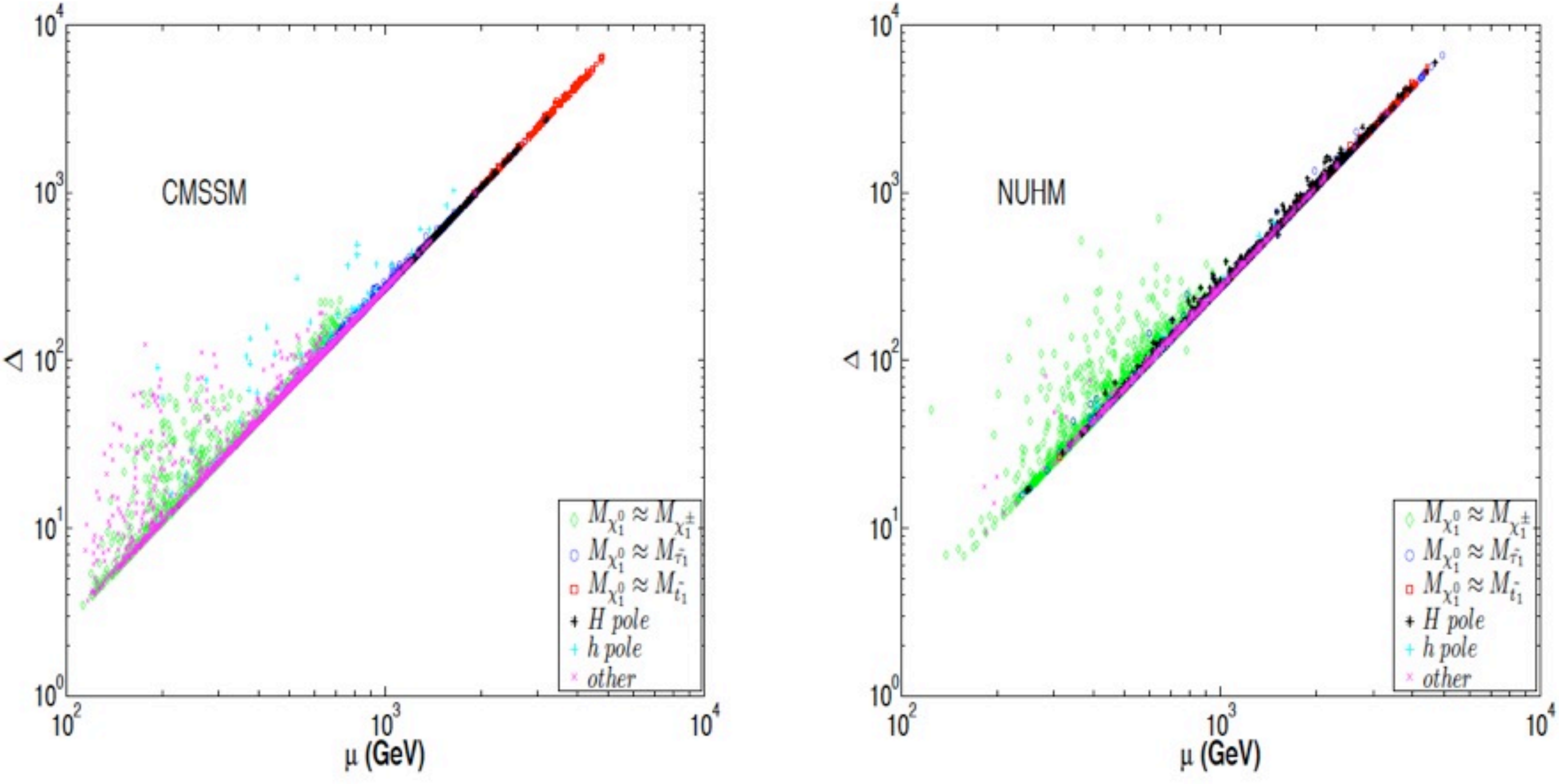
Perelstein & Spethmann
JHEP (2007)

$$A(\xi) = \left| \frac{\partial \log m_Z^2}{\partial \log \xi} \right|$$

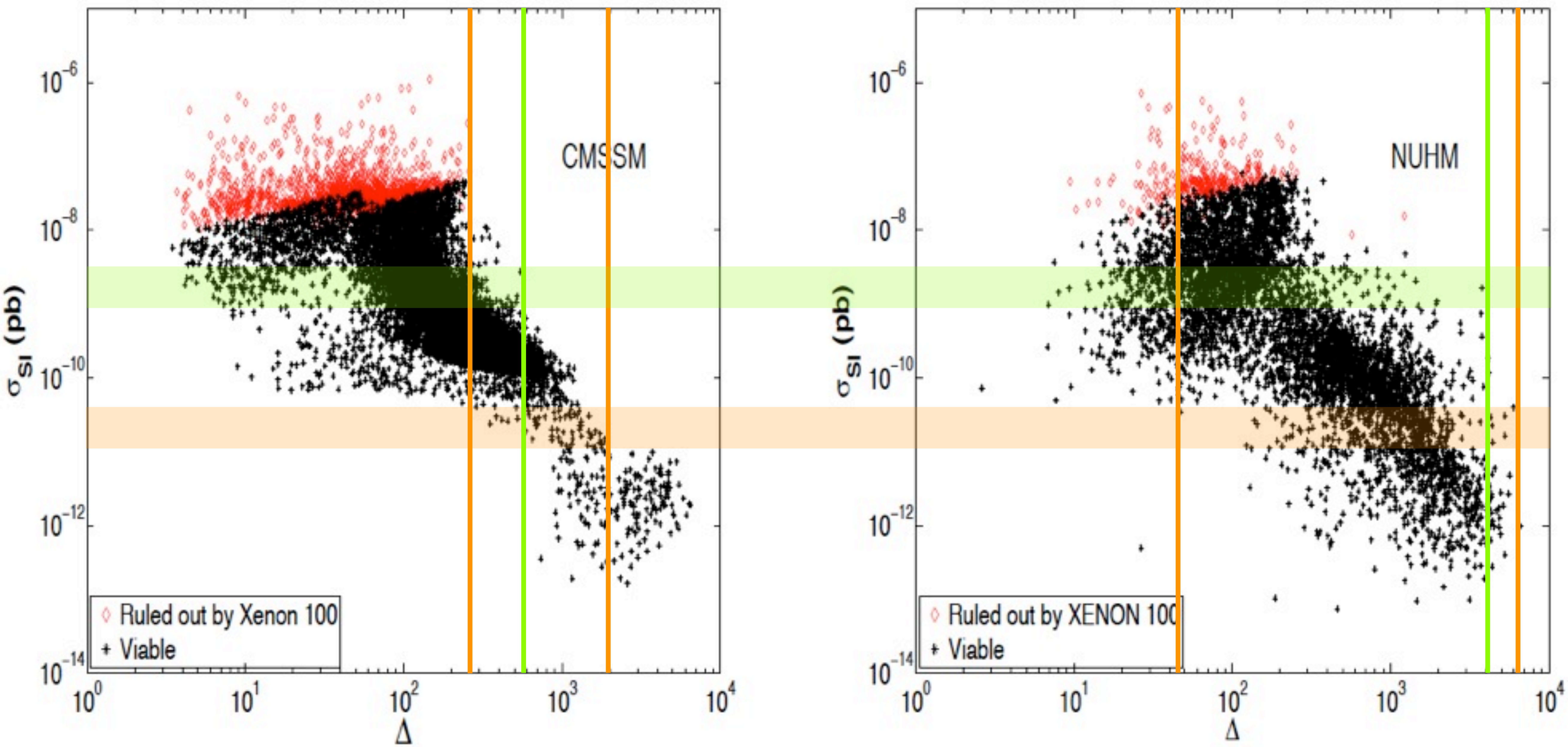
$$\Delta = \sqrt{A(\mu)^2 + A(b)^2 + A(m_{H_u}^2)^2 + A(m_{H_d}^2)^2}$$



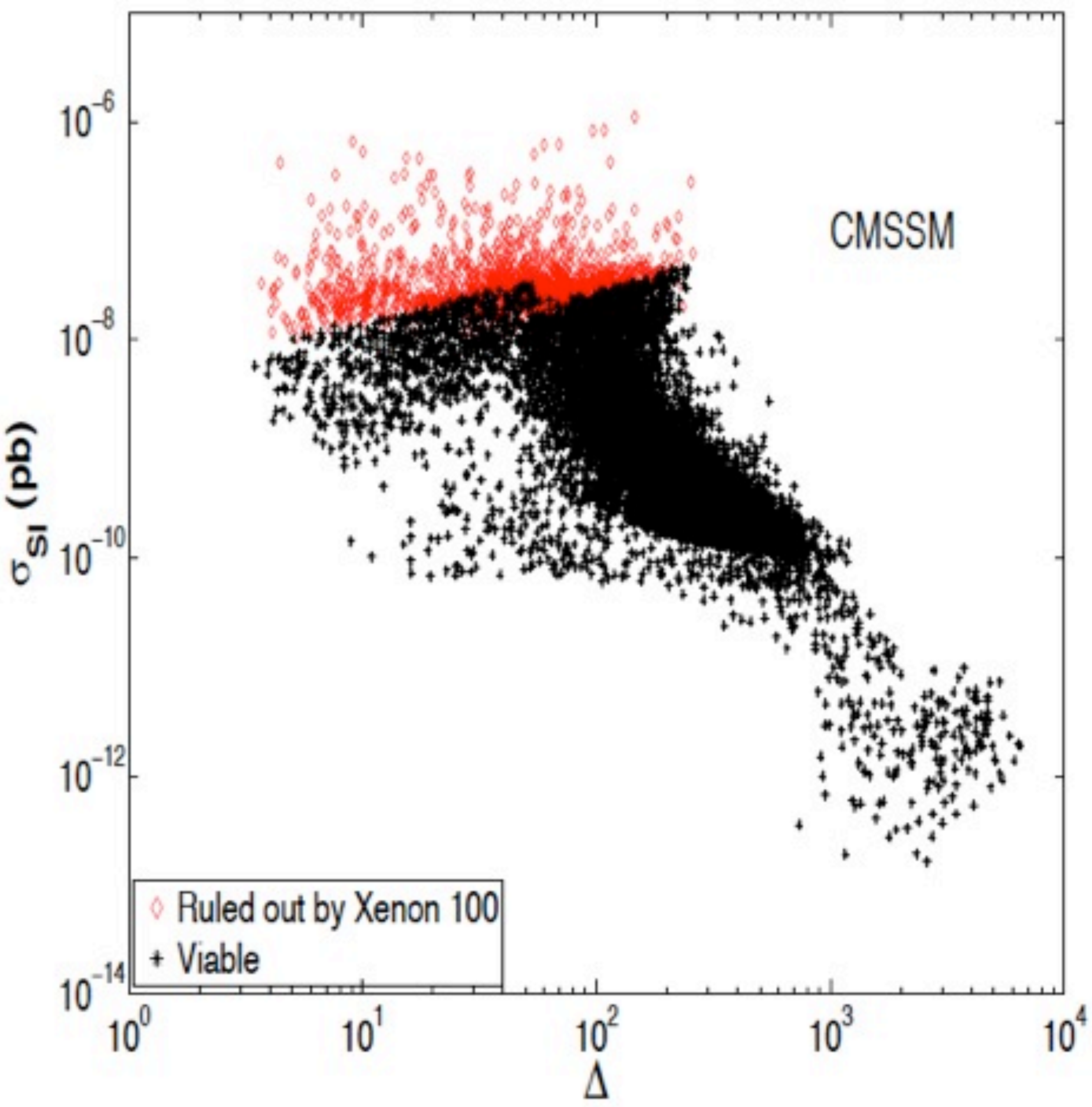
Fine-tuning and μ

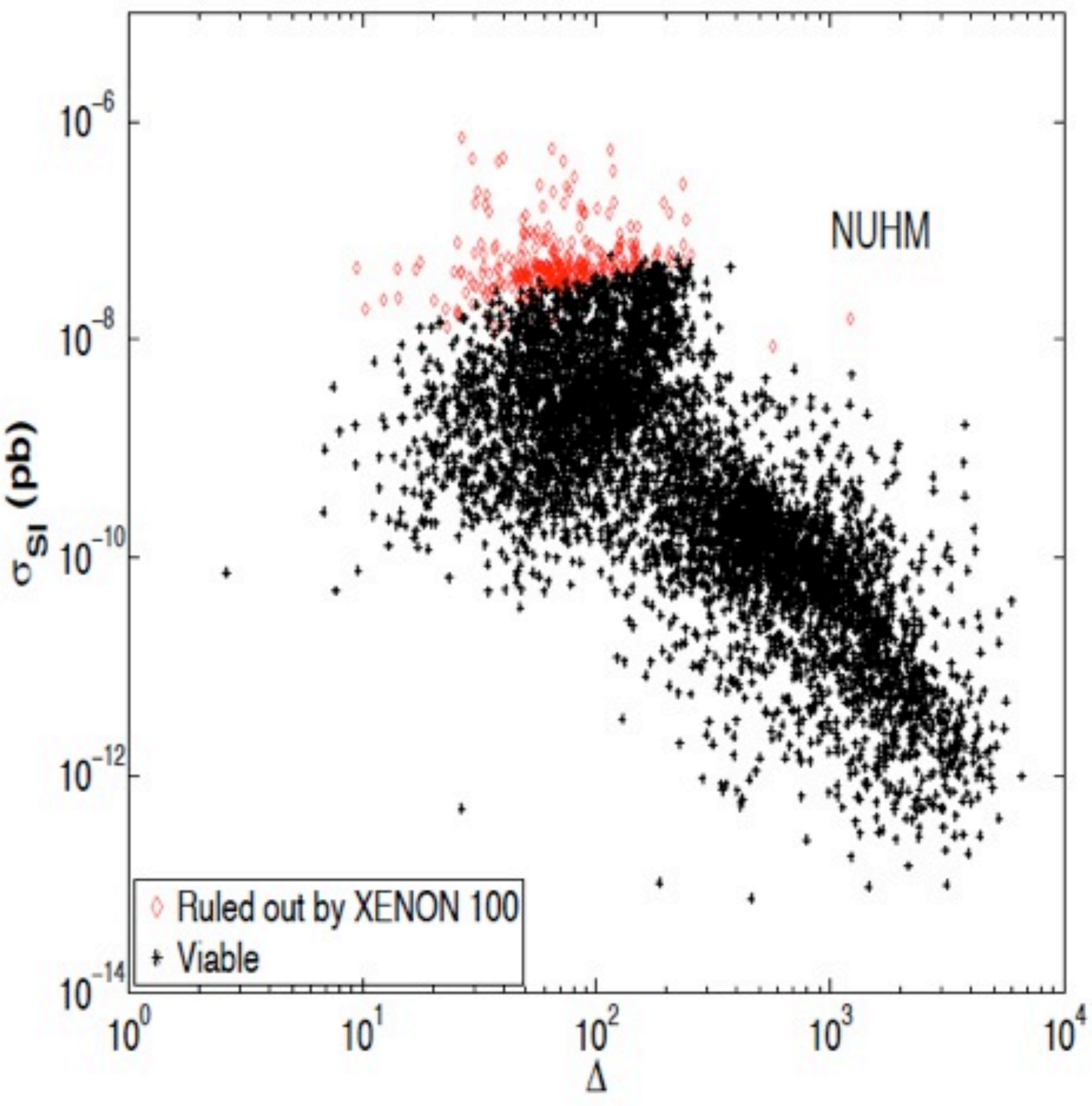


Dark Matter Direct Detection

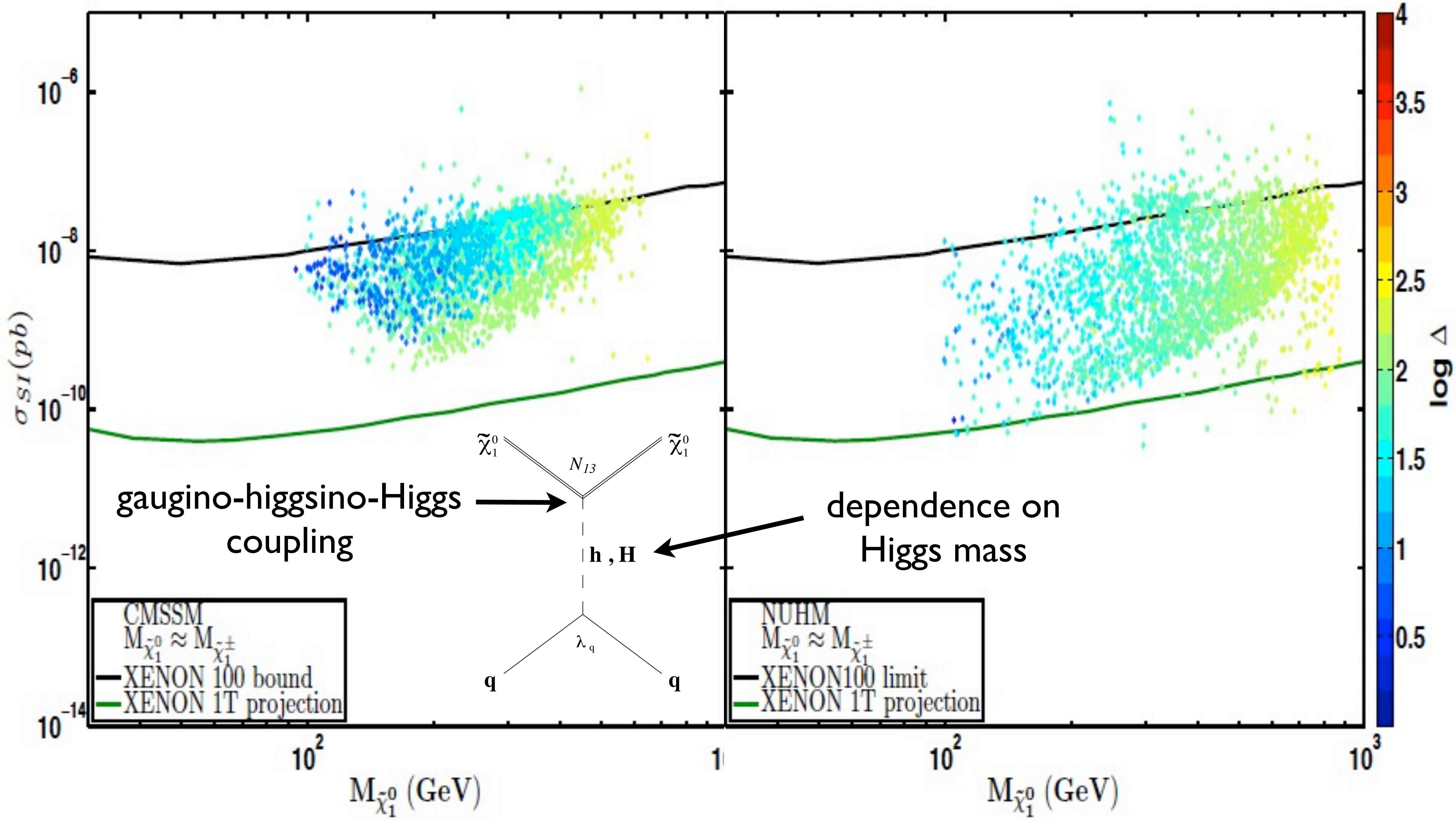


By Mass Hierarchy

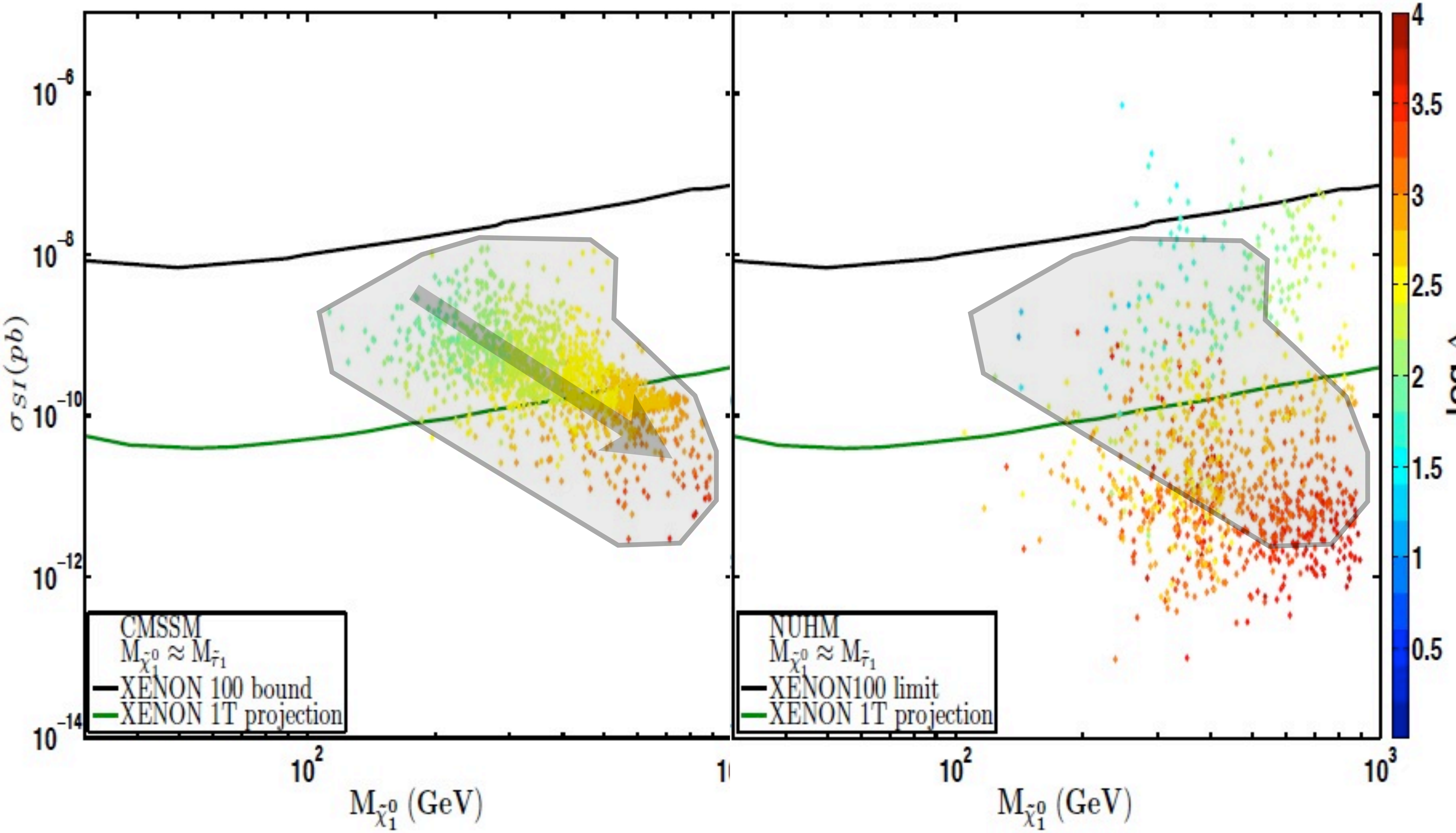




$$M_{\tilde{\chi}_1^0} \approx M_{\tilde{\chi}_1^\pm}$$



$$M_{\tilde{\chi}_1^0} \approx M_{\tilde{\tau}_1}$$

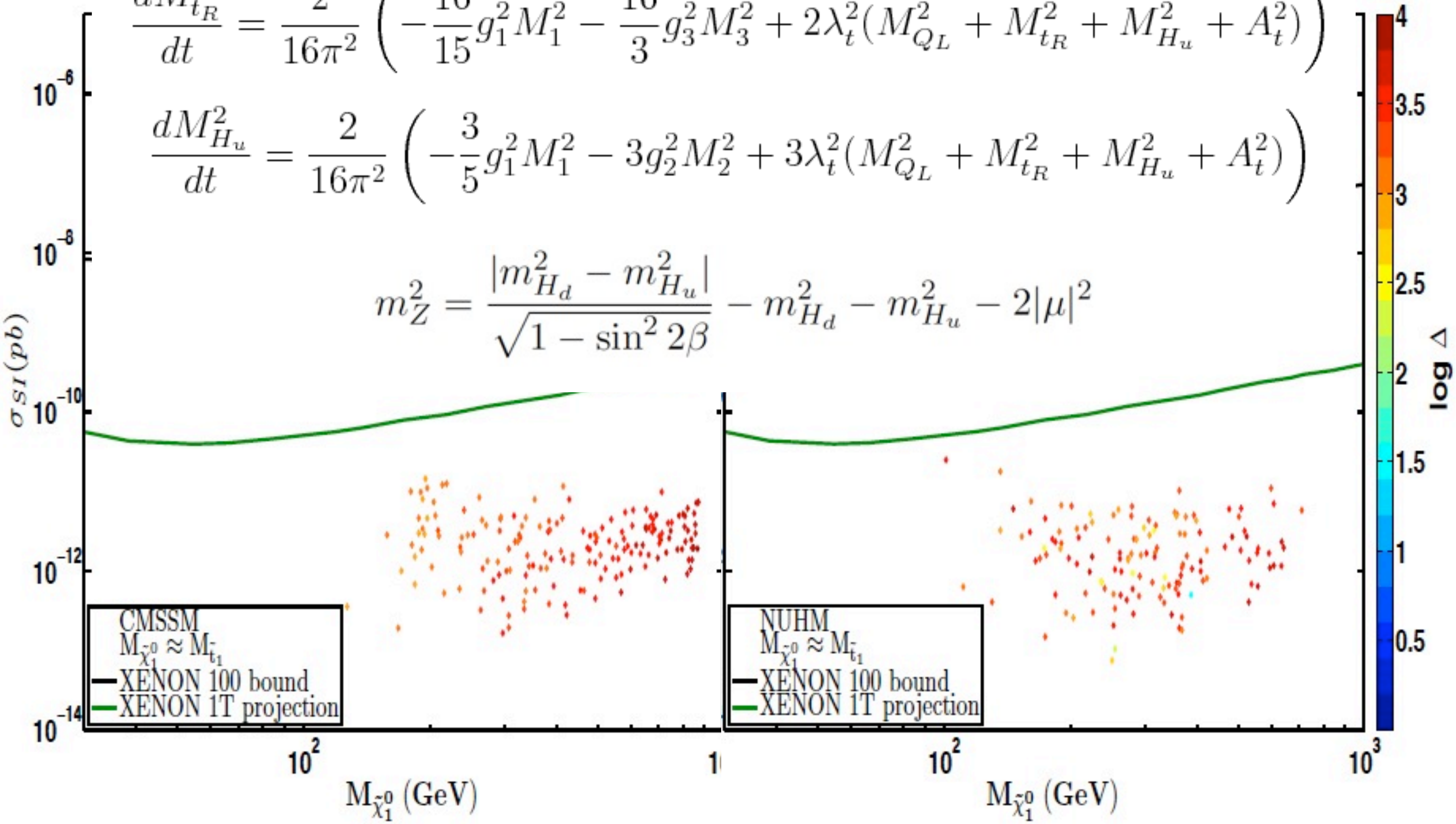


$$M_{\tilde{\chi}_1^0} \approx M_{\tilde{t}_1}$$

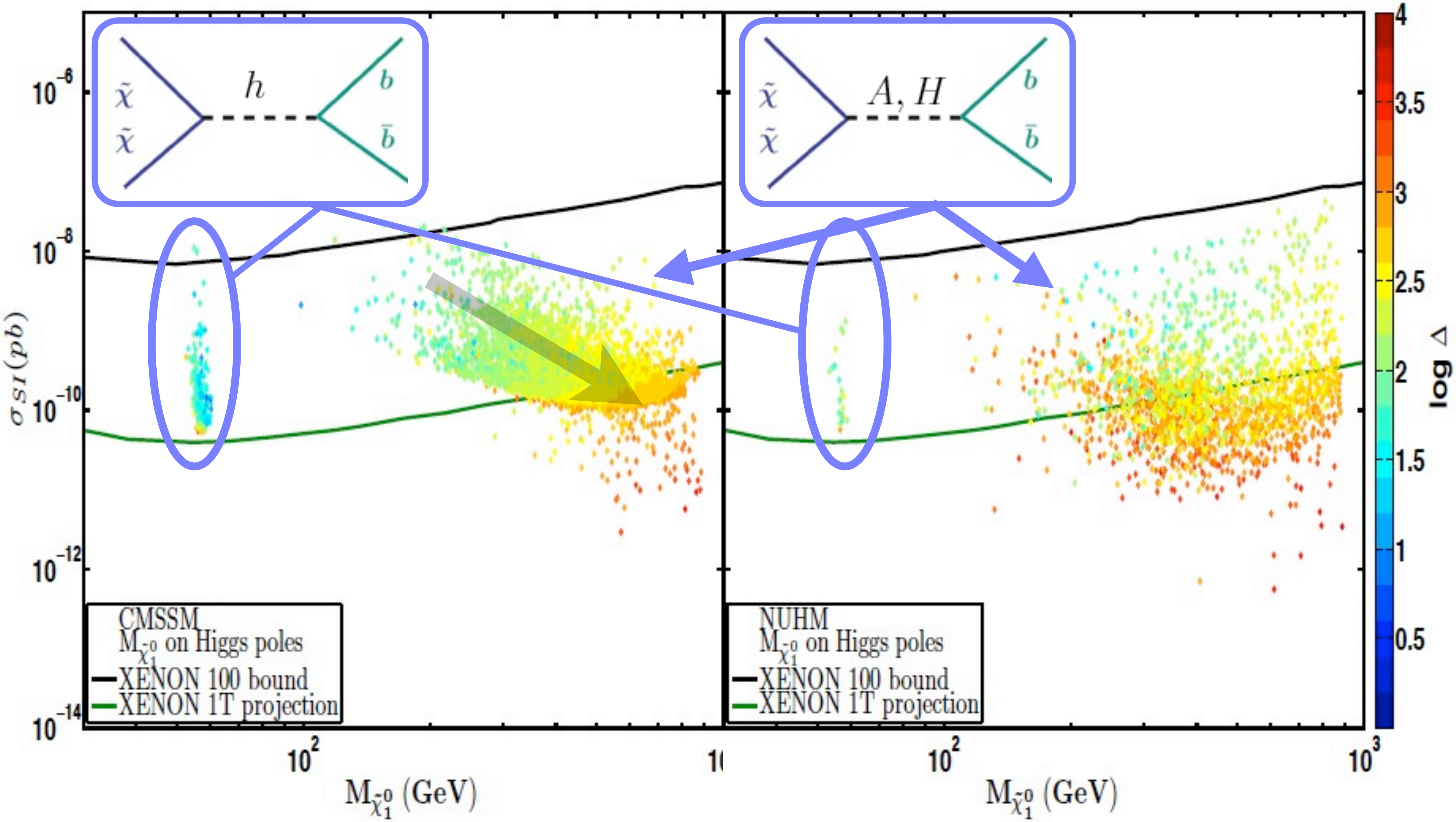
$$\frac{dM_{t_R}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{16}{15}g_1^2M_1^2 - \frac{16}{3}g_3^2M_3^2 + 2\lambda_t^2(M_{Q_L}^2 + M_{t_R}^2 + M_{H_u}^2 + A_t^2)\right)$$

$$\frac{dM_{H_u}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + 3\lambda_t^2(M_{Q_L}^2 + M_{t_R}^2 + M_{H_u}^2 + A_t^2)\right)$$

$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2 2\beta}} - m_{H_d}^2 - m_{H_u}^2 - 2|\mu|^2$$

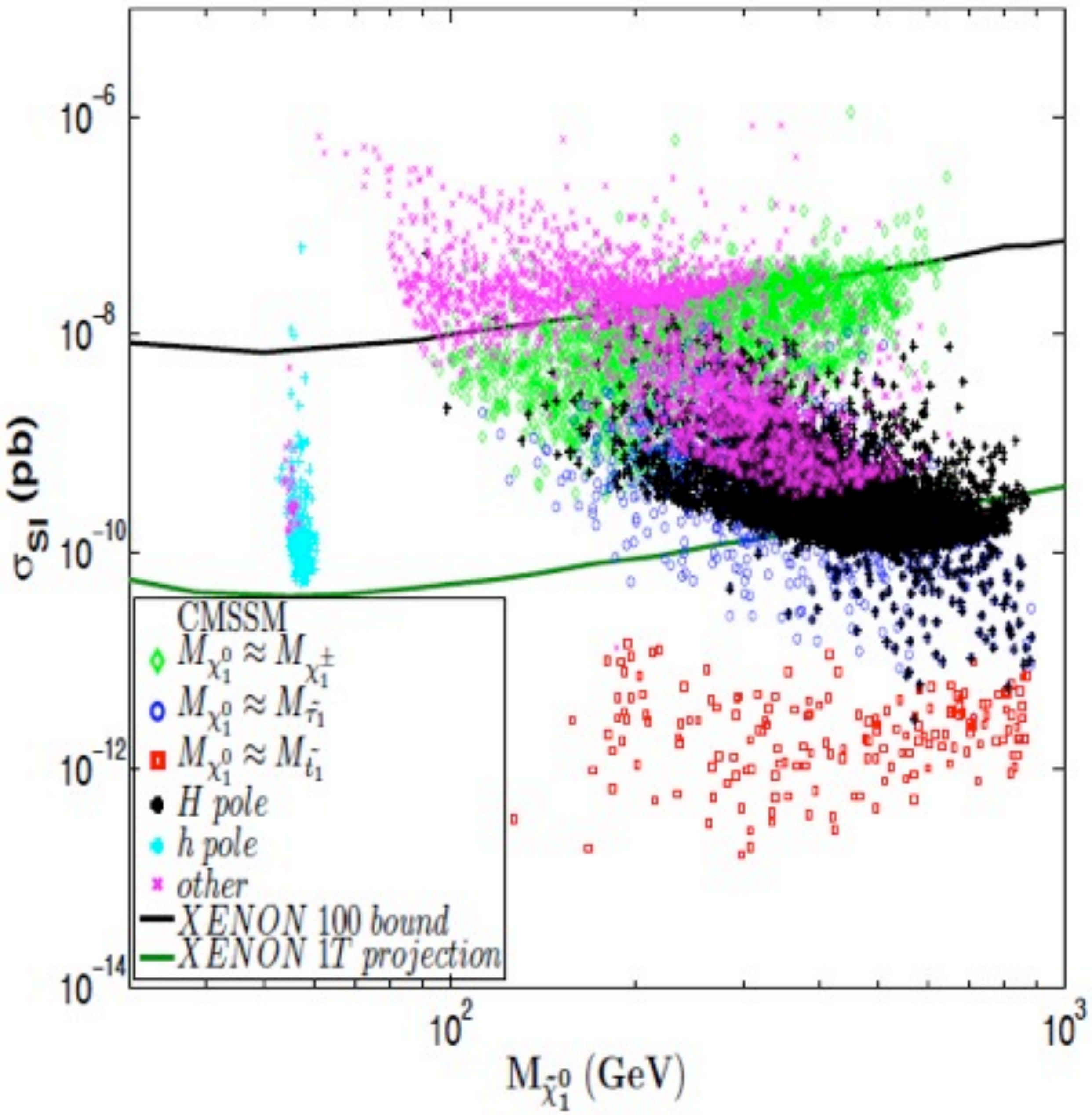


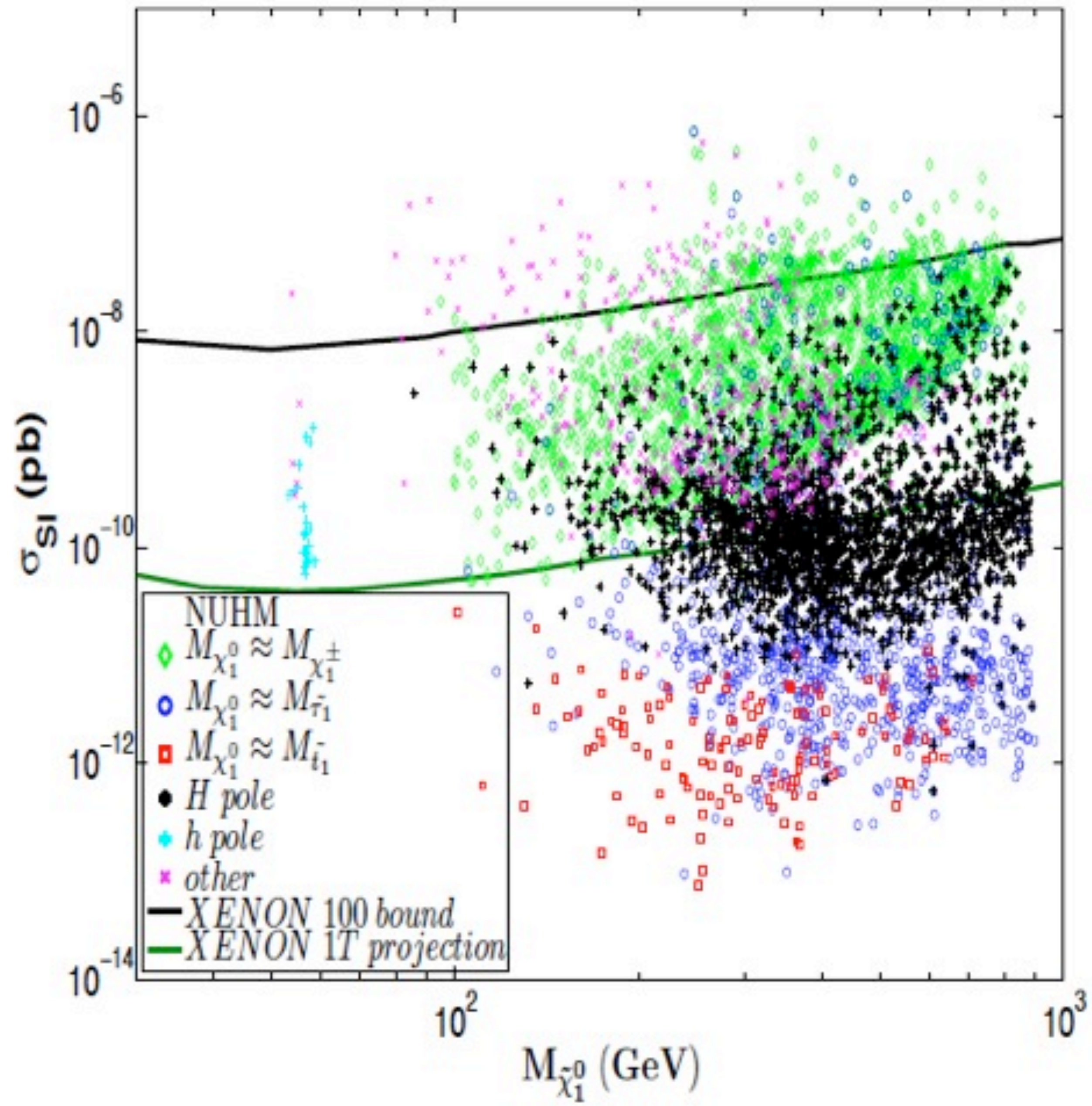
Higgs Poles



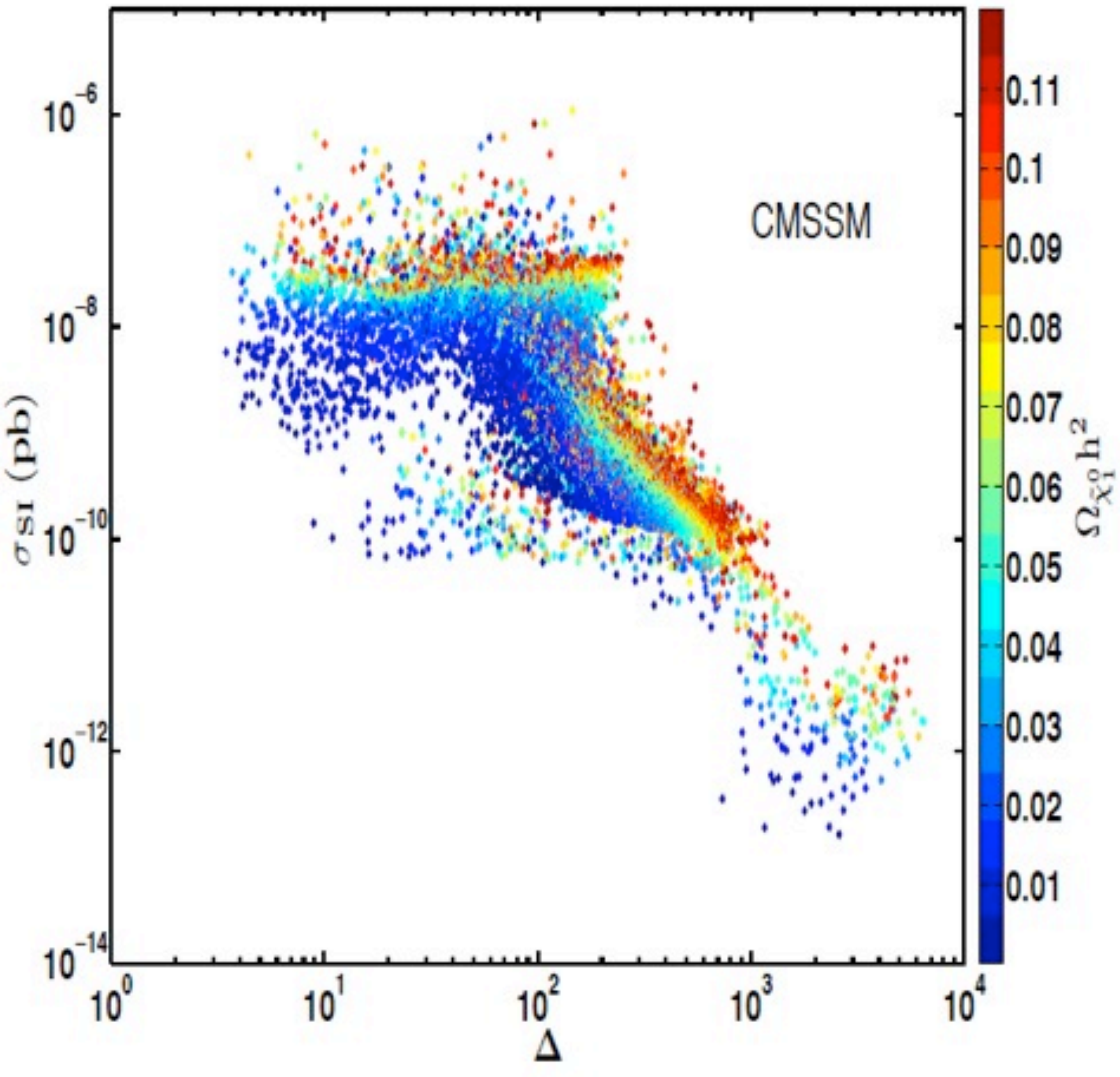
$\tilde{\chi}$
$\tilde{\chi}$
h
b
$\bar{b}$
$\tilde{\chi}$
$\tilde{\chi}$
A, H
b
$\bar{b}$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
$\sigma_{SI}(pb)$
10^{2}
10^{3}
$M_{\tilde{\chi}_1^0}$ (GeV)
CMSSM
$M_{\tilde{\chi}_1^0}$ on Higgs poles
XENON 100 bound
XENON 1T projection
NUHM
$M_{\tilde{\chi}_1^0}$ on Higgs poles
XENON 100 bound
XENON 1T projection
log Δ
4
3.5
3
2.5
2
1.5
1
0.5

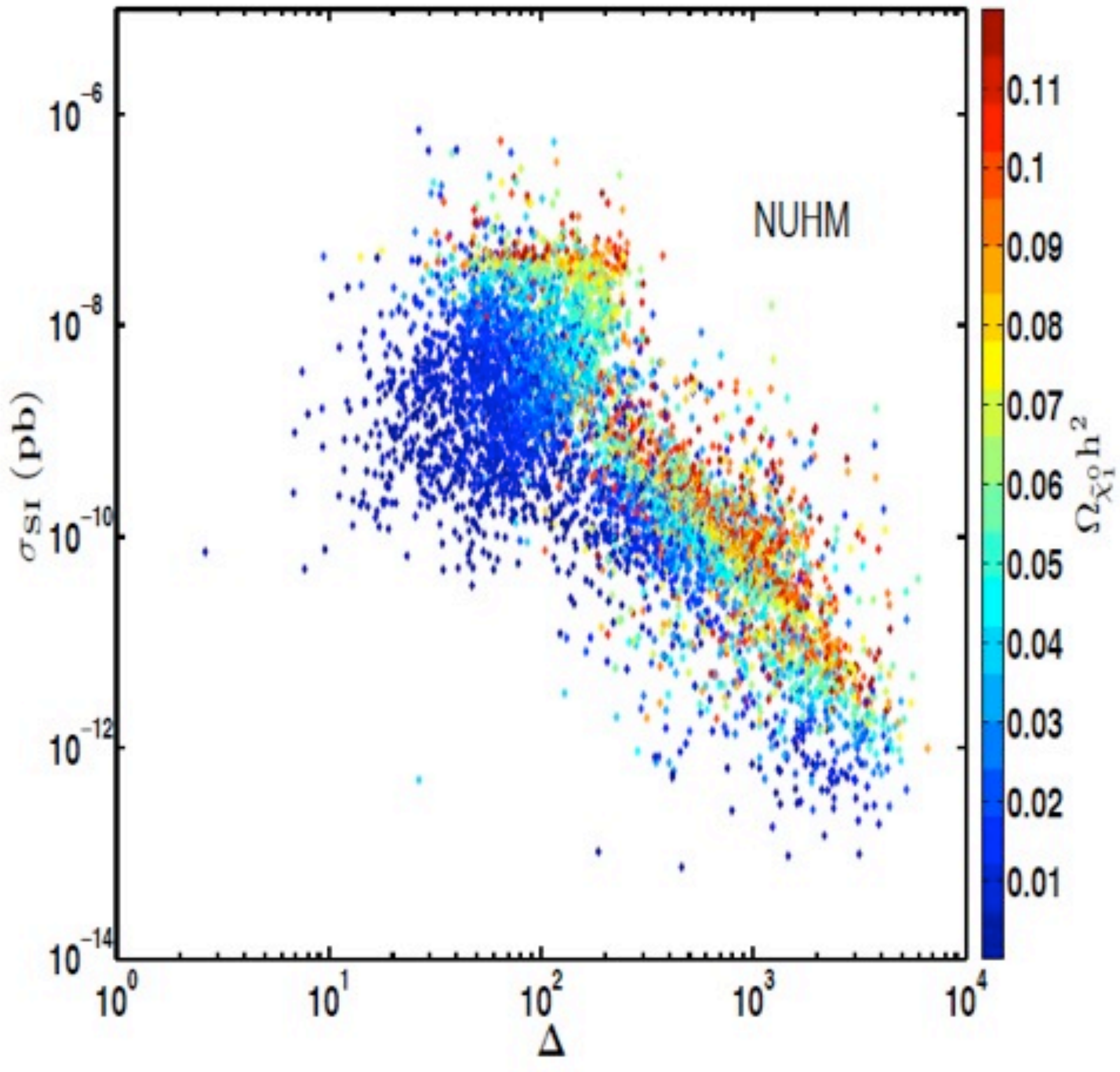
The Whole Picture



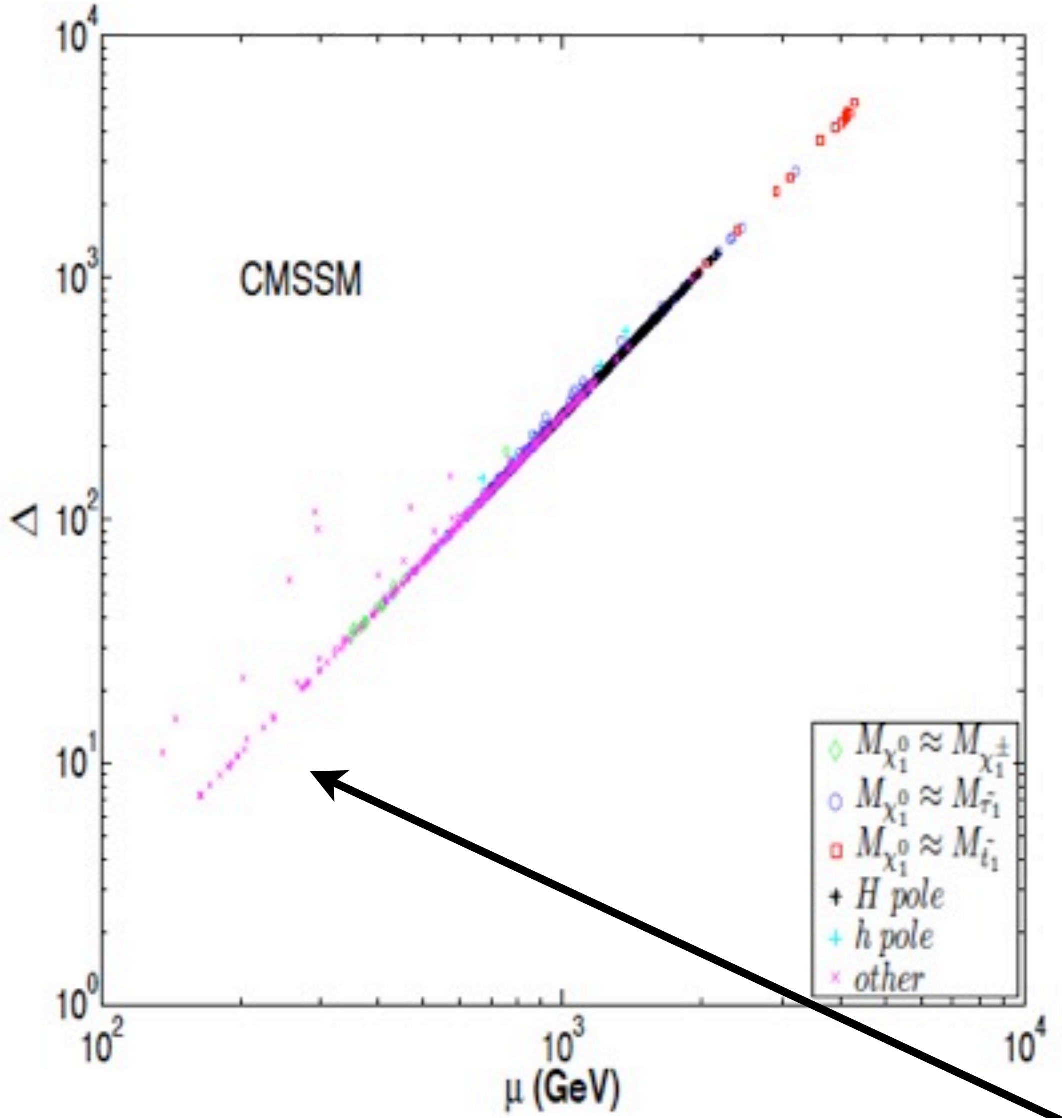


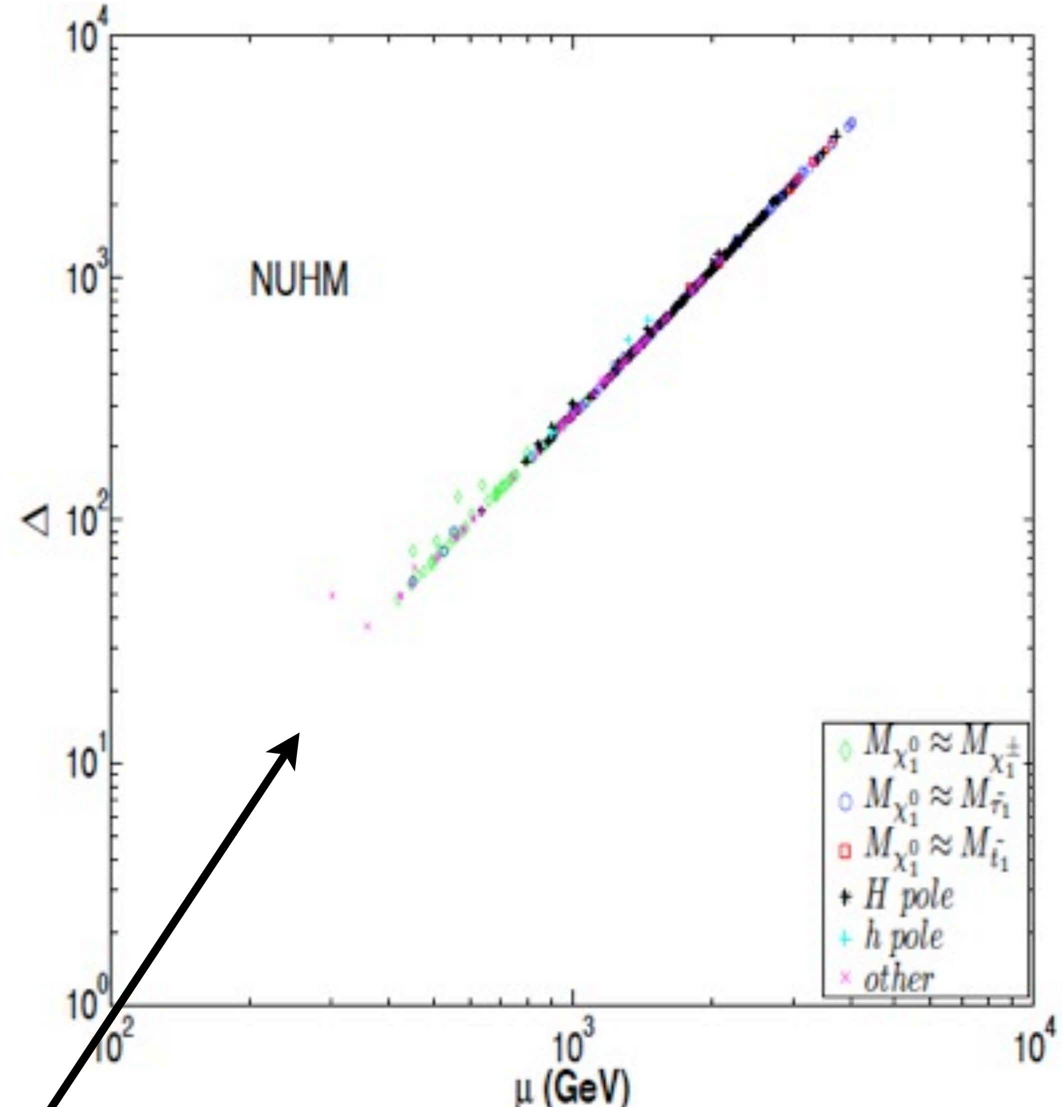
Relic Abundance





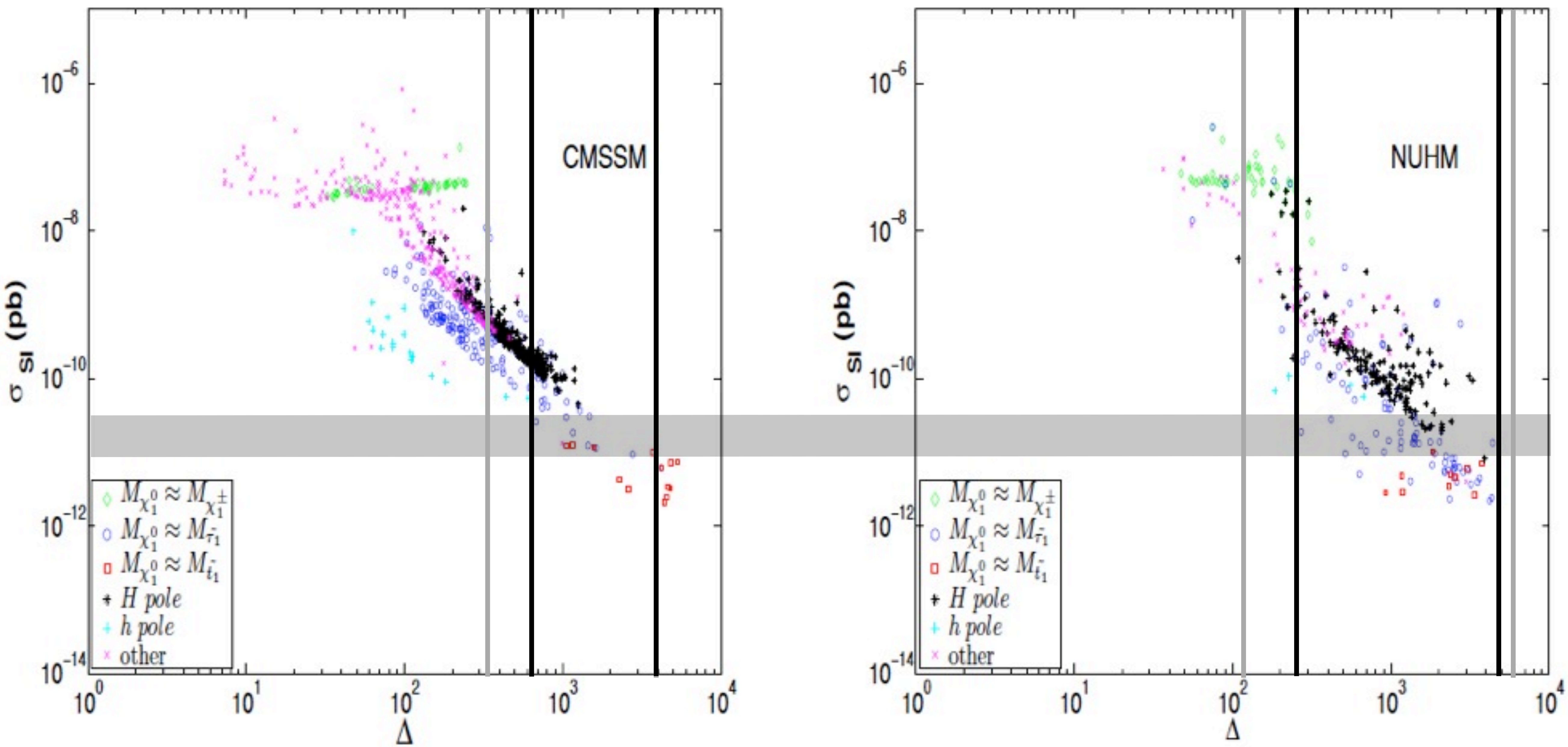
$\Omega_\chi = \Omega_{CDM}$



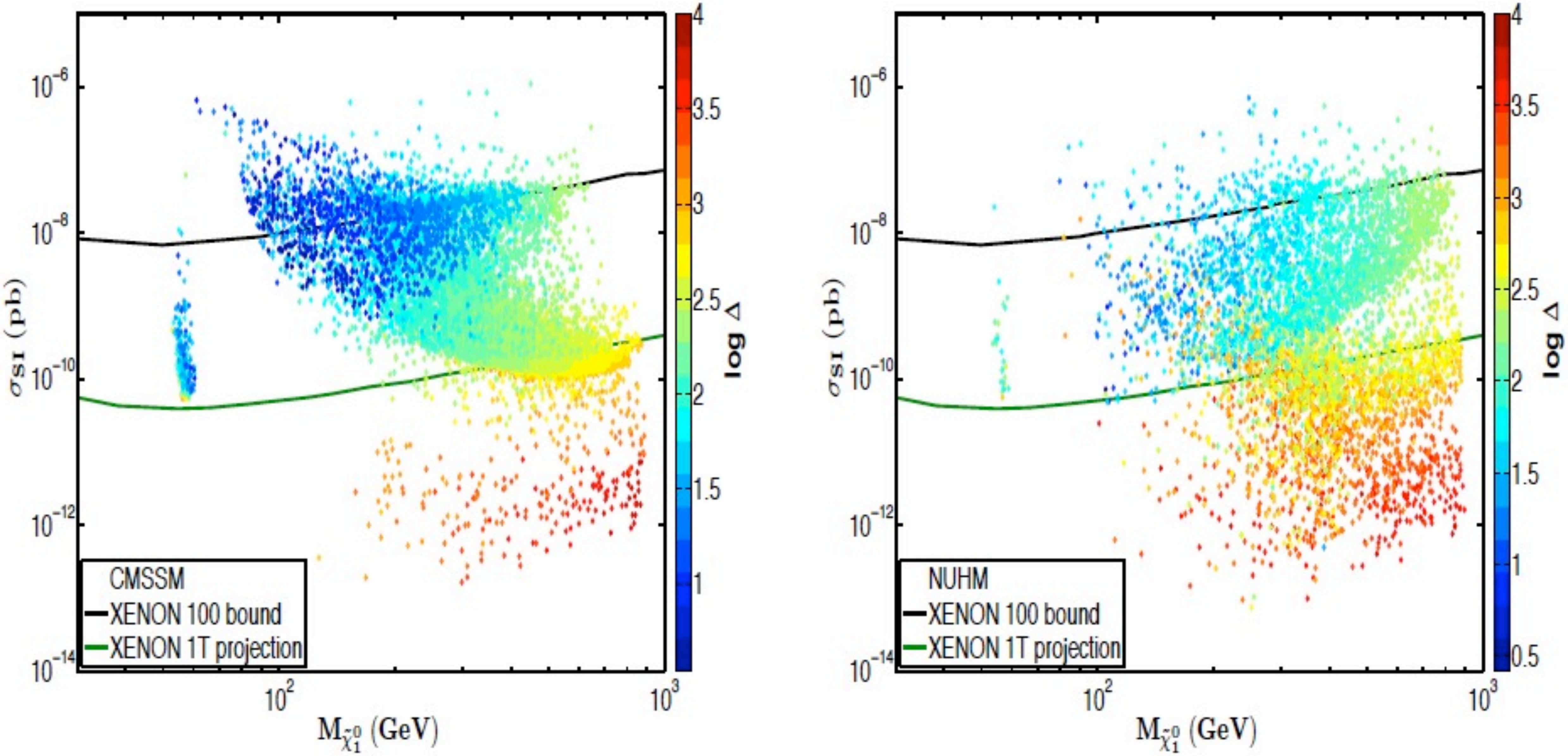


most higgsino-like points disappear

$\Omega_\chi = \Omega_{CDM}$



$\Omega_\chi = \Omega_{CDM}$



"Certain things have come to light."

"New **** Has Come to Light": Information Seeking Behavior in *The Big Lebowski*

EMILY DILL AND KAREN JANKE

> It just seemed interesting to us to thrust that character into the most confusing situation possible the person it would seem on the face of it least-equipped to deal with it.
>
> Ethan Coen ("Making" 1:33)

> And there was something attractive about having the main character not be a private eye, but just some pothead intuitively figuring out the ins and outs of an elaborate intrigue. And then there's Walter, whose instincts are always wrong.
>
> Ethan Coen (Stone 88)

WHEN STUDYING INFORMATION SEEKING BEHAVIOR, THE TERM information is often subjectively defined, framed by the academic discipline in which the word is used. In many definitions information is passive—referred to as "a collection of facts" or "a numerical measure;" yet in others it is an active pursuit—"the communication of knowledge" or "knowledge derived from study, experience, or instruction" ("Information" 927). Although knowledge, facts, and numbers are invoked in these particular definitions of information, others in the information science discipline itself have chosen more general terms, i.e., "any *difference* you perceive, in your environment or within yourself. It is any aspect that you notice in the pattern of reality" (Case 5). Any notion of information as intrinsically linked to reality is particularly interesting when applied to *The Big Lebowski*, a film that often requires the viewer to watch several times before understanding the fantastically contrived plot, let alone before appreciating the central message of the film, if one actually exists.

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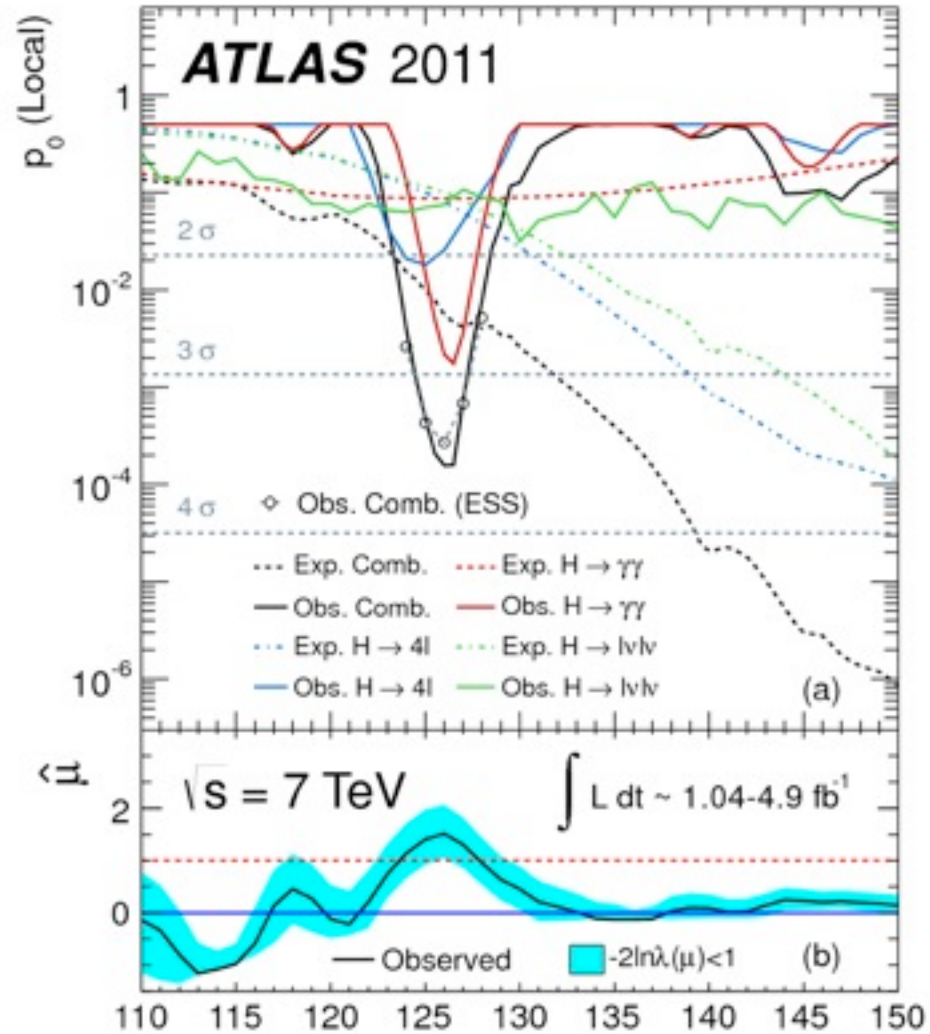
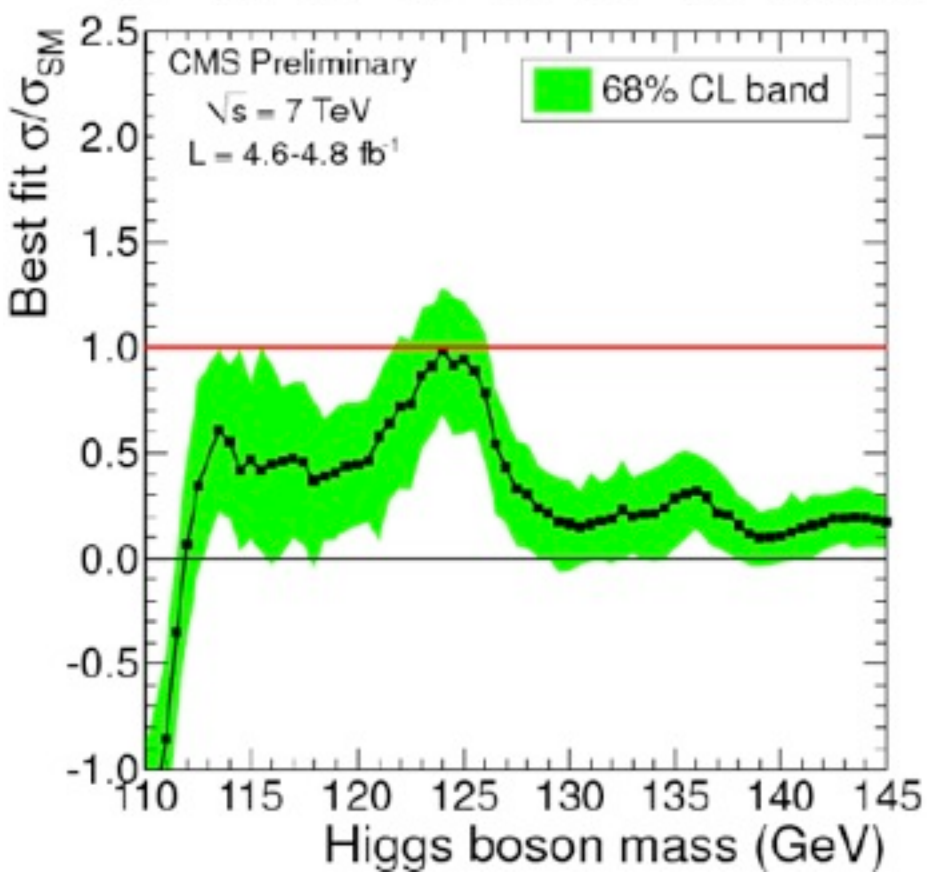
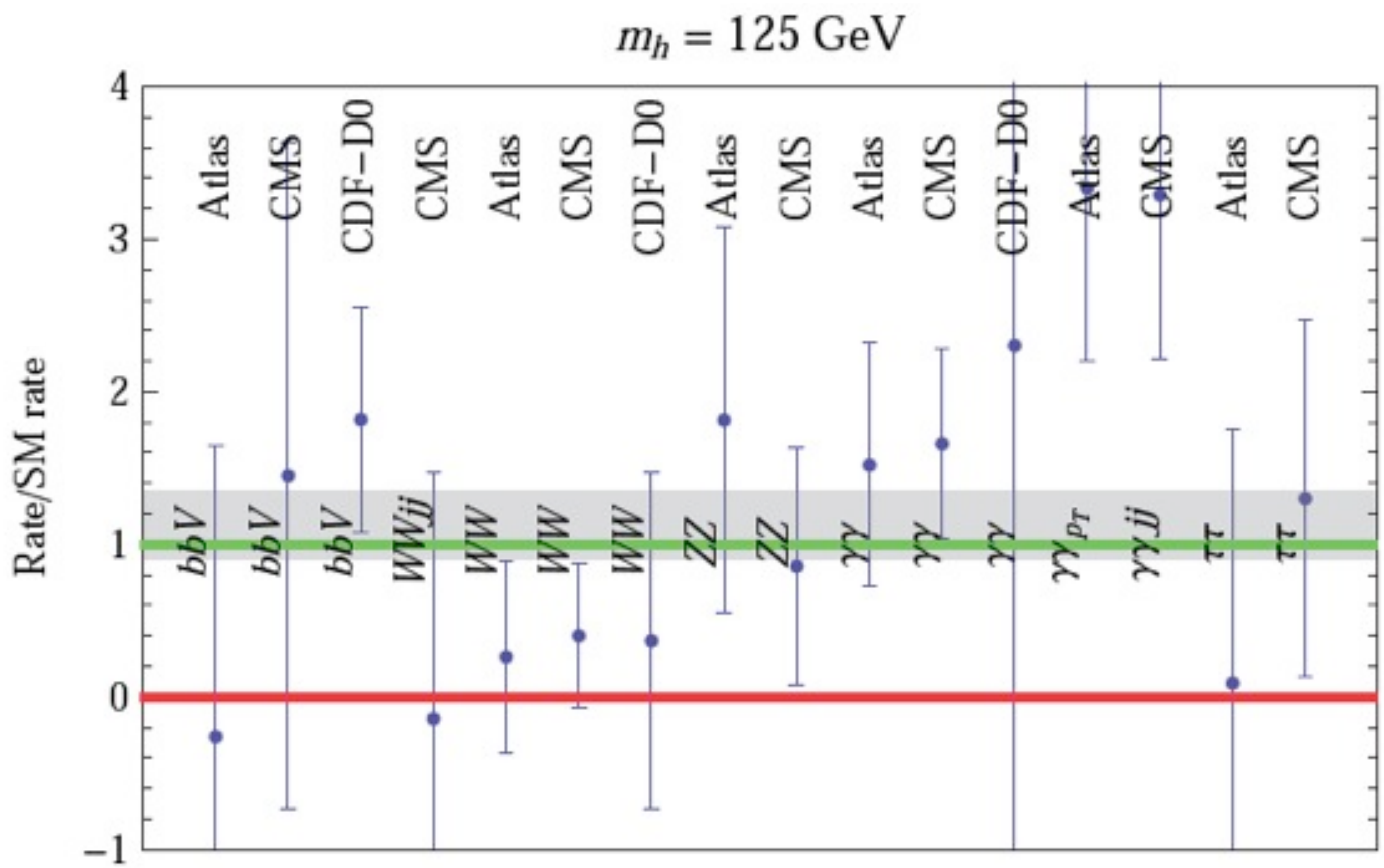
Higgs at LHC?







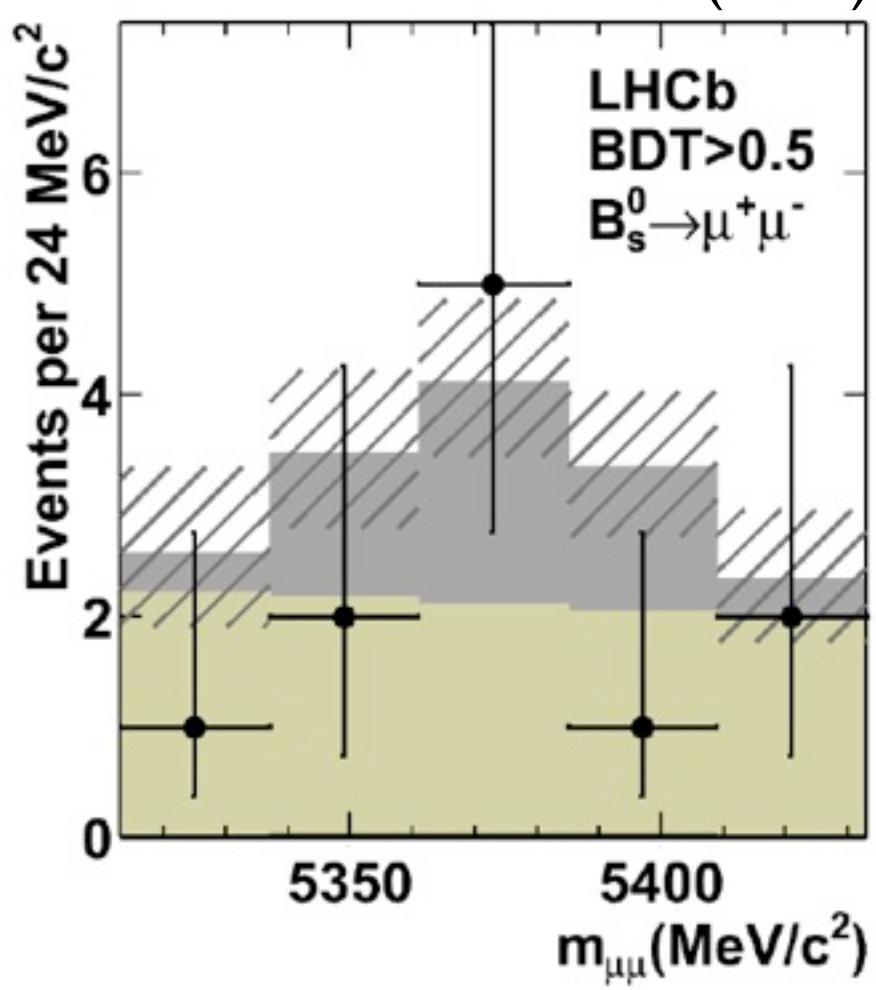
Giardino et al. (2012)

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

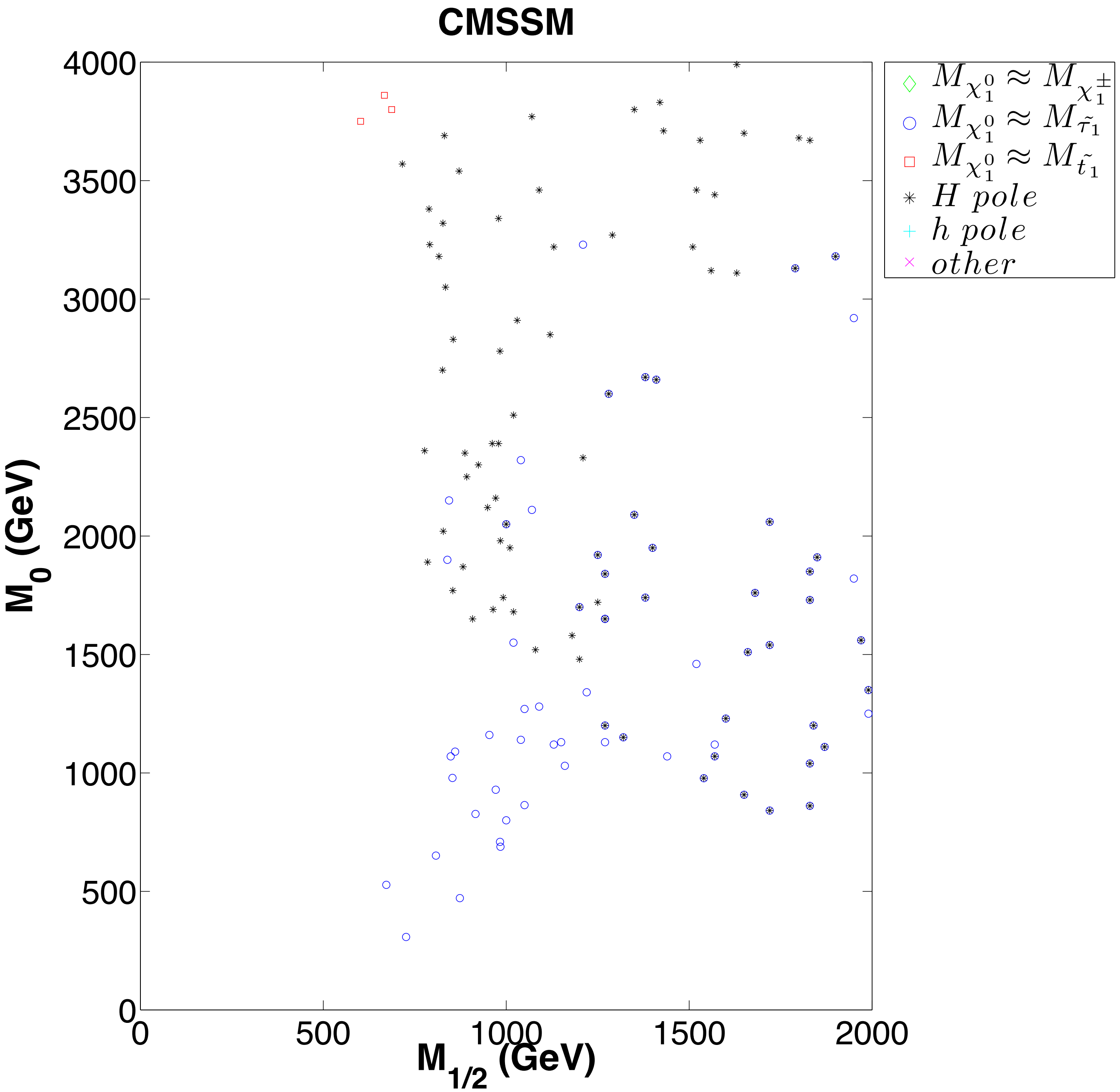
- LHCb progress
- Current 95% CL limit:

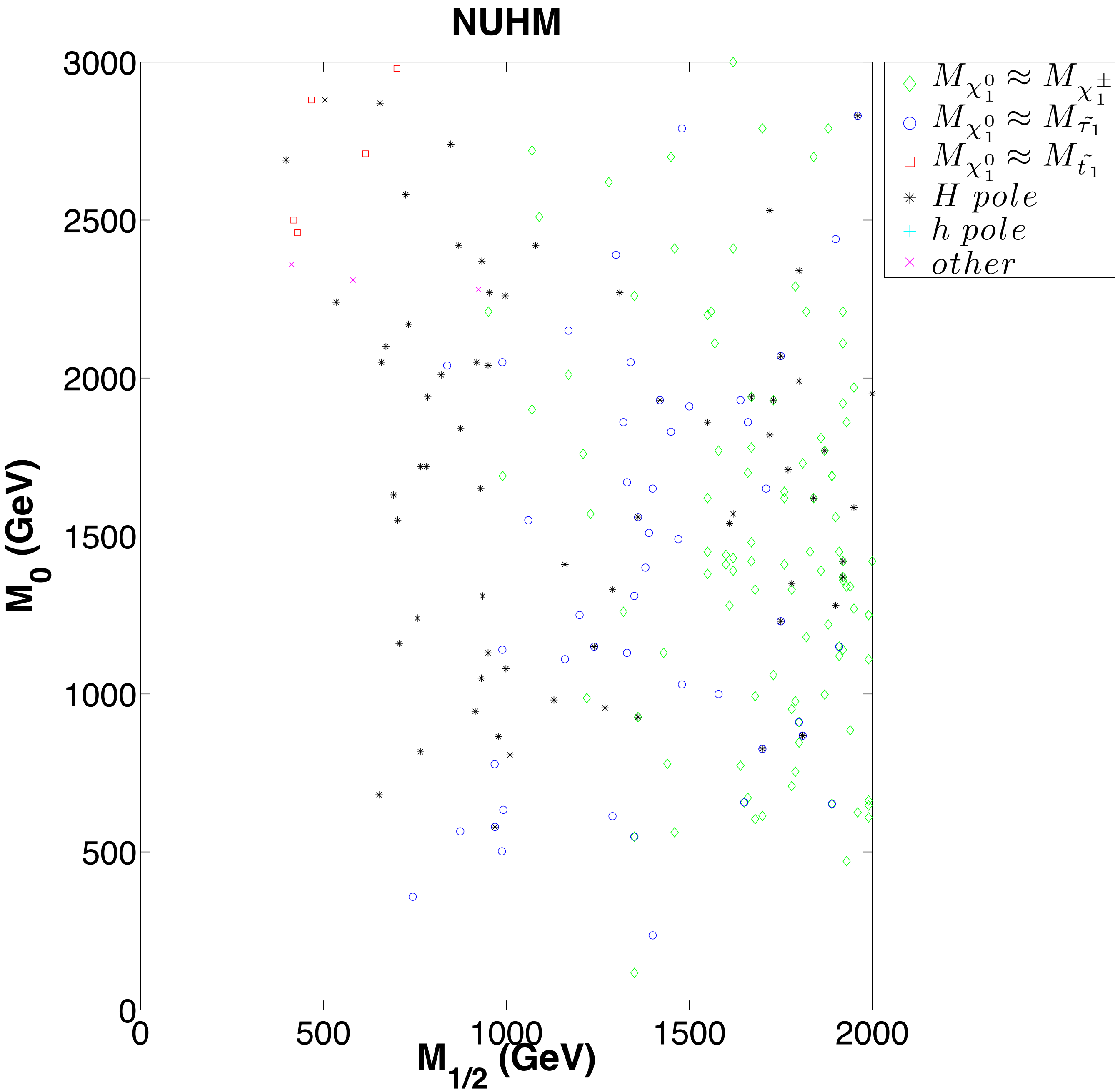
$$\mathrm{BR}(B_s^0 \rightarrow \mu^+\mu^-) < 4.5 \times 10^{-9}$$

PRL (2012)

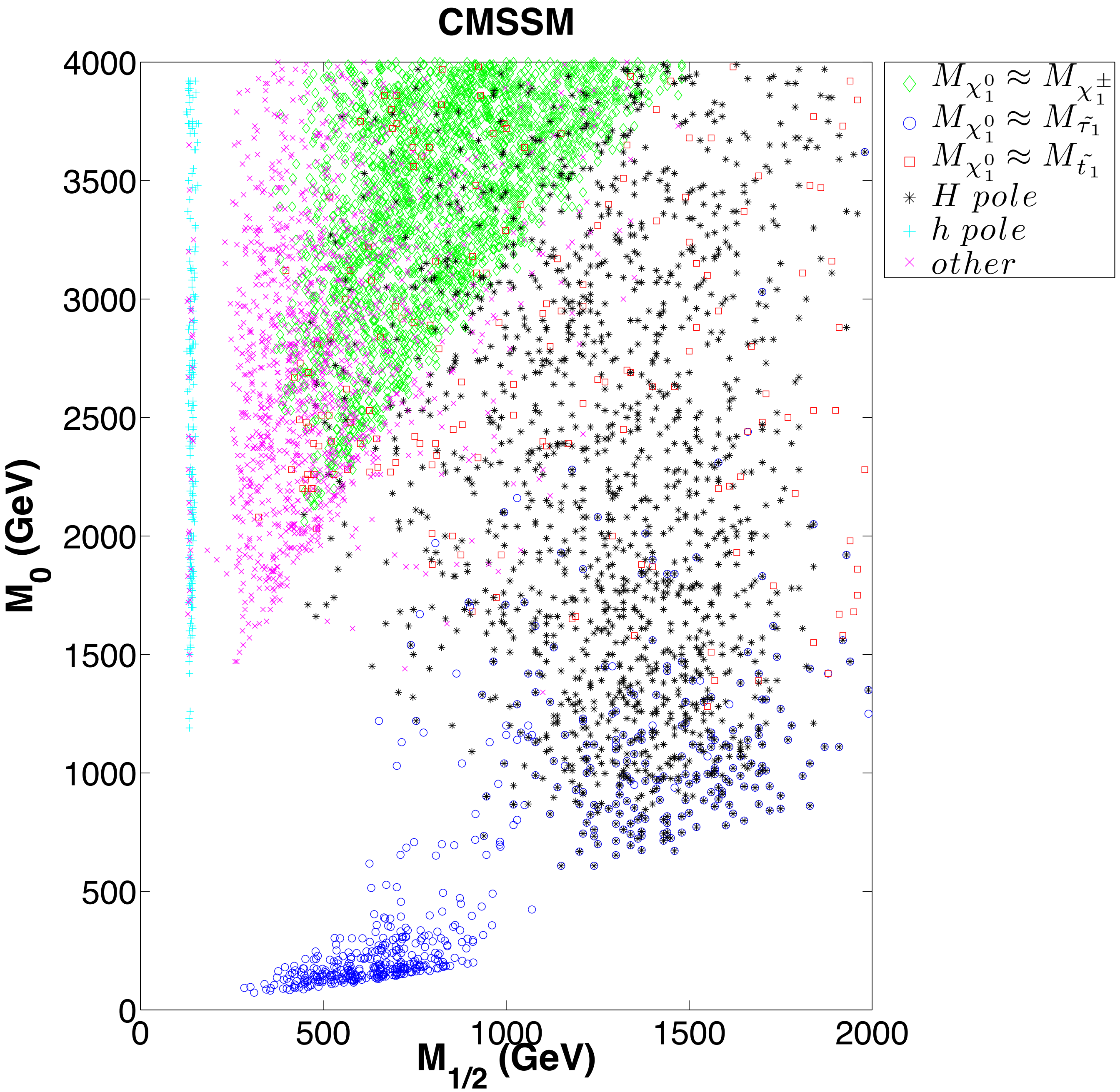


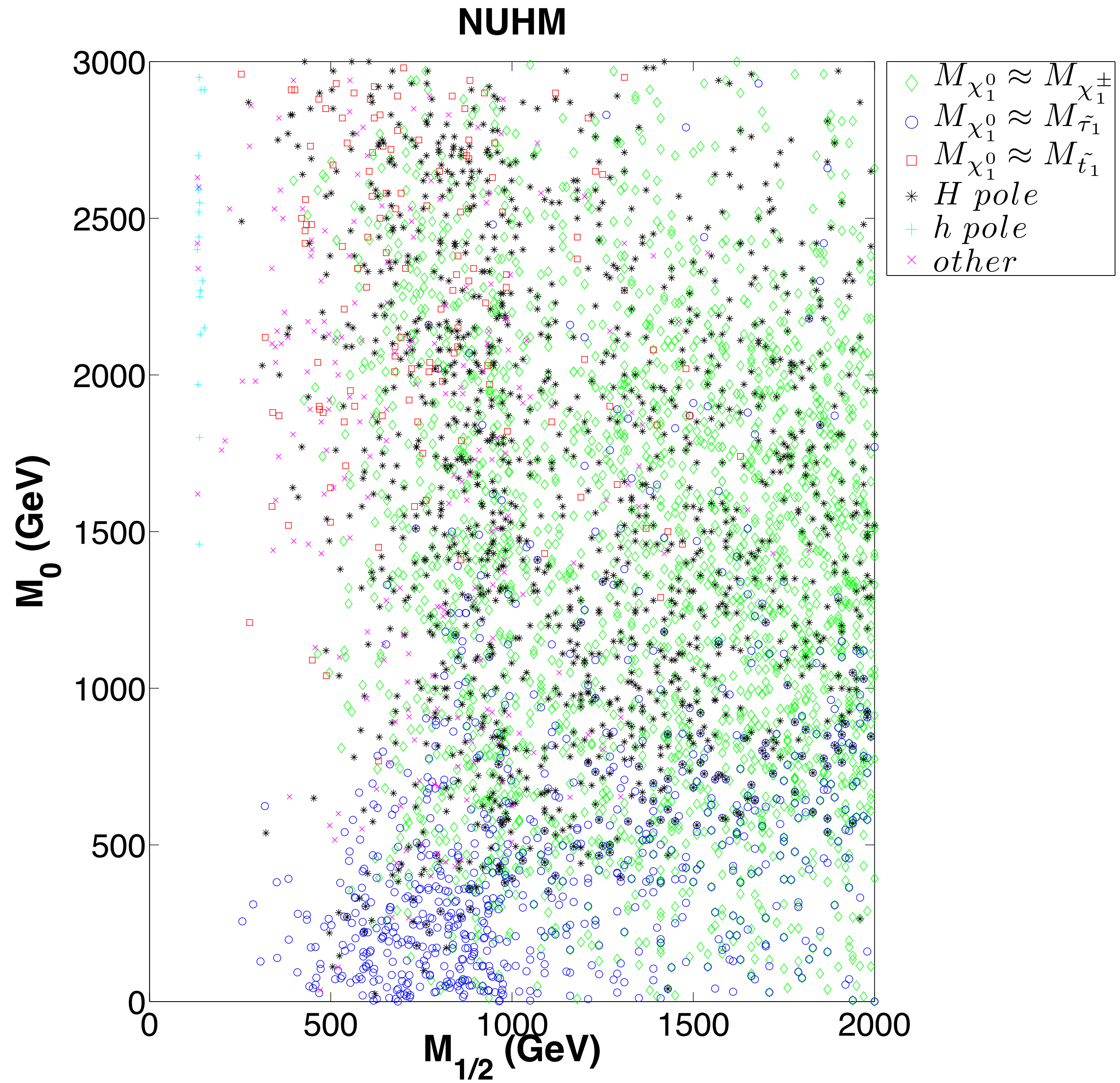
Higgs Mass



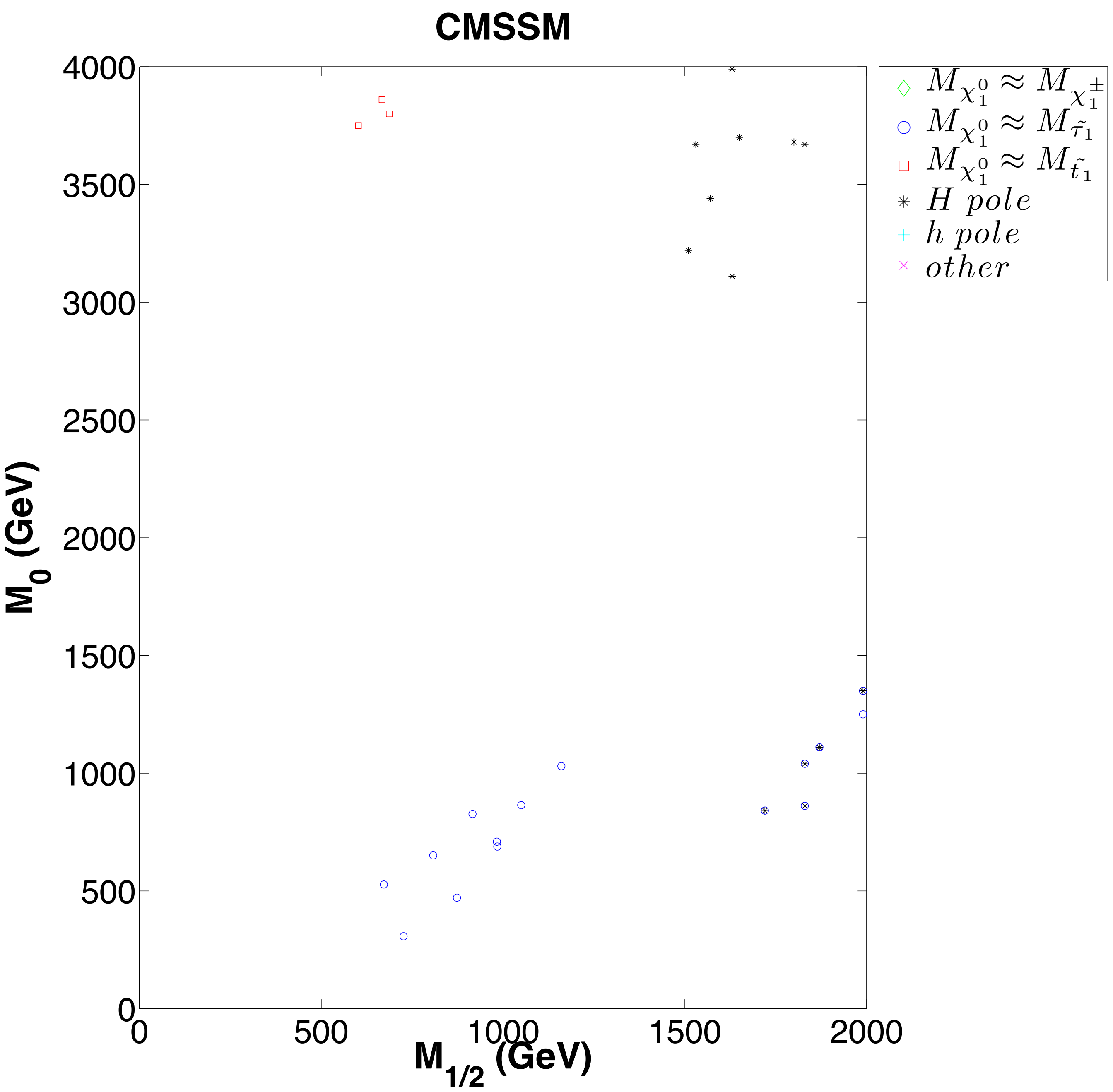


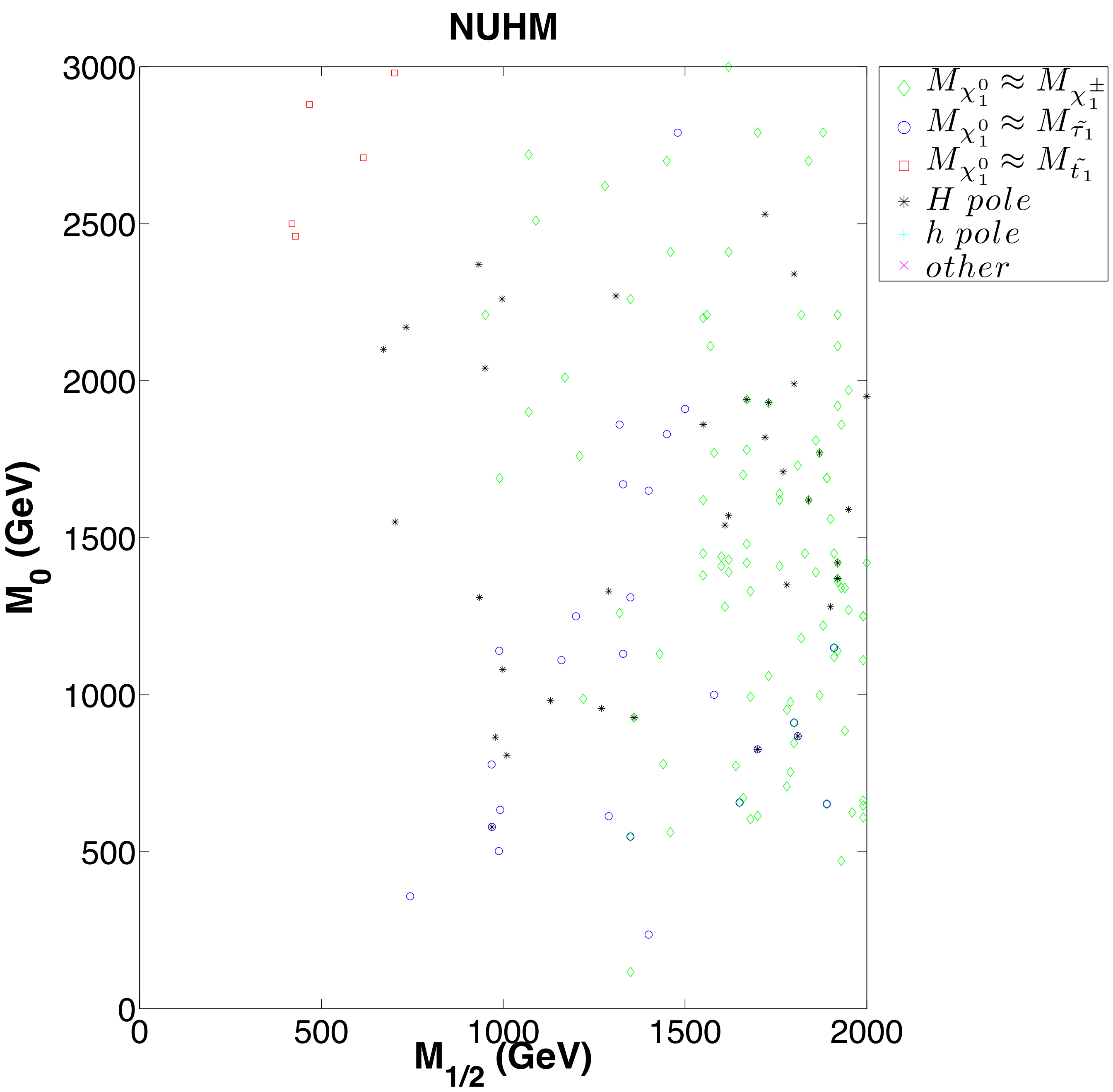
$BR(B_s \to \mu^+\mu^-)$

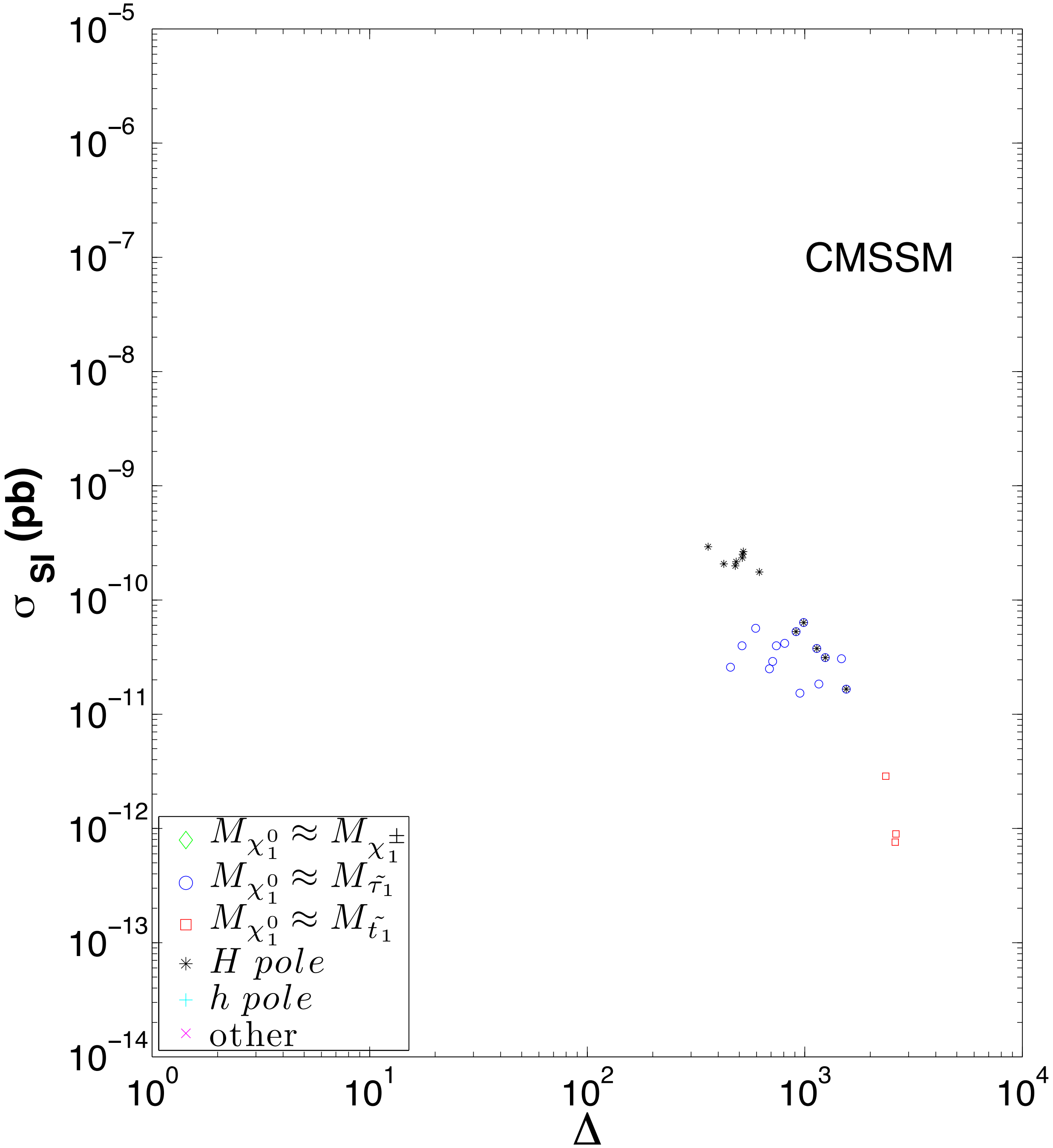

CMSSM
$M_{\chi_1^0} \approx M_{\chi_1^\pm}$
$M_{\chi_1^0} \approx M_{\tilde{\tau}_1}$
$M_{\chi_1^0} \approx M_{\tilde{t}_1}$
H pole
h pole
other
M0 (GeV)
M1/2 (GeV)
0
500
1000
1500
2000
2500
3000
3500
4000


NUHM
$M_{\chi_1^0} \approx M_{\chi_1^\pm}$
$M_{\chi_1^0} \approx M_{\tilde{\tau}_1}$
$M_{\chi_1^0} \approx M_{\tilde{t}_1}$
H pole
h pole
other
M0 (GeV)
M1/2 (GeV)
0
500
1000
1500
2000
2500
3000

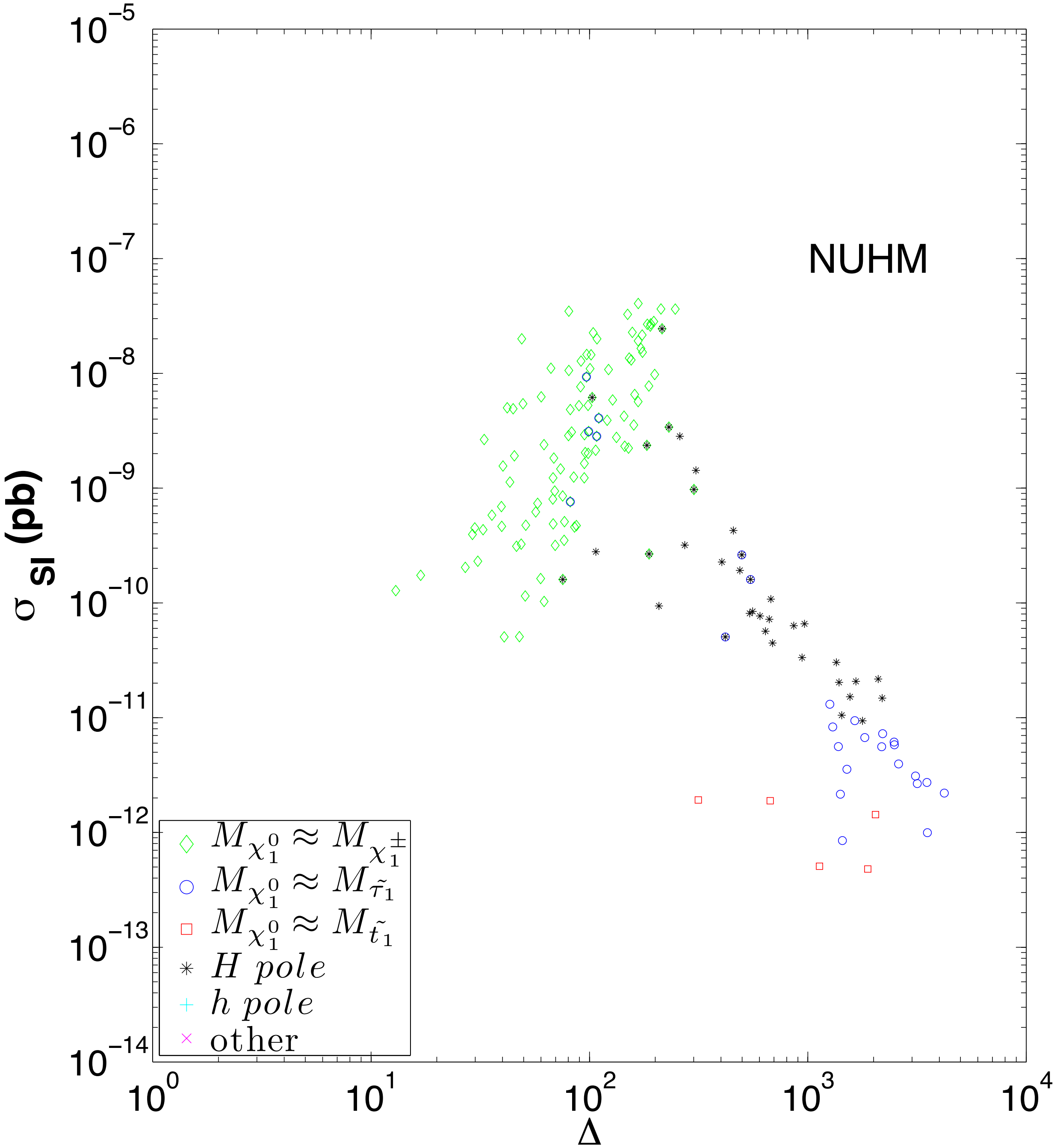
$BR(B_s \to \mu^+\mu^-) + m_H$





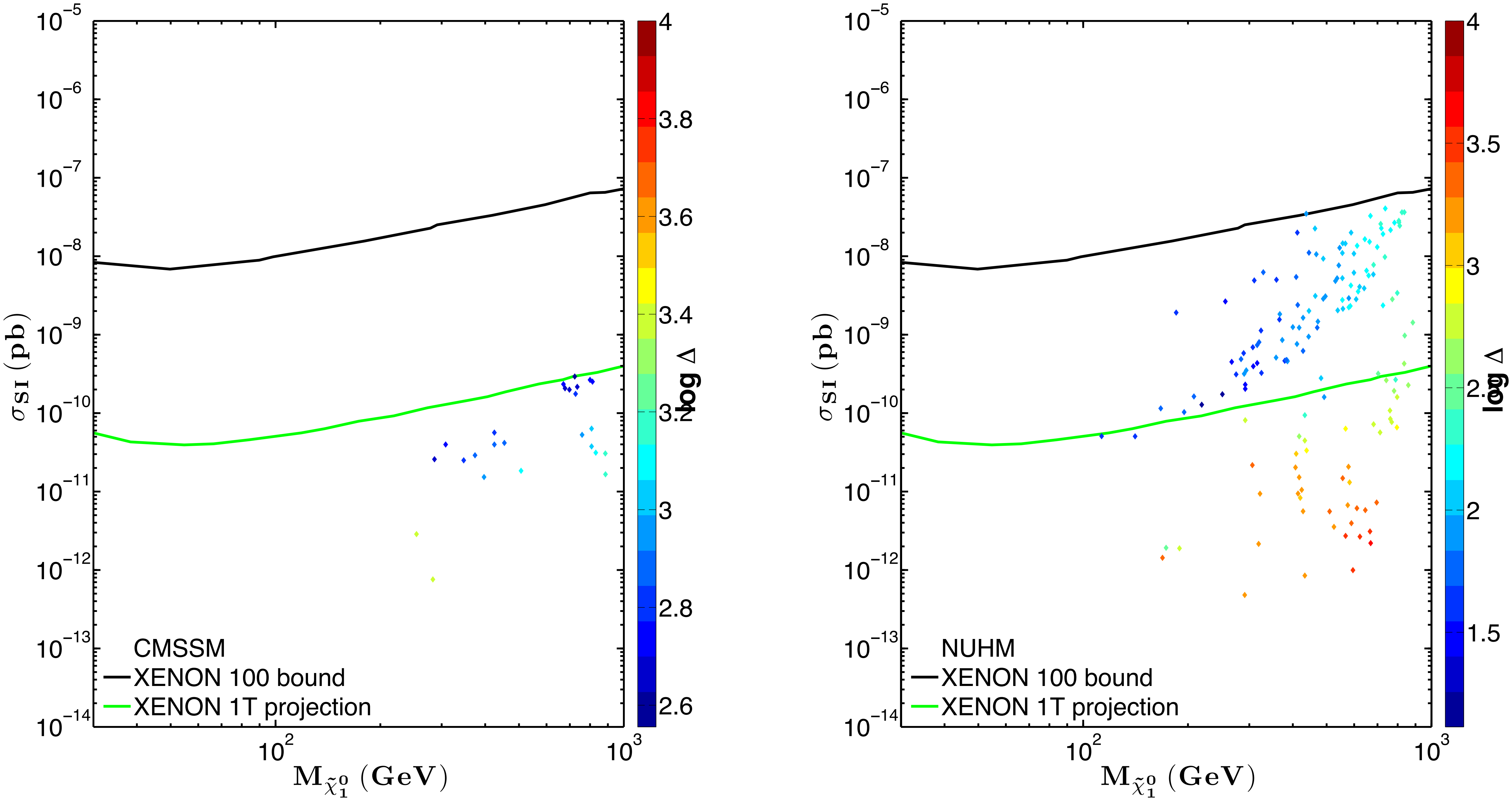


CMSSM
σ_{SI} (pb)
Δ
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
$M_{\chi_1^0} \approx M_{\chi_1^\pm}$
$M_{\chi_1^0} \approx M_{\tilde{\tau}_1}$
$M_{\chi_1^0} \approx M_{\tilde{t}_1}$
H pole
h pole
other

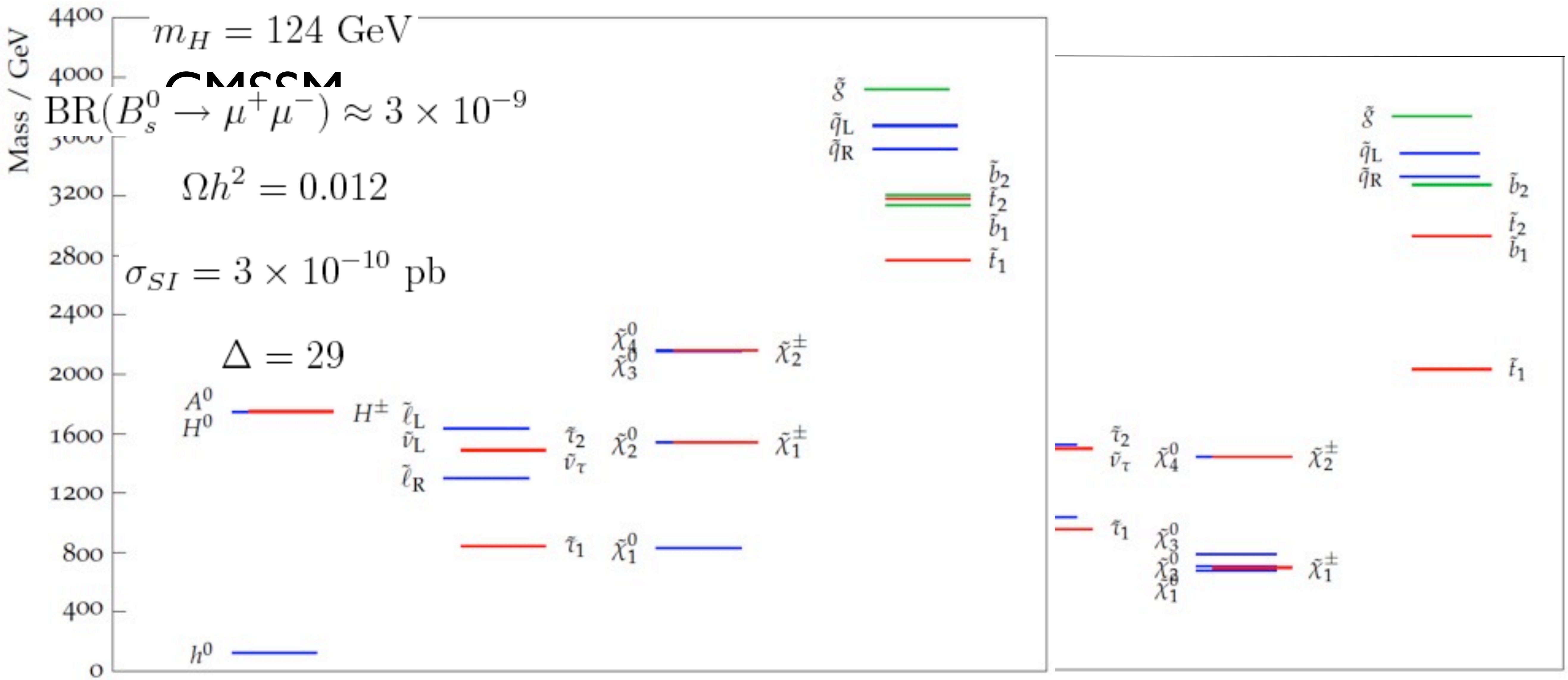


NUHM
σ_{SI} (pb)
Δ
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
$M_{\chi_1^0} \approx M_{\chi_1^\pm}$
$M_{\chi_1^0} \approx M_{\tilde{\tau}_1}$
$M_{\chi_1^0} \approx M_{\tilde{t}_1}$
H pole
h pole
other

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



Example Spectra



Take Home Message

- More variation in the spin-independent neutralino-nucleon elastic scattering cross section in the NUHM than in the CMSSM → less correlation between degree of fine-tuning and direct detection prospects.
- In the CMSSM, the least fine-tuned models by our definition are being (will be) tested first (soon) by direct dark matter searches.
- In the NUHM, sort of.

Take Home Message