Phenomenological Aspects of Supersymmetric Dark Matter

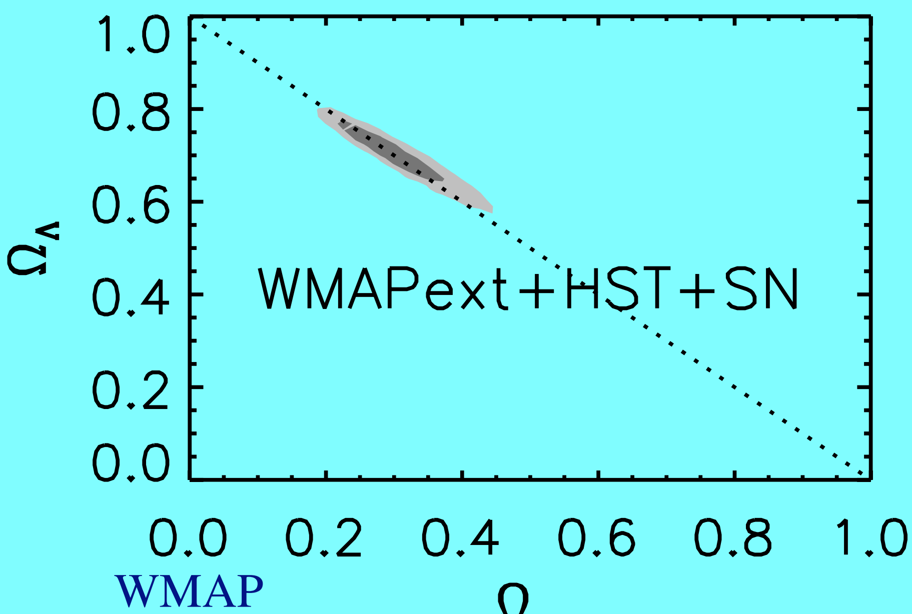
Dark Matter in variations of constrained MSSM models: A comparison between accelerator and direct detection constraints

- CMSSM
- mSUGRA
- Sub-GUT
- NUHM
- A hint of Higgs?

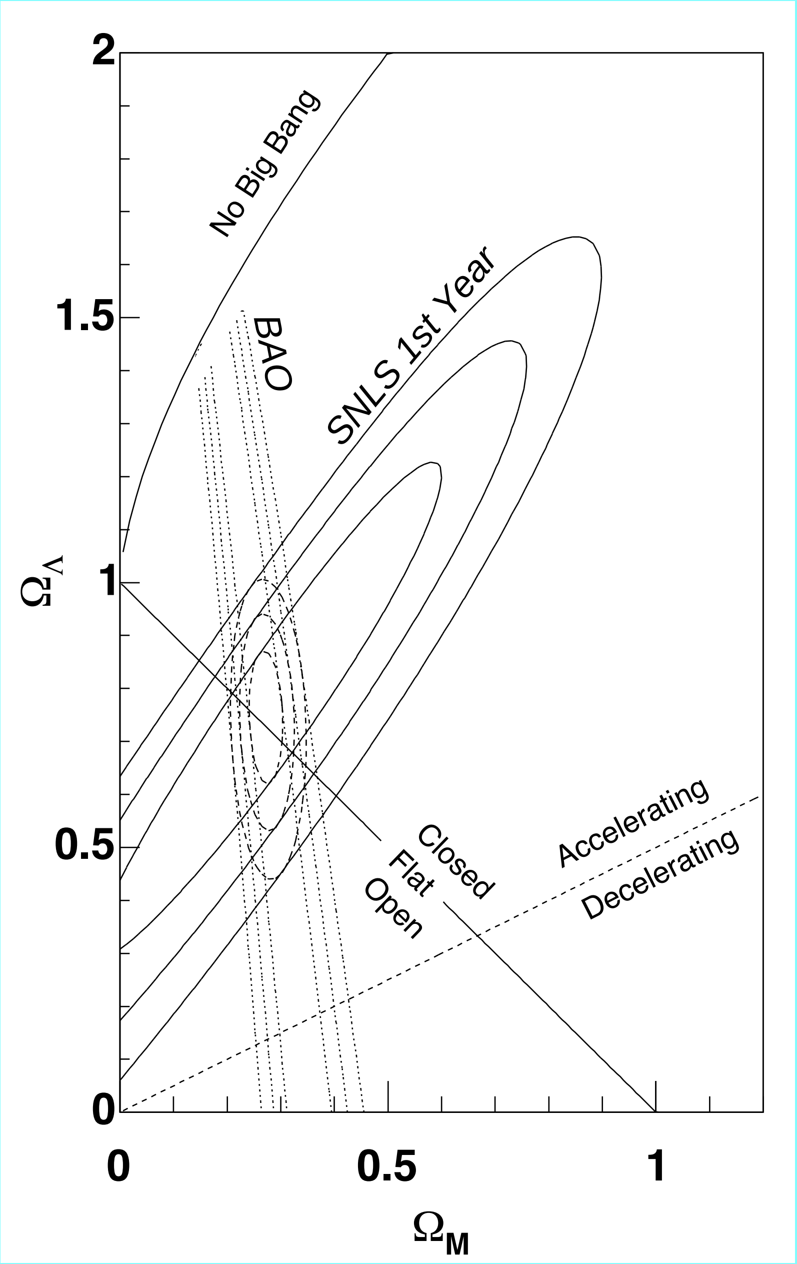
with: Ellis, Hahn, Heinemeyer, Sandick, Santoso, Savage, Spanos, Weber, Weiglein

Evidence for Dark Matter

Clowe et al.



WMAP



SNLS

How Much Dark Matter

WMAP 3 Spergel etal

Precise bounds on matter content

$$\Omega_m h^2 = 0.1265^{+0.0081}_{-0.0080} \qquad \Omega_b h^2 = 0.0223 \pm 0.0007$$

$$\Omega_{cdm} h^2 = 0.1042^{+0.0081}_{-0.0080}$$

or

$$\Omega_{cdm}\, h^2 = 0.0882 - 0.1204 \quad (2\ \sigma)$$

Guage Hierarchy Problem

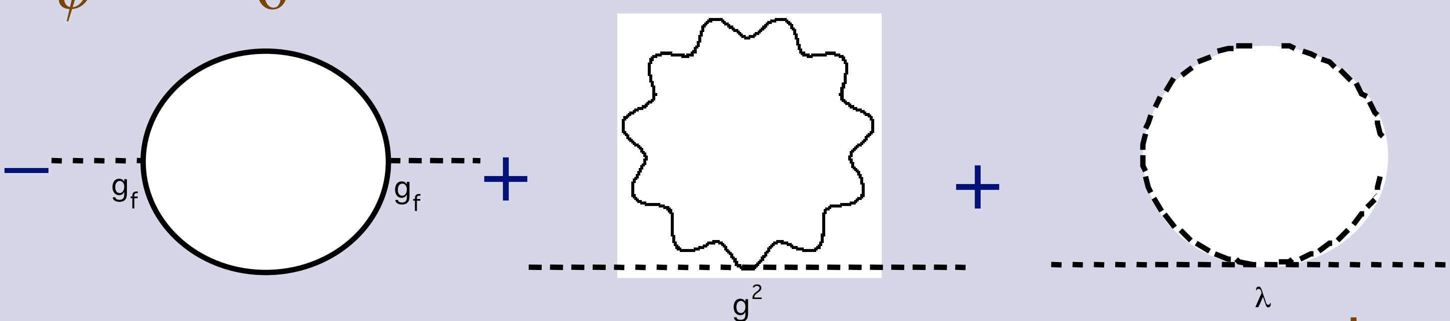
$M_P \approx 10^{19}$ GeV

$M_X \approx 10^{15}$ GeV

$M_W \approx 10^{2}$ GeV

Scalar masses corrected by loops

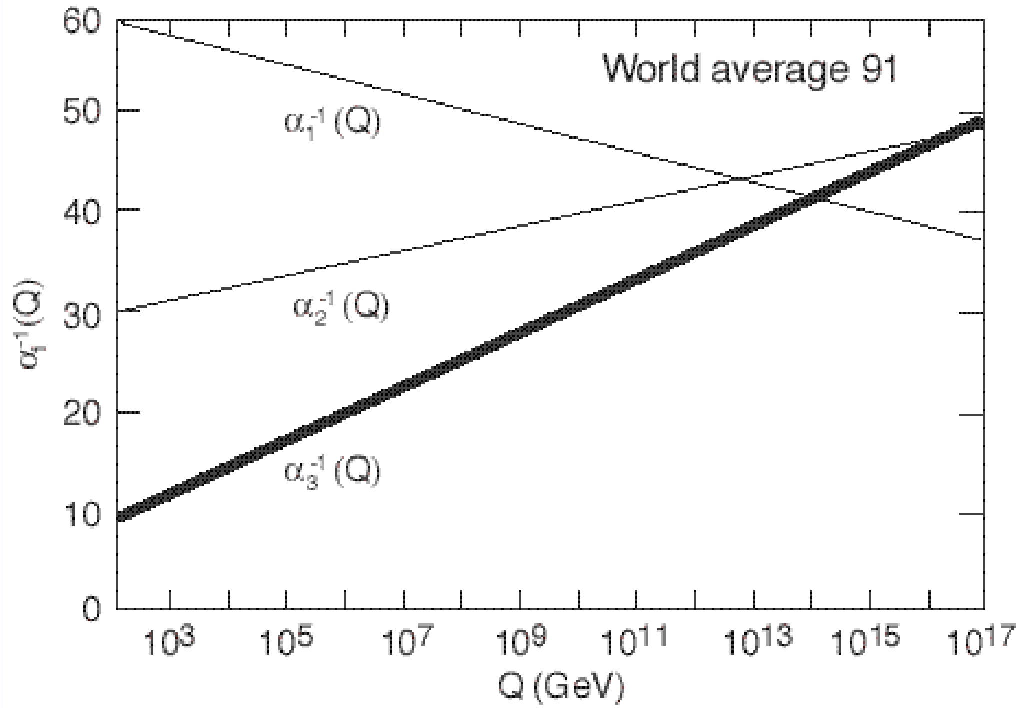
$m_\phi^2 = m_o^2 +$



$+ \ldots.$

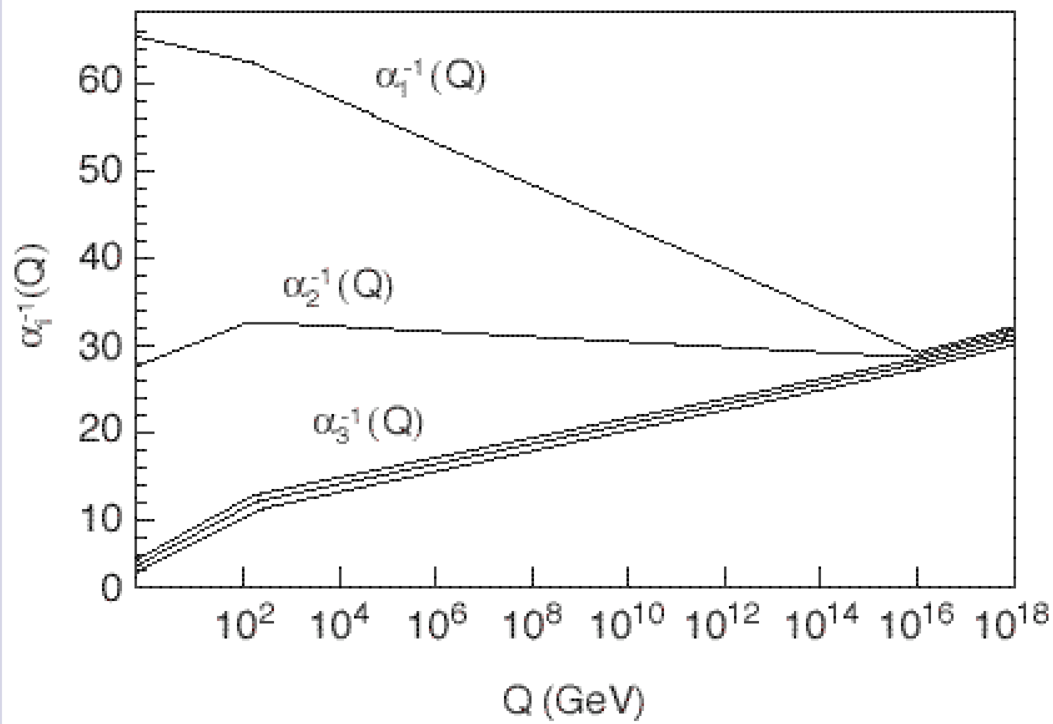
$= m_o^2$

Set it and Forget it!



Running of the Gauge couplings
in the standard model

Running of the Gauge couplings
in the supersymmetric
standard model



What is the MSSM

1) Add minimal number of new particles:
Partners for all SM particles + 1 extra Higgs EW doublet.

2) Add minimal number of new interactions:
Impose R-parity to eliminate many UNWANTED interactions.

$$R = (-1)^{3B+L+2S}$$

Particle Content of the MSSM

Gauge

γ		B		$\tilde{B}$	neutralinos
Z	or	W^3	$\Rightarrow$	$\tilde{W}^3$	
$W^{\pm}$		W^i		$\tilde{W}^{\pm}$	charginos

Higgs

H_1	$\Rightarrow$	$\tilde{H}_{1,2}$	neutralinos
H_2		$\tilde{H}^{\pm}$	charginos

Matter

q	$\Rightarrow$	$\tilde{q}_{L,R}$	squarks
l		$\tilde{l}_{L,R}$	sleptons

SUSY Dark Matter

MSSM and R-Parity $\Longrightarrow$ Stable DM candidate

1) Neutralinos

$$\boldsymbol{\chi_i = \alpha_i \widetilde{B} + \beta_i \widetilde{W} + \gamma_i \widetilde{H}_1 + \delta_i \widetilde{H}_2}$$

2) Sneutrino

Excluded (unless add L-violating terms)

3) Other:

Axinos, Gravitinos, etc

Parameters

Higgs mixing mass: μ

Ratio of Higgs vevs: $\tan\beta$

Gaugino masses: M_i

Soft scalar masses: m_o

Bi and Trilinear Terms: B and A_i

Phases: θ_μ, θ_A

The Relic Density

At high temperatures $T \gg m_\chi$;

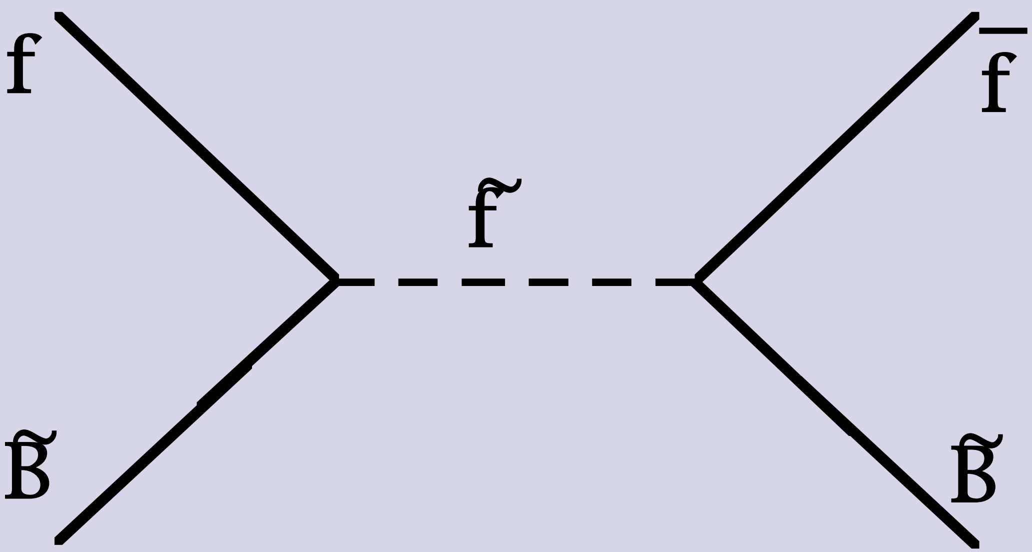
χ's in equilibrium $\Gamma > H$ $n_\chi \sim n_\gamma$

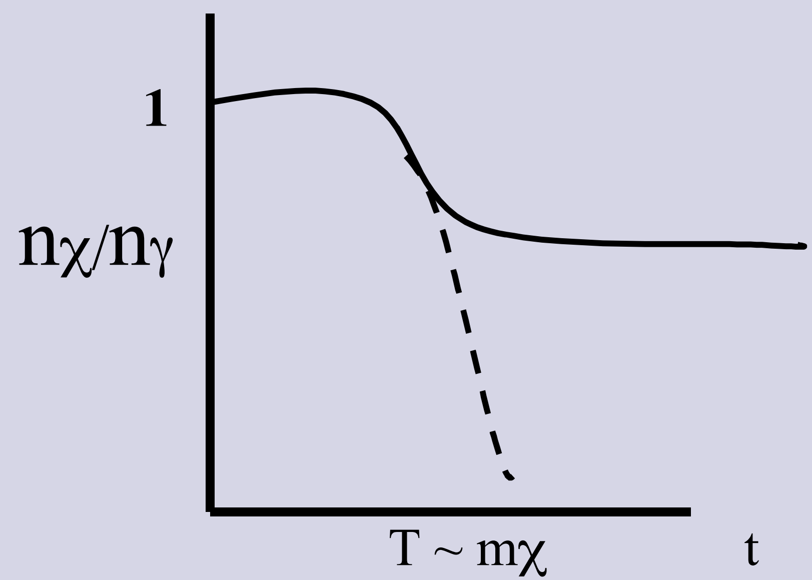
$\Gamma \sim n\sigma v \sim T^3 \sigma v$; $HM_p \sim \sqrt{\rho} \sim T^2$

As $T < m_\chi$; annihilations drop n_χ

$n_\chi \sim e^{-m_\chi/T} n_\gamma$

Until freeze-out, $\Gamma < H$ $n_\chi/n_\gamma \sim$ constant





Direct Detection

- Elastic scattering cross sections for χ p

- Dominant contribution to spin-independent scattering

$$\mathcal{L} = \alpha_{3i}\bar{\chi}\chi\bar{q}_i q_i,$$

Through light squark exchange

– Dominant for binos

Through Higgs exchange

– Requires some Higgsino component

Uncertainties from hadronic matrix elements

The scalar cross section

$$\sigma_3 = \frac{4m_r^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2$$

where

$$\frac{f_p}{m_p} = \sum_{q=u,d,s} f_{Tq}^{(p)} \frac{\alpha_{3q}}{m_q} + \frac{2}{27} f_{TG}^{(p)} \sum_{c,b,t} \frac{\alpha_{3q}}{m_q}$$

and

$$m_p f_{Tq}^{(p)} \equiv \langle p | m_q \bar{q} q | p \rangle \equiv m_q B_q$$

determined by

$$\sigma_{\pi N} \equiv \Sigma = \frac{1}{2}(m_u + m_d)(B_u + B_d)$$

The strangeness contribution to the proton mass

$$y = \frac{2B_s}{B_u + B_d} = \frac{(m_u + m_d)\langle p|s\bar{s}|p\rangle}{\Sigma}$$

$$= 1 - \frac{\sigma_0}{\Sigma}$$

$\sigma_0 = 36 \pm 7$ MeV

For $\Sigma = 45$ MeV, $y = 0.2$

$$f_{T_u} = 0.020 \qquad f_{T_d} = 0.026 \qquad f_{T_s} = 0.117$$

For $\Sigma = 64$ MeV, $y = 0.44$

$$f_{T_u} = 0.027 \qquad f_{T_d} = 0.039 \qquad f_{T_s} = 0.363$$

For $\Sigma = 36$ MeV, $y = 0$

$$f_{T_u} = 0.016 \qquad f_{T_d} = 0.020 \qquad f_{T_s} = 0.$$

Constraints

- Chargino mass limit

$M_{\chi^\pm} \geq 104$ GeV

Constrains (M_2 and μ)/ $m_{1/2}$

- Higgs mass limit

$M_H \geq 114$ GeV

Constrains (m_A, M_2, A)/ $m_{1/2}$

particularly at low tan β

- b to s γ

Constrains (m_A)/ $m_{1/2}$ at high tan β and $\mu < 0$

- Also sfermion mass limits from LEP and CDF

$m_f \geq 99$ GeV (roughly)

χ is the LSP

Unification Conditions

- Gaugino masses: $M_i = m_{1/2}$
- Scalar masses: $m_i = m_0$
- Trilinear terms: $A_i = A_0$

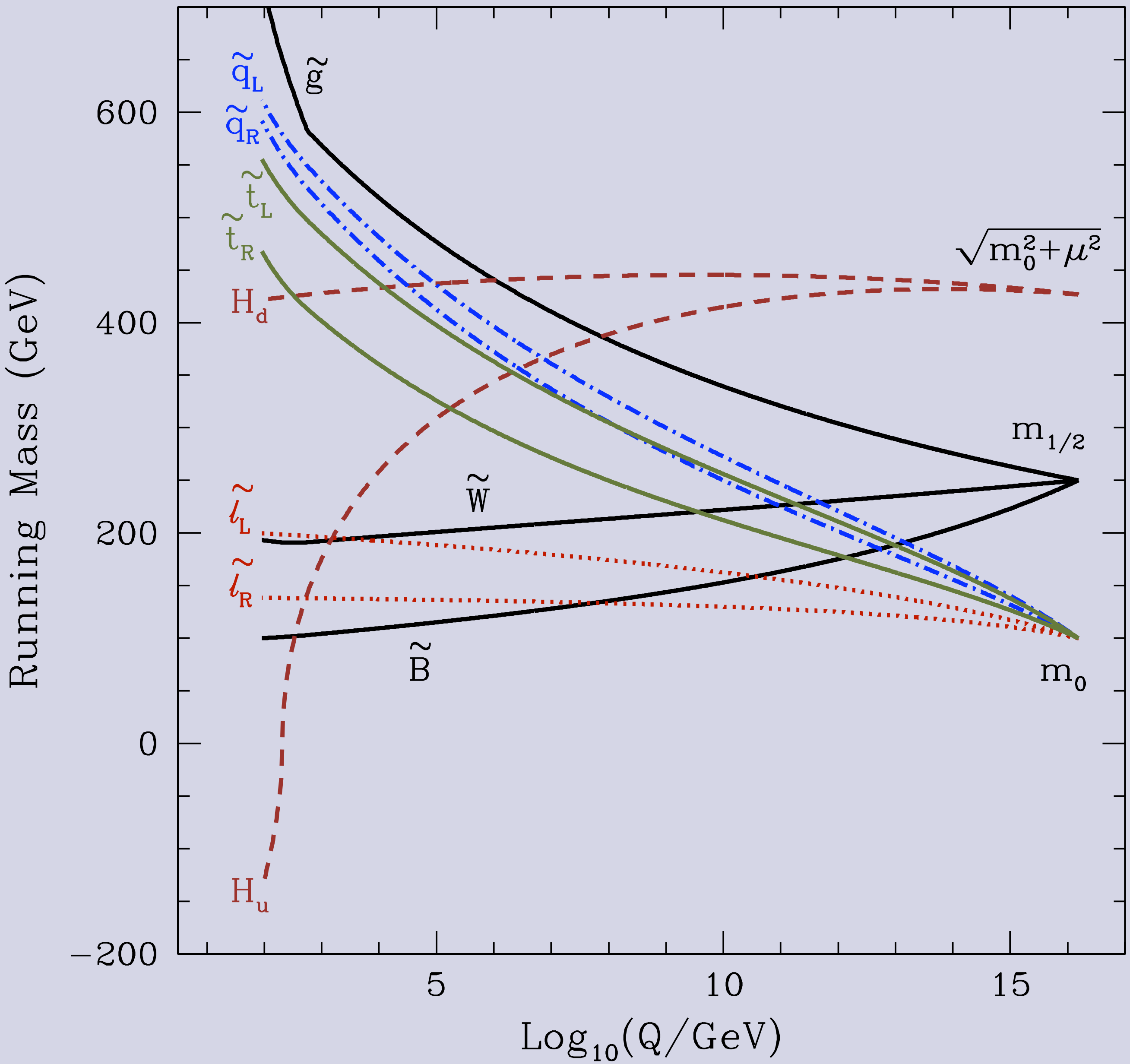
predict μ, B

mSugra Conditions

- Gaugino masses: $m_{3/2} = m_0$
- Bilinear term: $B_0 = A_0 - m_0$

predict μ, $\tan\beta$

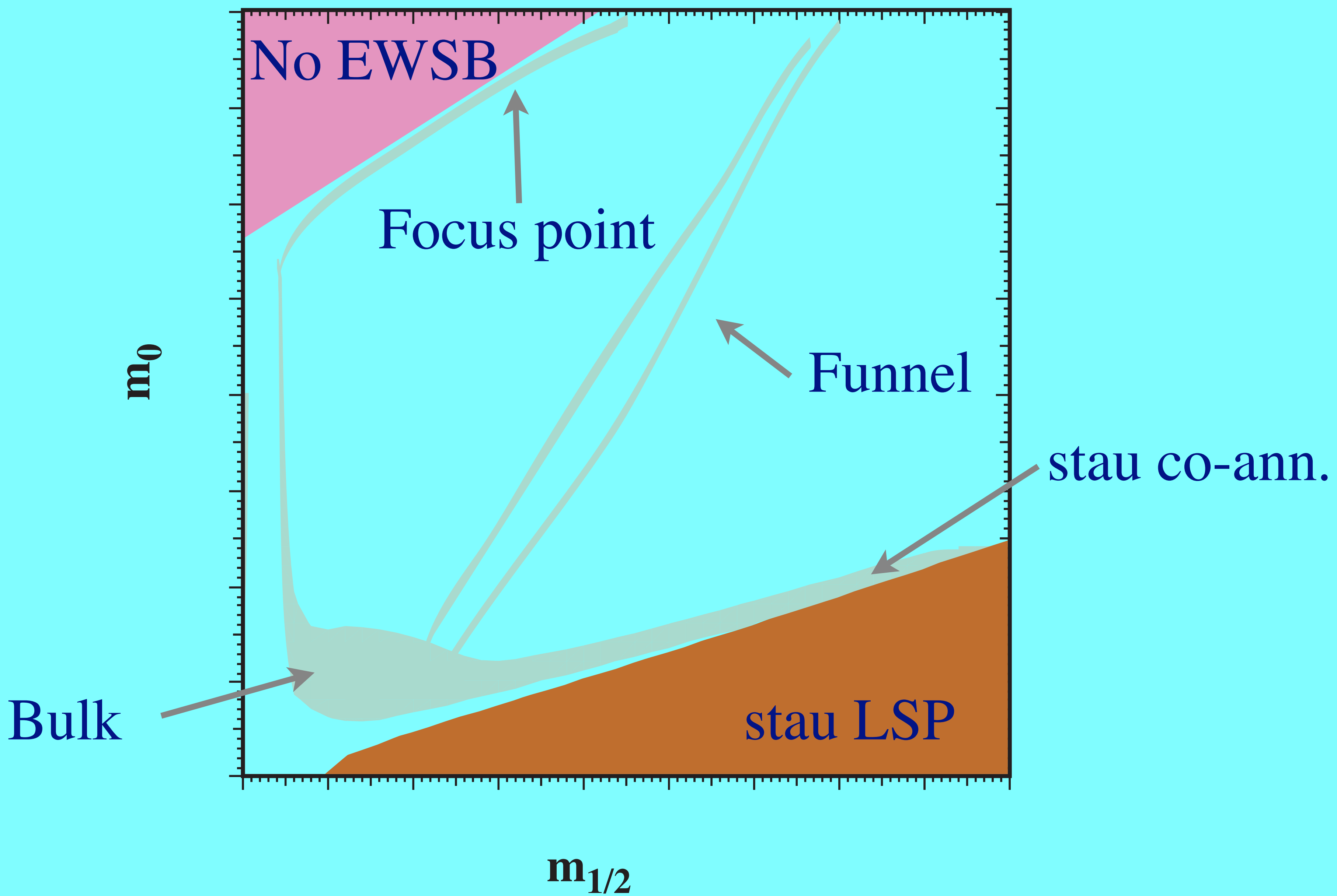
CMSSM Spectra



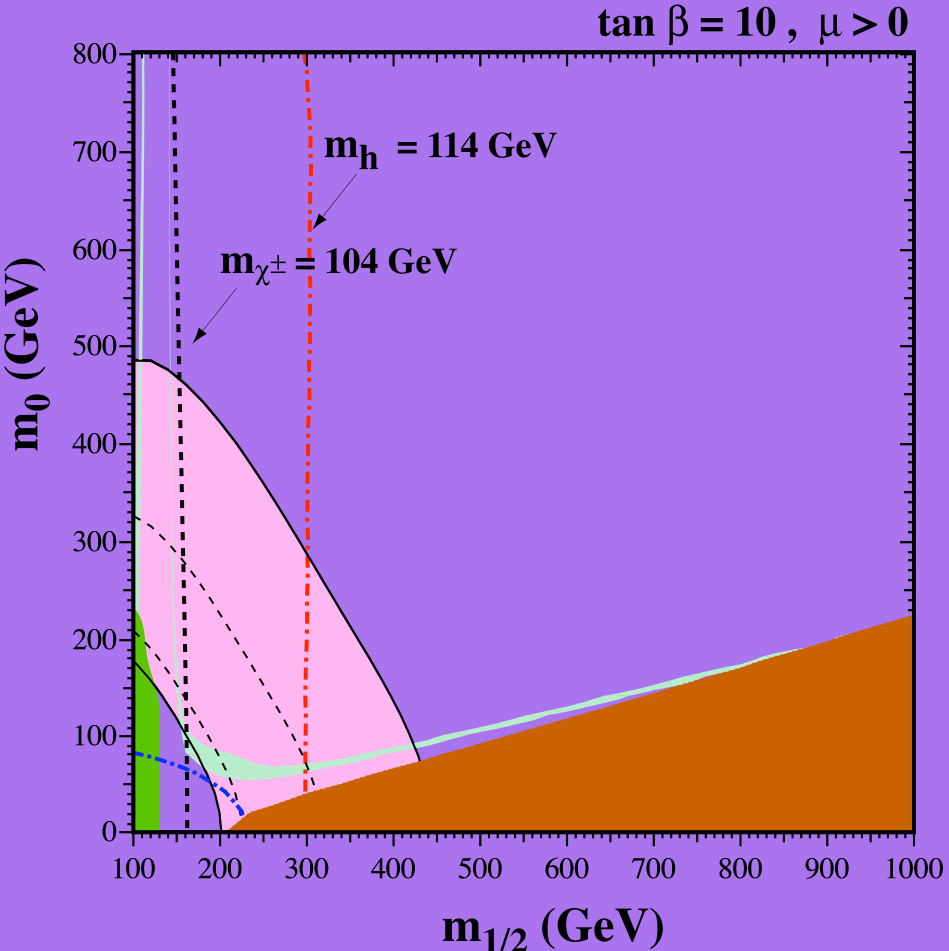
Falk

Unification to rich spectrum
+
EWSB

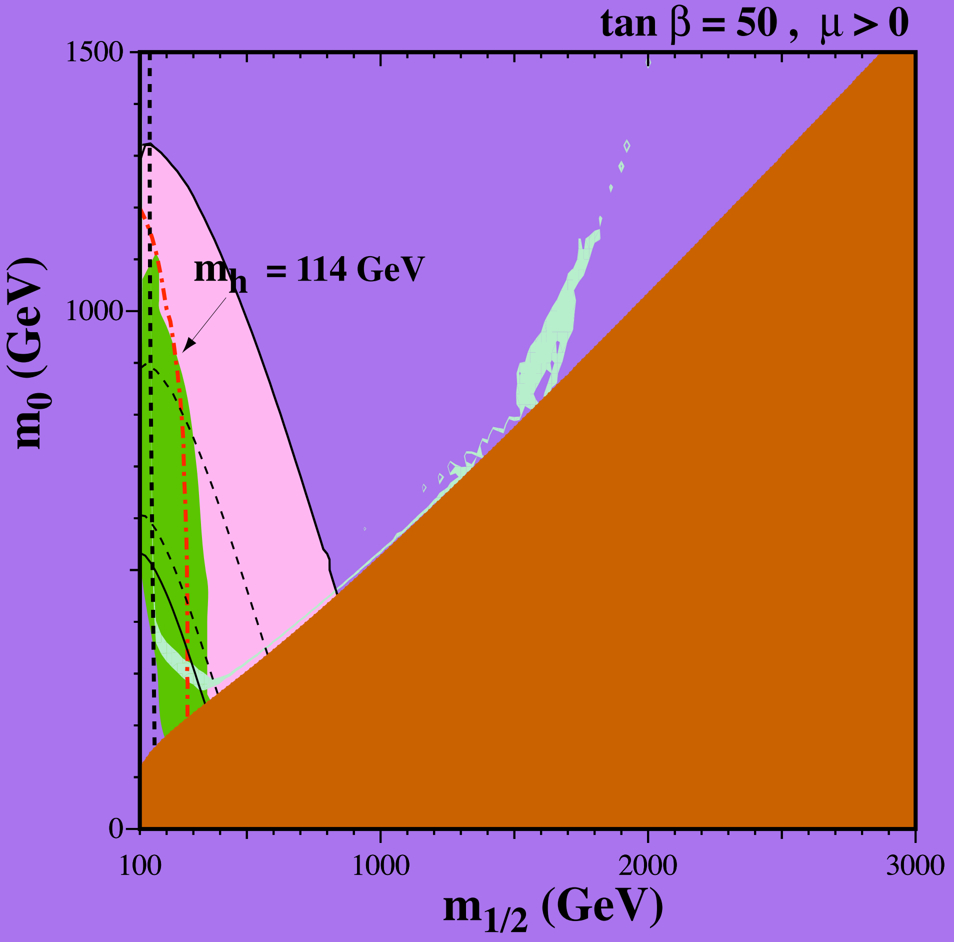
Typical Regions



CMSSM



tan β = 10 , μ > 0
m_h = 114 GeV
m_χ± = 104 GeV
m_0 (GeV)
m_1/2 (GeV)
800
700
600
500
400
300
200
100
0
100
200
300
400
500
600
700
800
900
1000

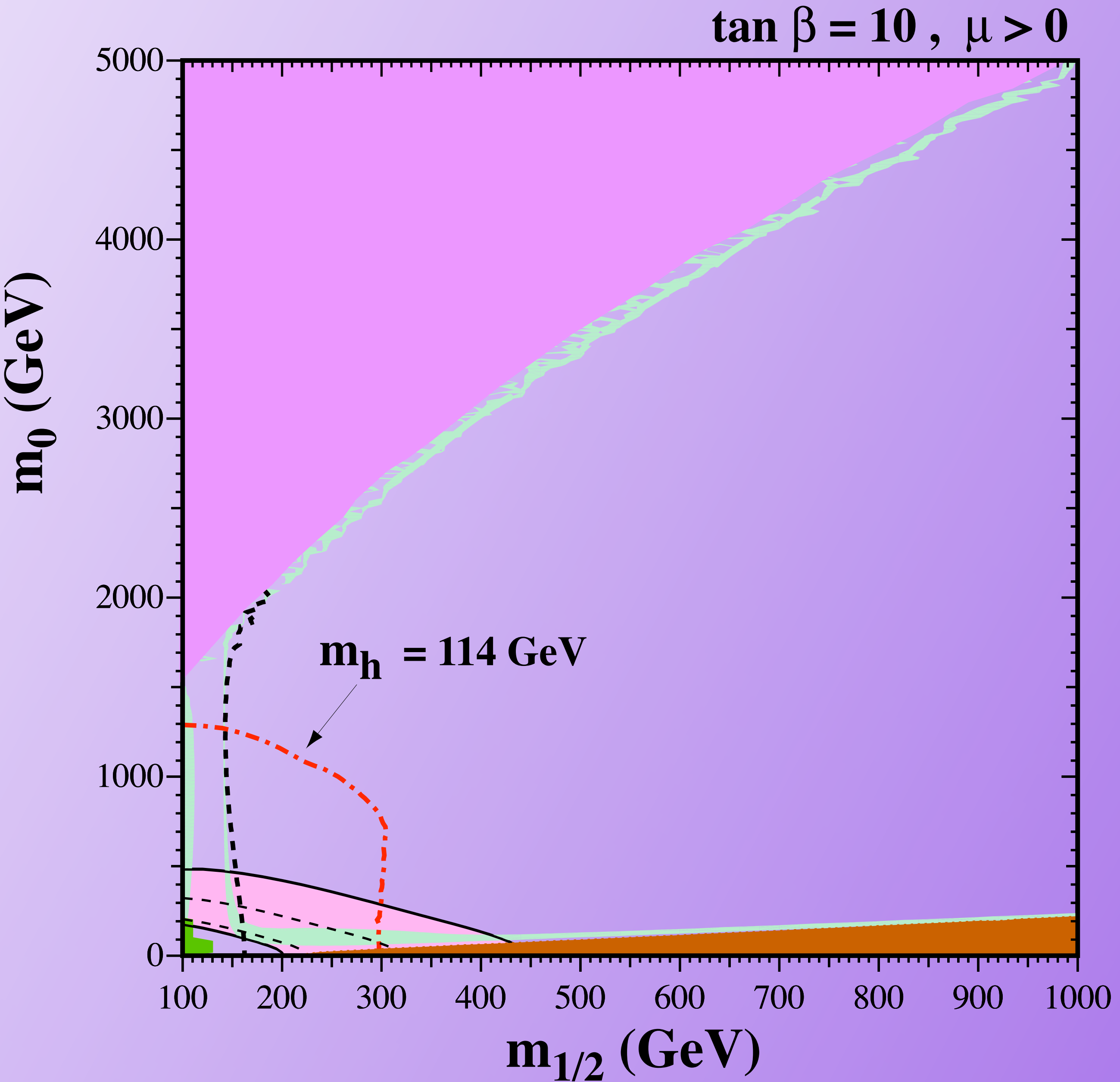


tan β = 50 , μ > 0
m_h = 114 GeV
m_0 (GeV)
m_1/2 (GeV)
1500
1000
0
100
1000
2000
3000

EOSS

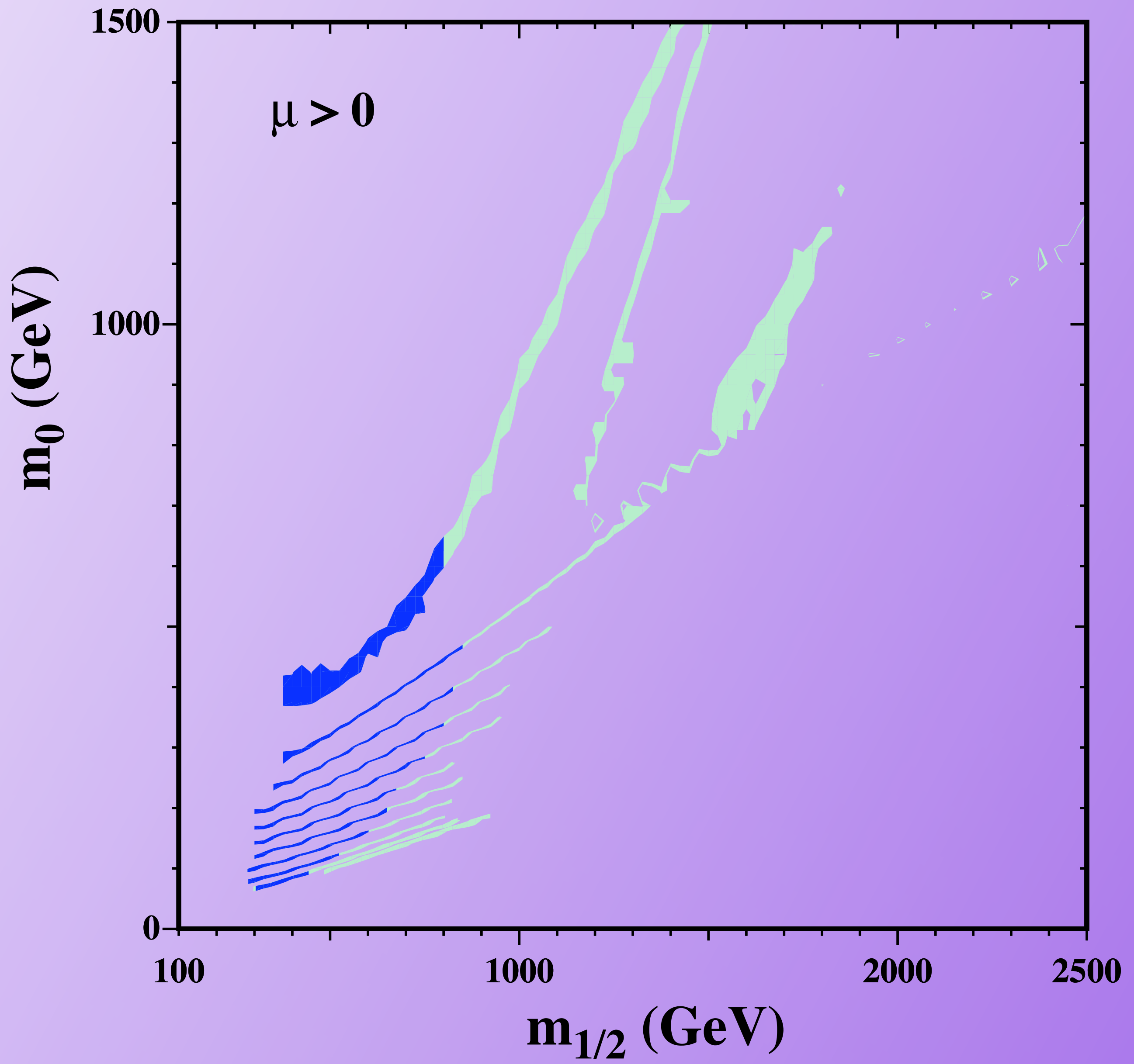
Focus Point Region

As m_0 gets very large, RGE's force μ to 0, allowing neutralino to become Higgsino like with an acceptable relic density.



Feng Matchev Moroi Wilczek

Foliation in tan β



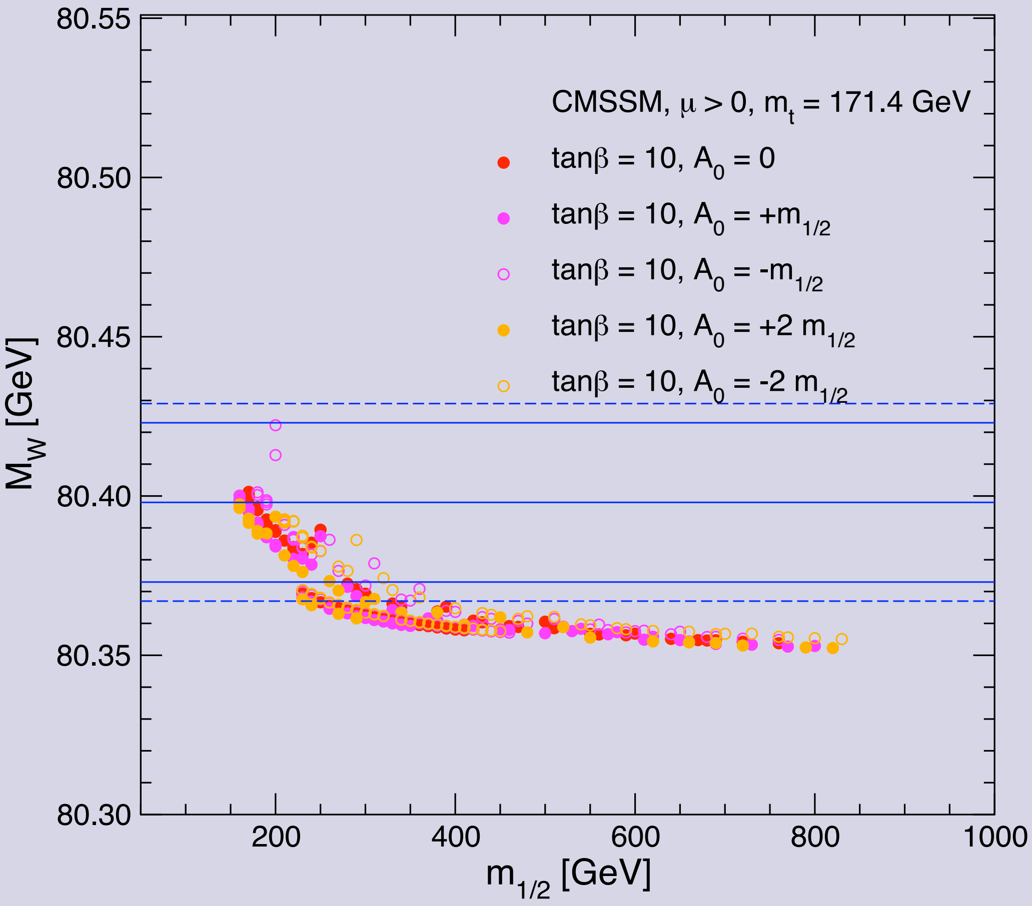
Indirect Sensitivities

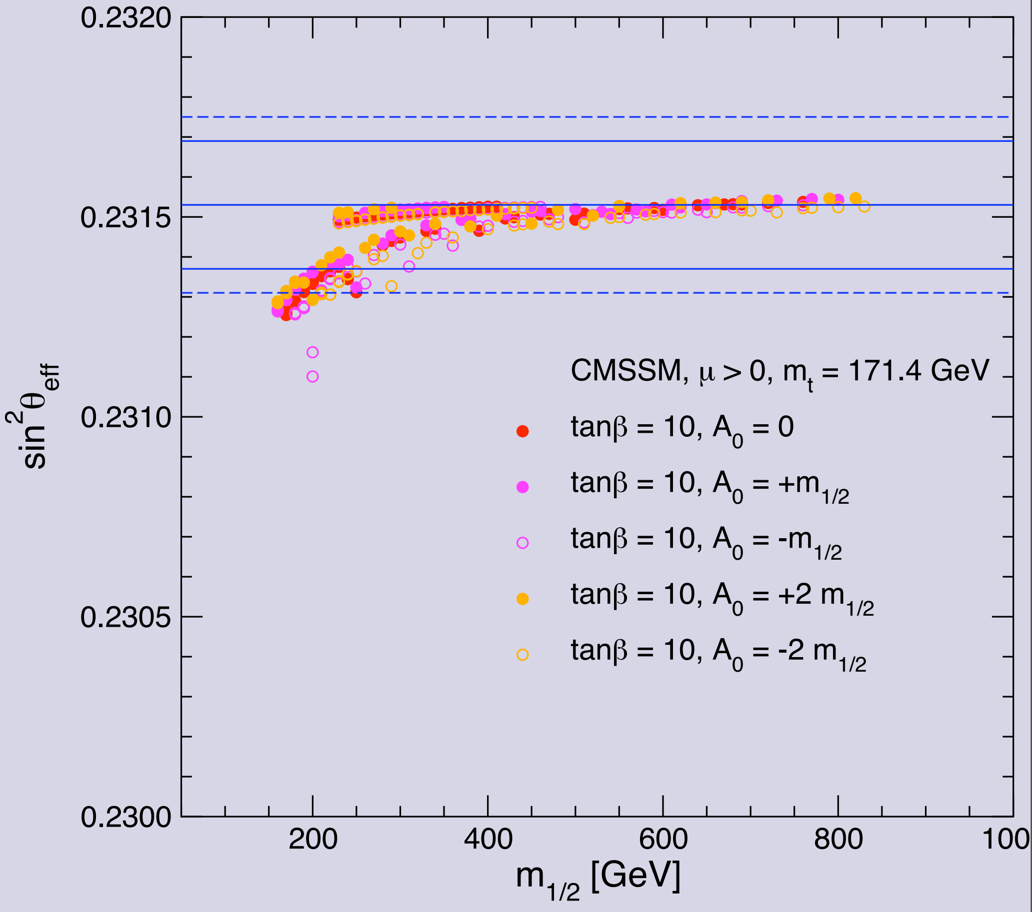
- M_W
- $\sin^2 \theta$
- Γ_Z
- $(g-2)_\mu$
- BR($b \to s\, \gamma$)
- BR($B_u \to \tau\, \nu_\tau$)
- ΔM_{B_s}
- M_h
- BR($B_s \to \mu^+\, \mu^-$)

$$\chi^2 \equiv \sum_{n=1}^{4} \left(\frac{R_n^{\rm exp} - R_n^{\rm theo}}{\sigma_n} \right)^2 + \chi^2_{M_h}$$

Ellis, Heinemeyer, Olive, Weber, Weiglein

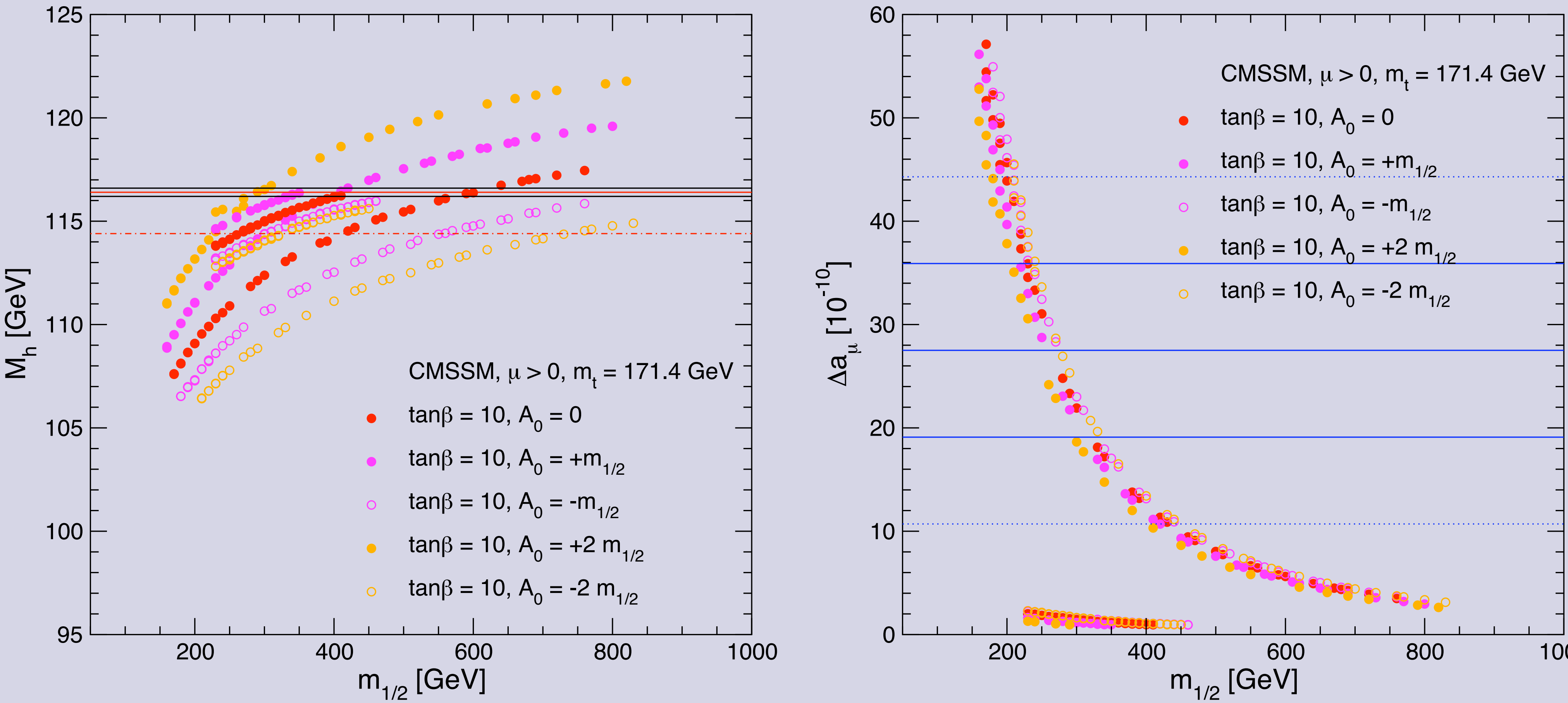
Sensitivity to M_W and $\sin^2\theta_W$





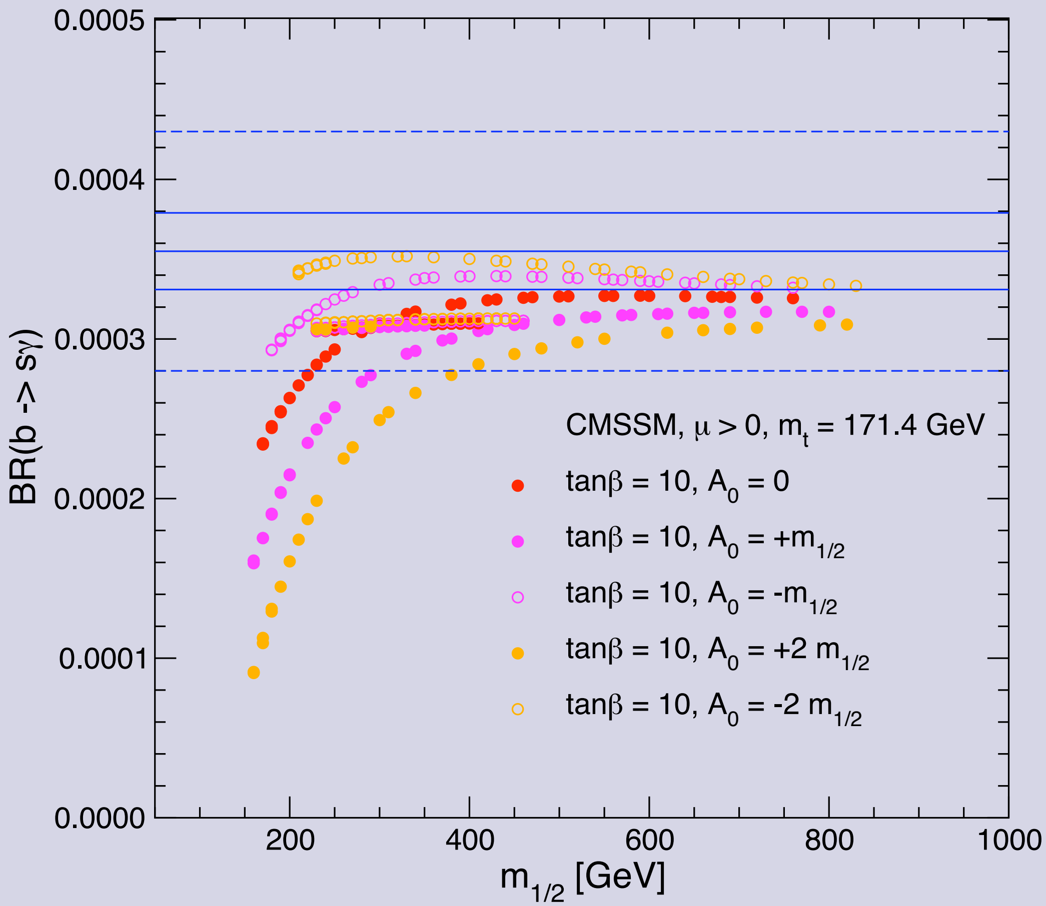
Ellis, Heinemeyer, Olive, Weber, Weiglein

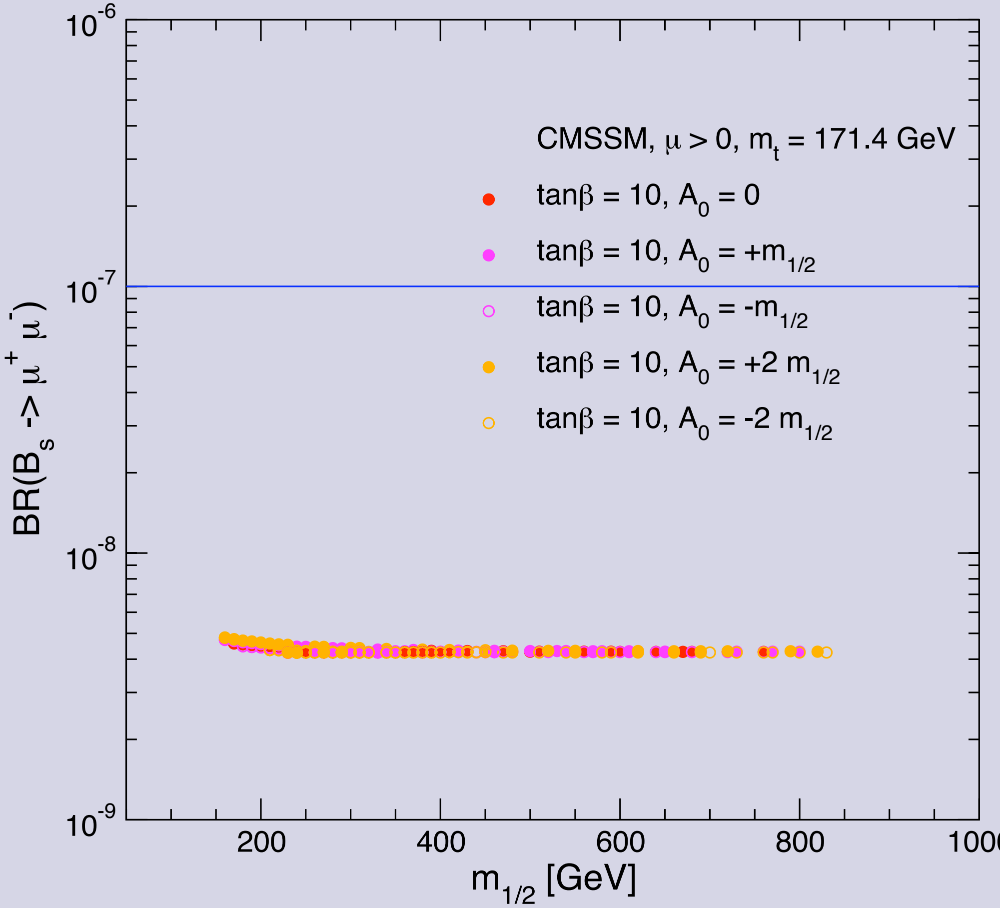
Sensitivity to M_h and g-2



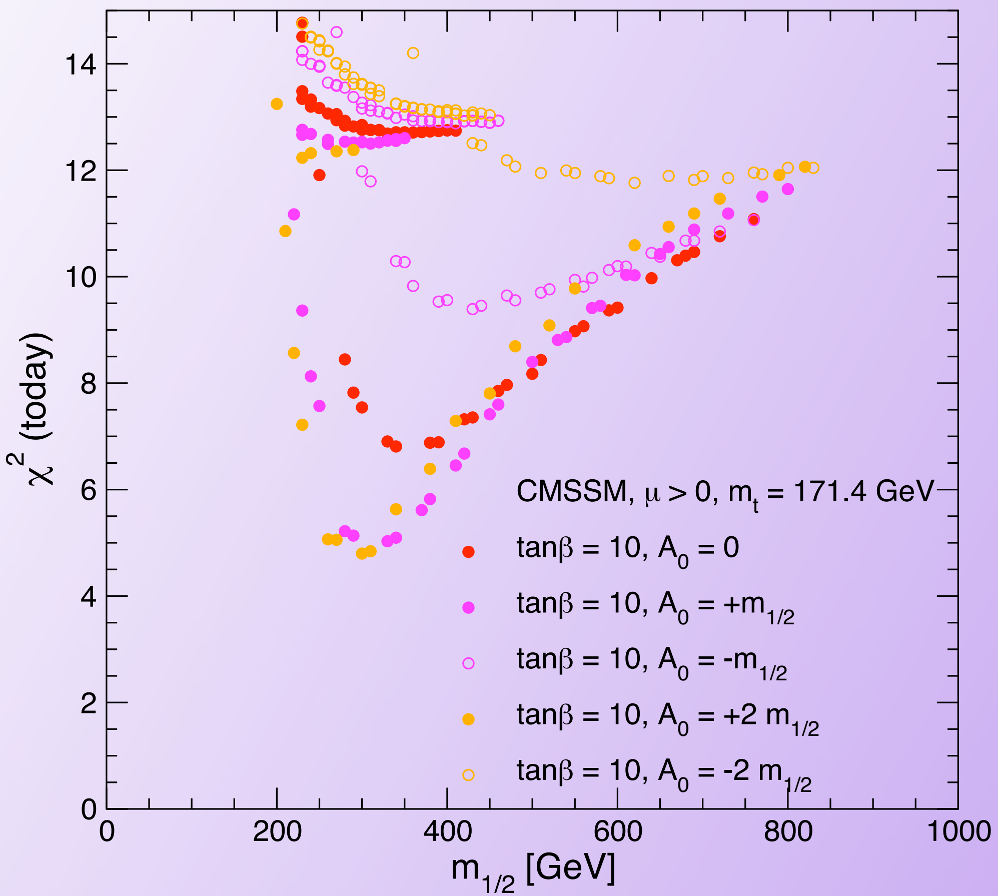
Ellis, Heinemeyer, Olive, Weber, Weiglein

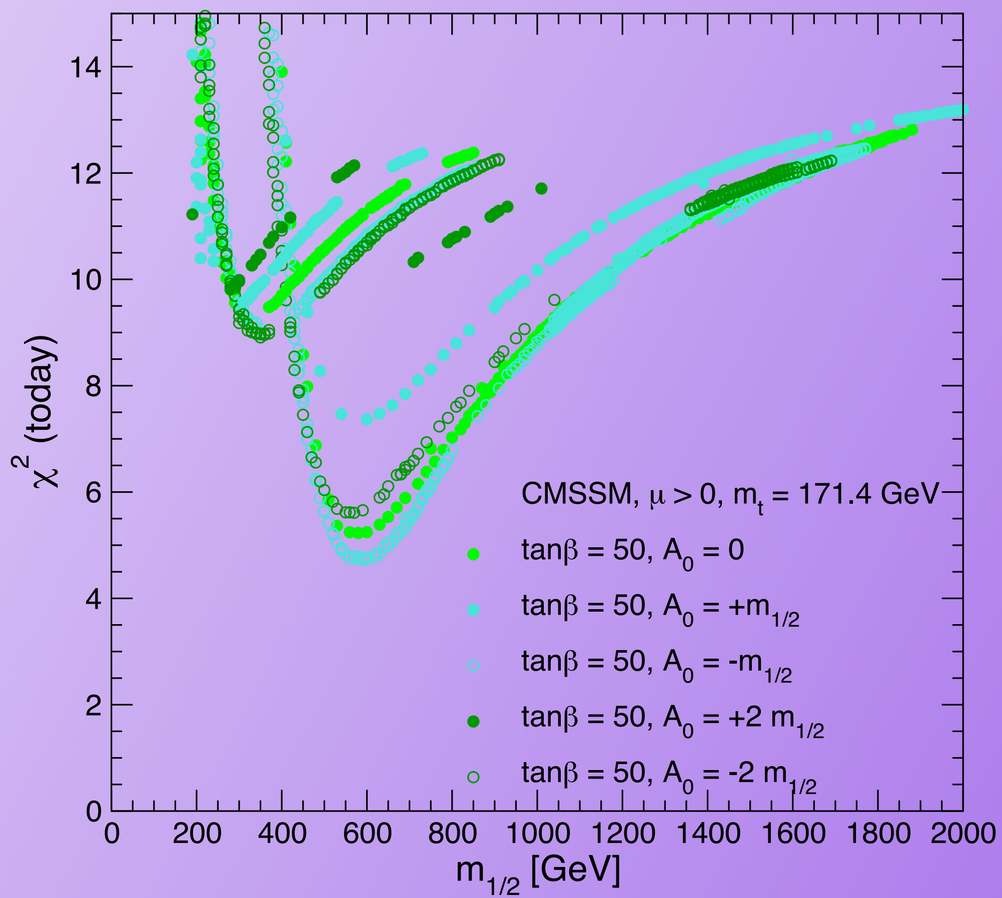
Sensitivity to b → s γ and B → μ μ





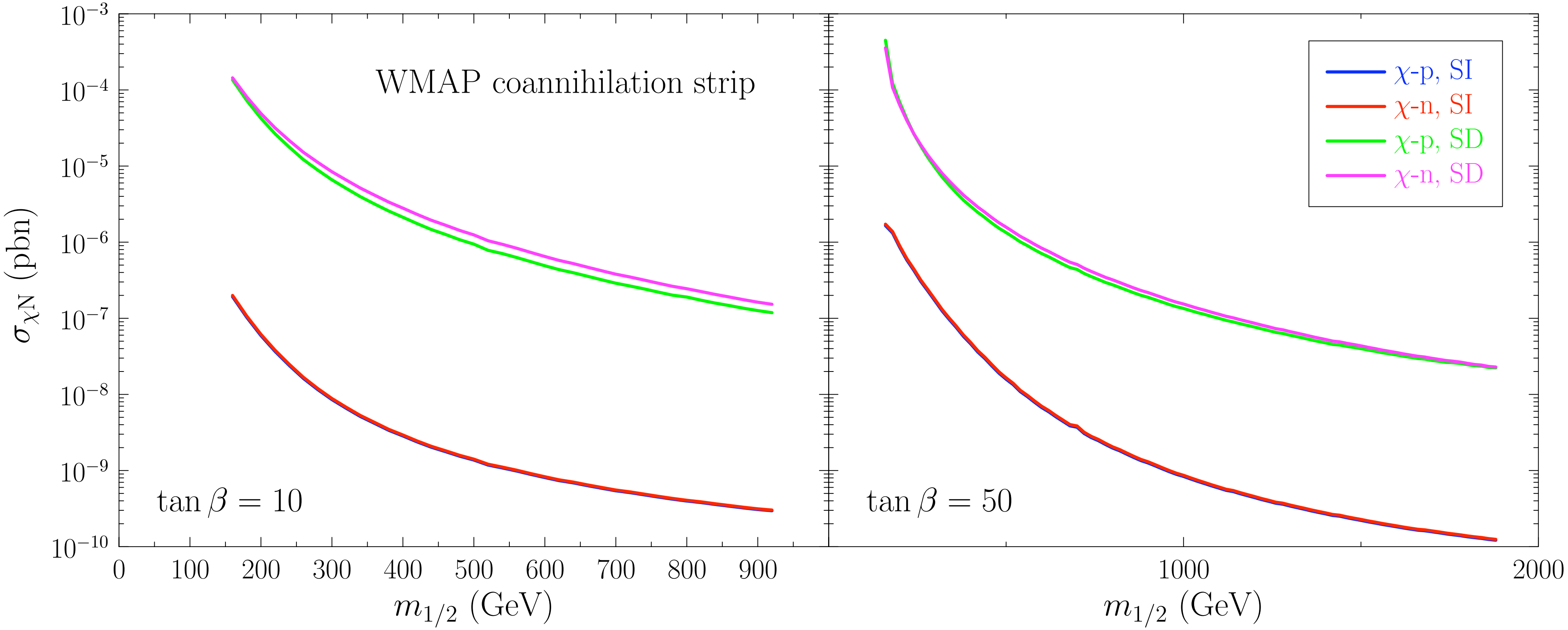
Indirect Sensitivities to CMSSM models



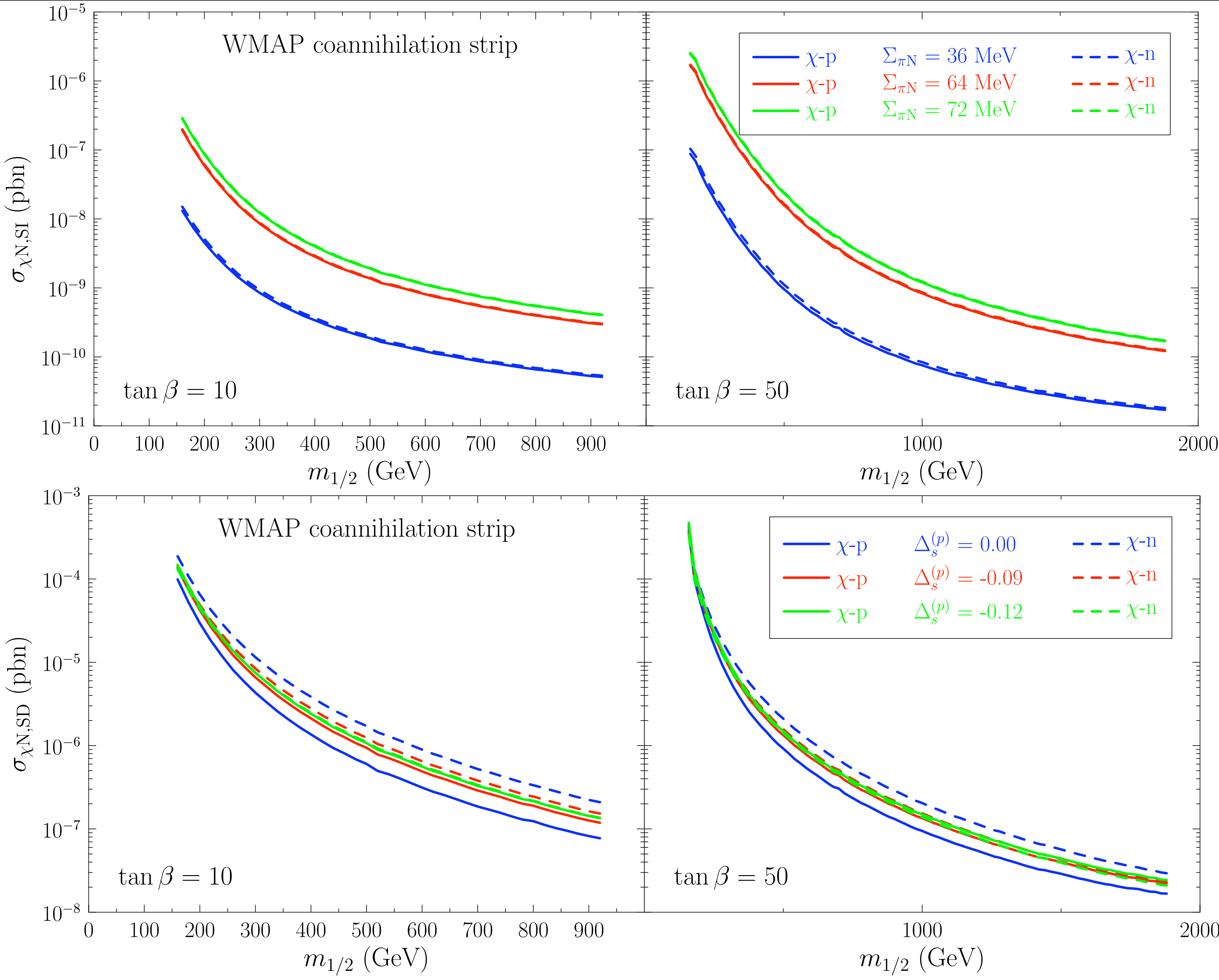


EHOWW

Direct Detection in the CMSSM

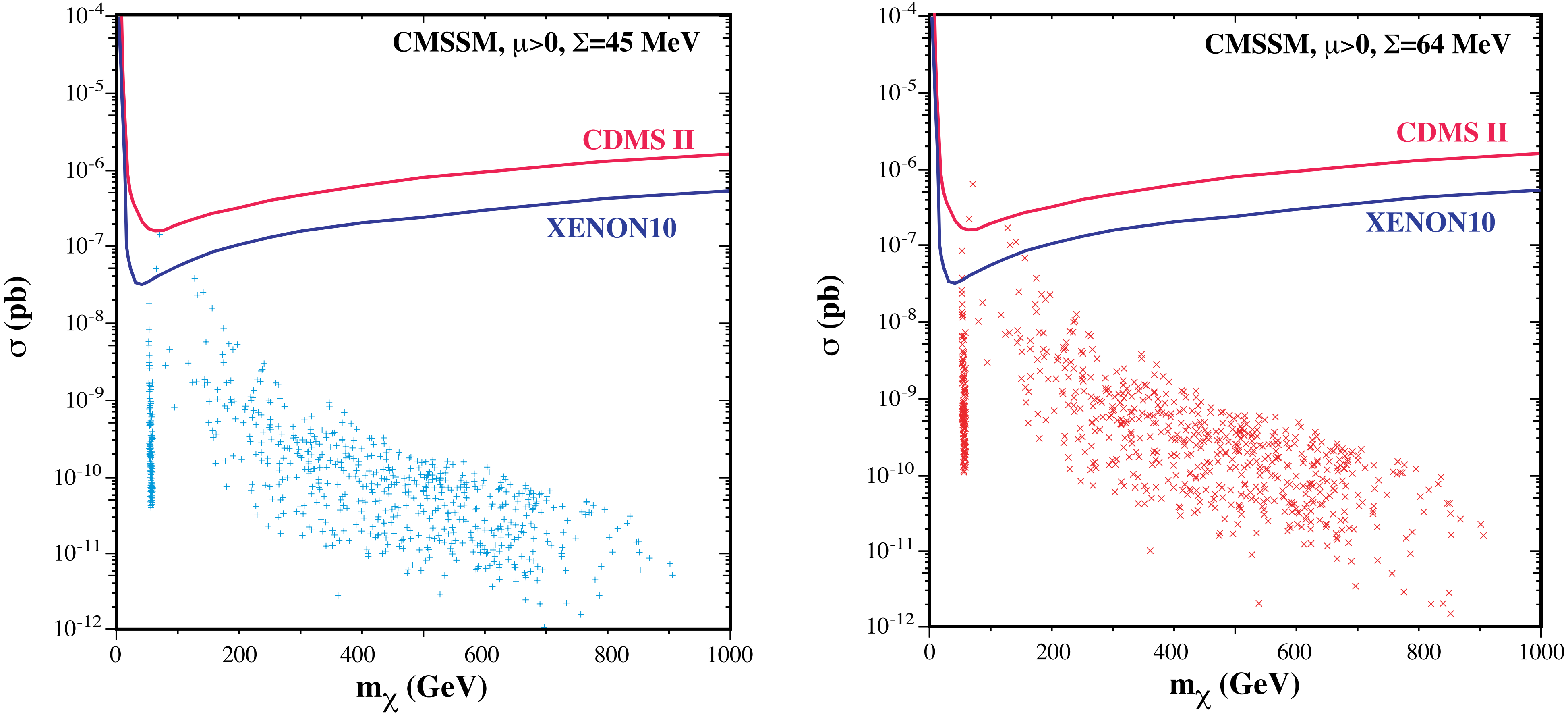


Ellis, Olive, Savage



WMAP coannihilation strip
$\sigma_{\chi N,SI}$ (pbn)
tan β = 10
tan β = 50
χ-p $\Sigma_{\pi N}$ = 36 MeV χ-n
χ-p $\Sigma_{\pi N}$ = 64 MeV χ-n
χ-p $\Sigma_{\pi N}$ = 72 MeV χ-n
$m_{1/2}$ (GeV)
WMAP coannihilation strip
$\sigma_{\chi N,SD}$ (pbn)
tan β = 10
tan β = 50
χ-p $\Delta_s^{(p)}$ = 0.00 χ-n
χ-p $\Delta_s^{(p)}$ = -0.09 χ-n
χ-p $\Delta_s^{(p)}$ = -0.12 χ-n
$m_{1/2}$ (GeV)

Direct Detection in the CMSSM



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Sub-GUT models

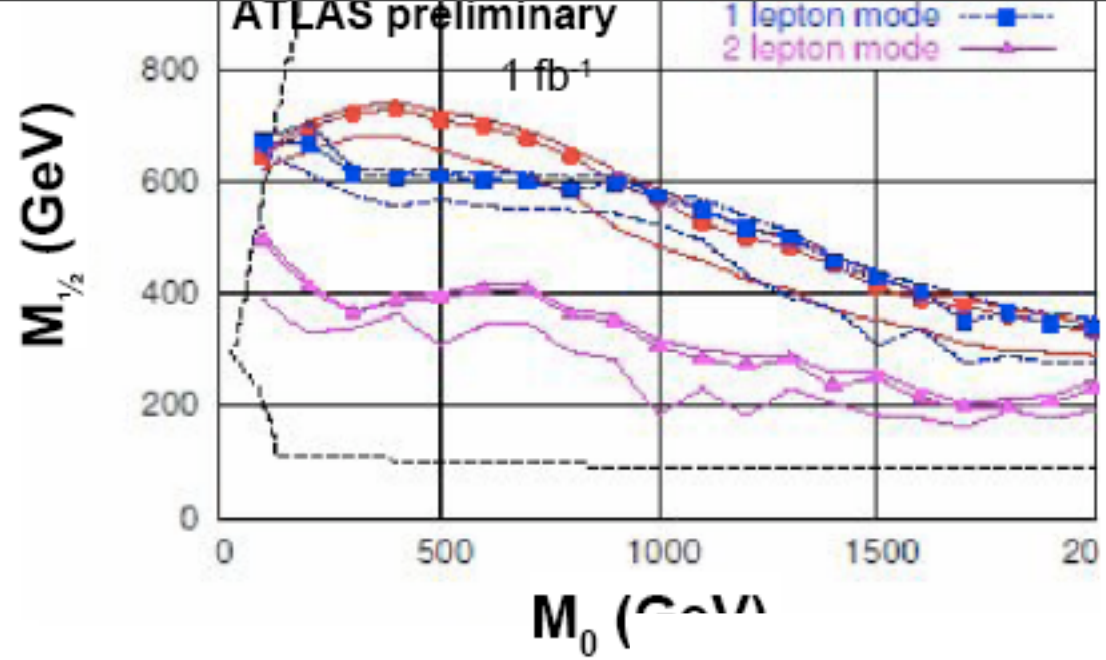
Why assume that the supersymmetry breaking scale is M_{GUT} ?

Flavor-blind supersymmetry breaking → universality
but at what scale?

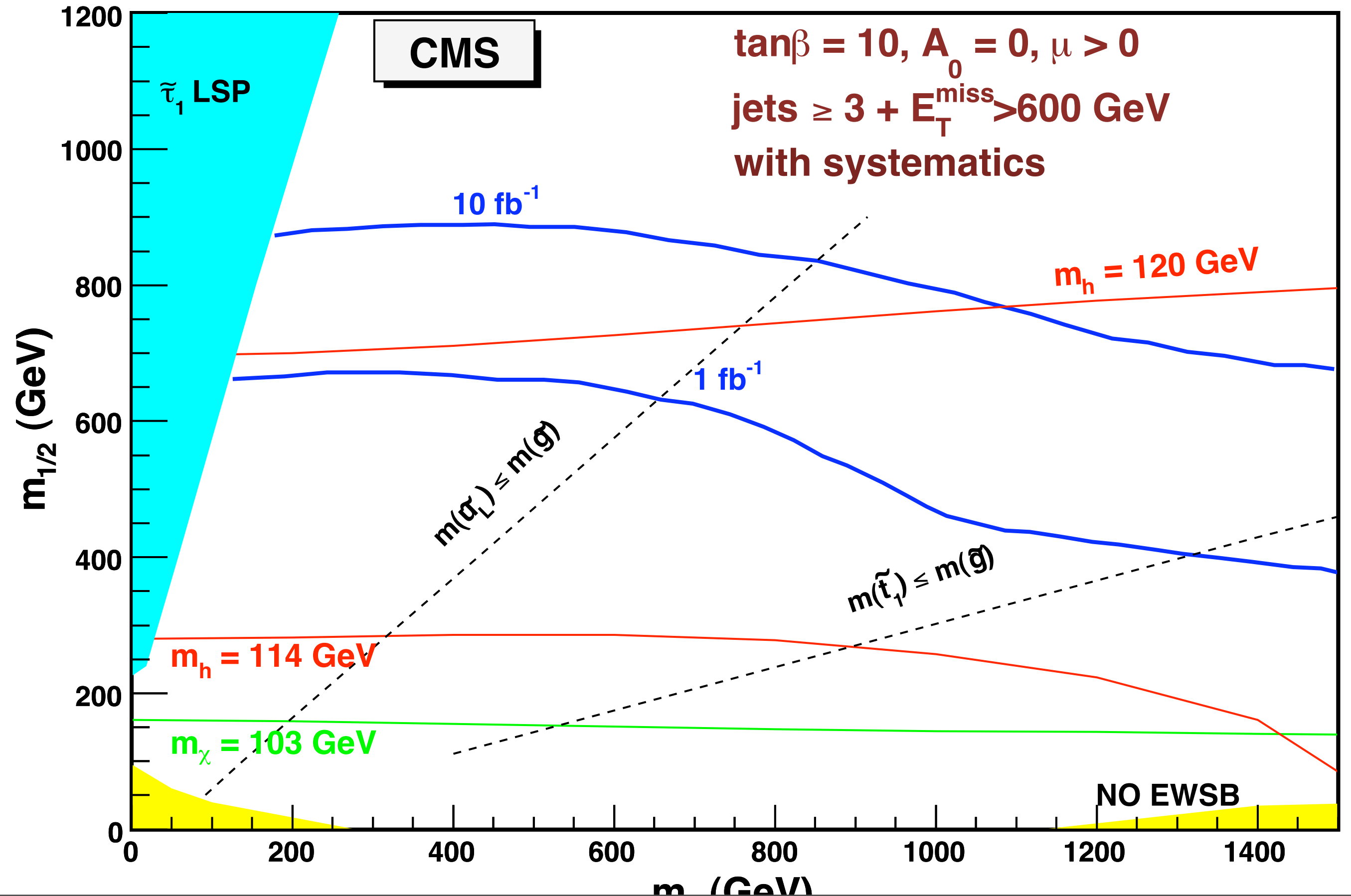
Gauge coupling unification maintained (at the GUT scale)

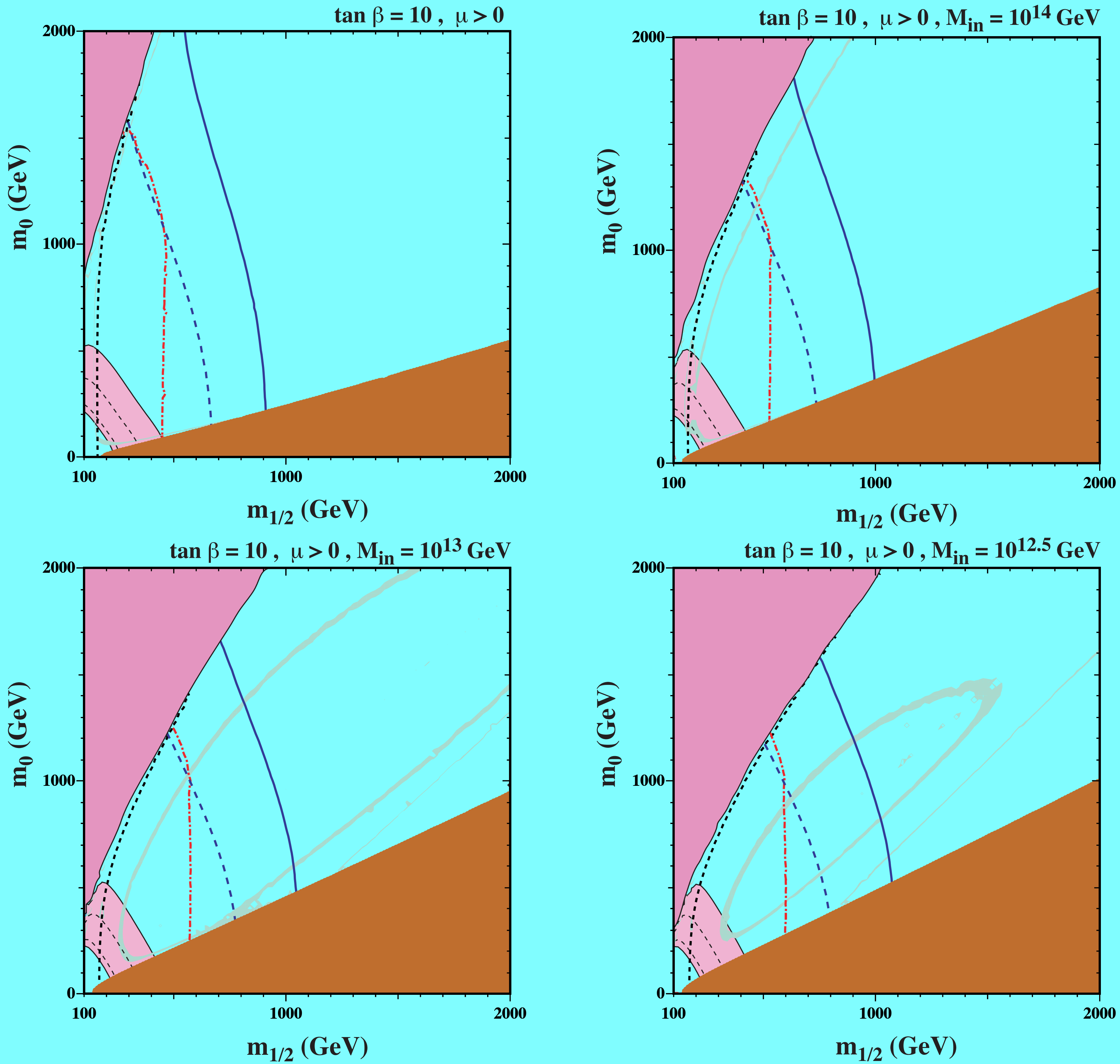
Gaugino and scalar masses unified at some scale $M_{in} < M_{GUT}$

Ellis, Olive, Sandick

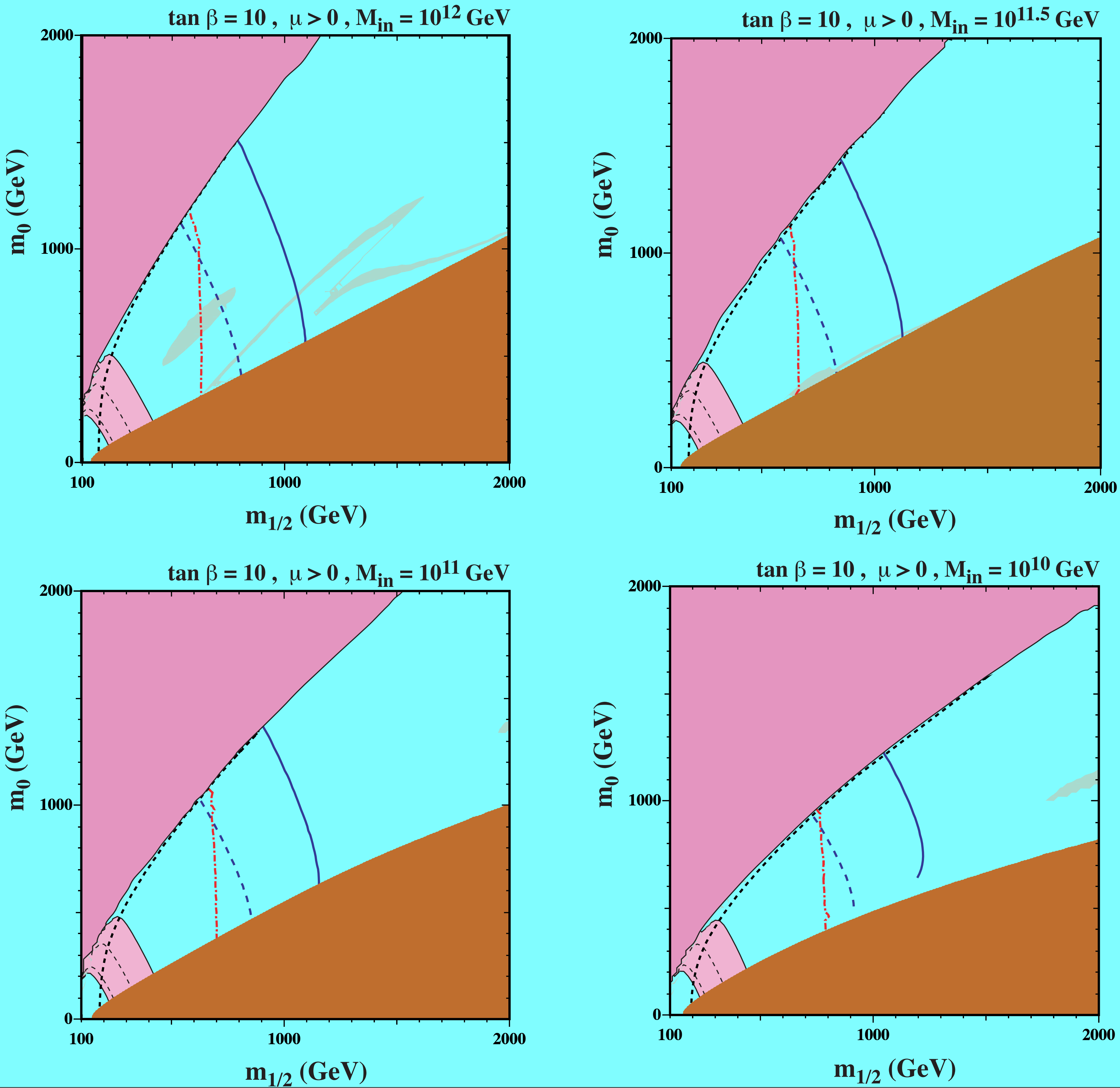


S ≥ 10 and S/√B > 5
2-lepton channel: oppo
Fast simulation.
Generator-level syster



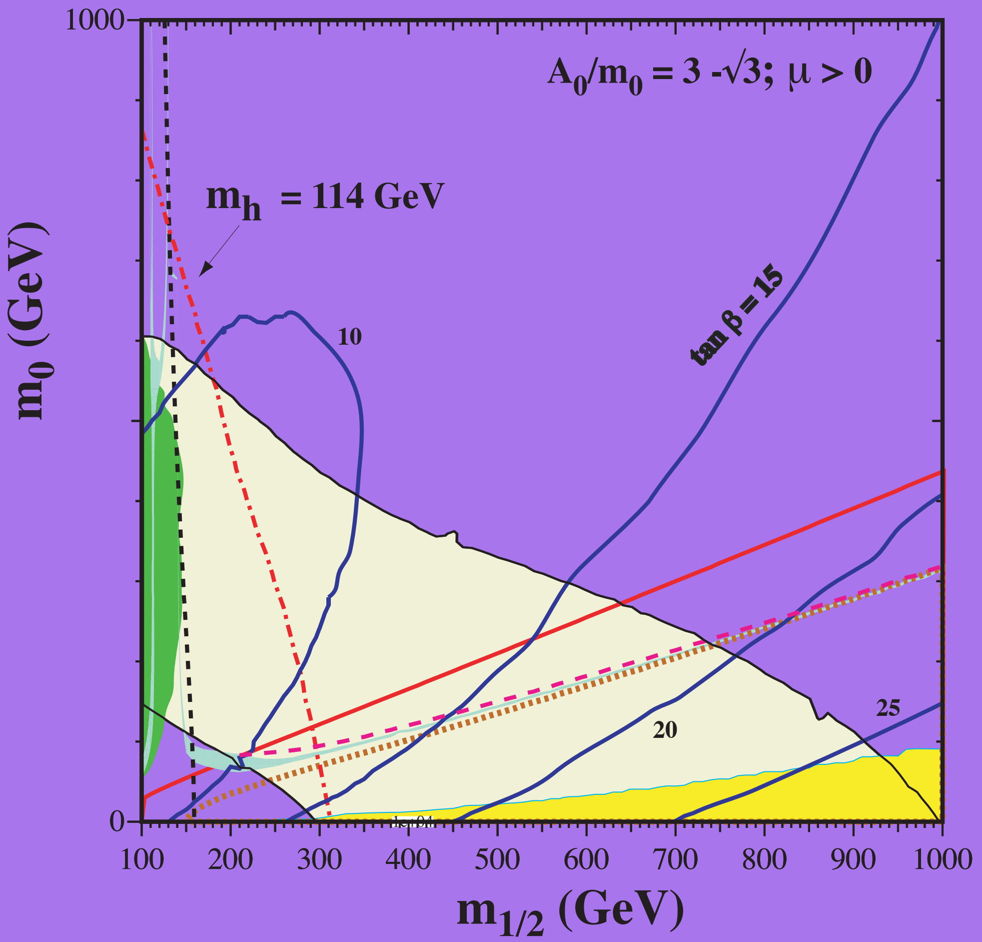


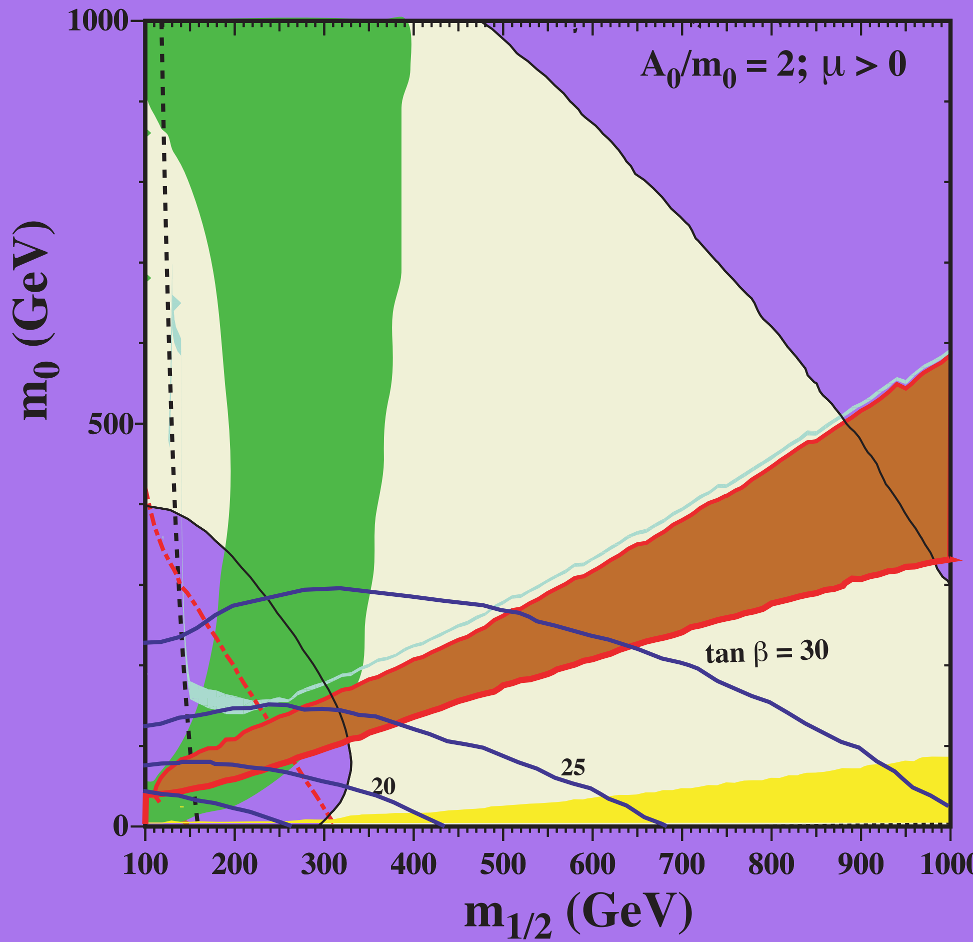
tan β = 10 , μ > 0
tan β = 10 , μ > 0 , M_in = 10^14 GeV
tan β = 10 , μ > 0 , M_in = 10^13 GeV
tan β = 10 , μ > 0 , M_in = 10^12.5 GeV
m_0 (GeV)
m_1/2 (GeV)
0
1000
2000
100
1000
2000


tan β = 10 , μ > 0 , M_in = 10^12 GeV
tan β = 10 , μ > 0 , M_in = 10^11.5 GeV
tan β = 10 , μ > 0 , M_in = 10^11 GeV
tan β = 10 , μ > 0 , M_in = 10^10 GeV
m_0 (GeV)
m_1/2 (GeV)
0
1000
2000
100
1000
2000

mSugra models

- tan β fixed by boundary conditions ($B_0 = A_0 - m_0$)
- ``planes'' determined by A_0/m_0
- Gravitino often the LSP ($m_{3/2} = m_0$)
- No Funnels
- No Focus Point

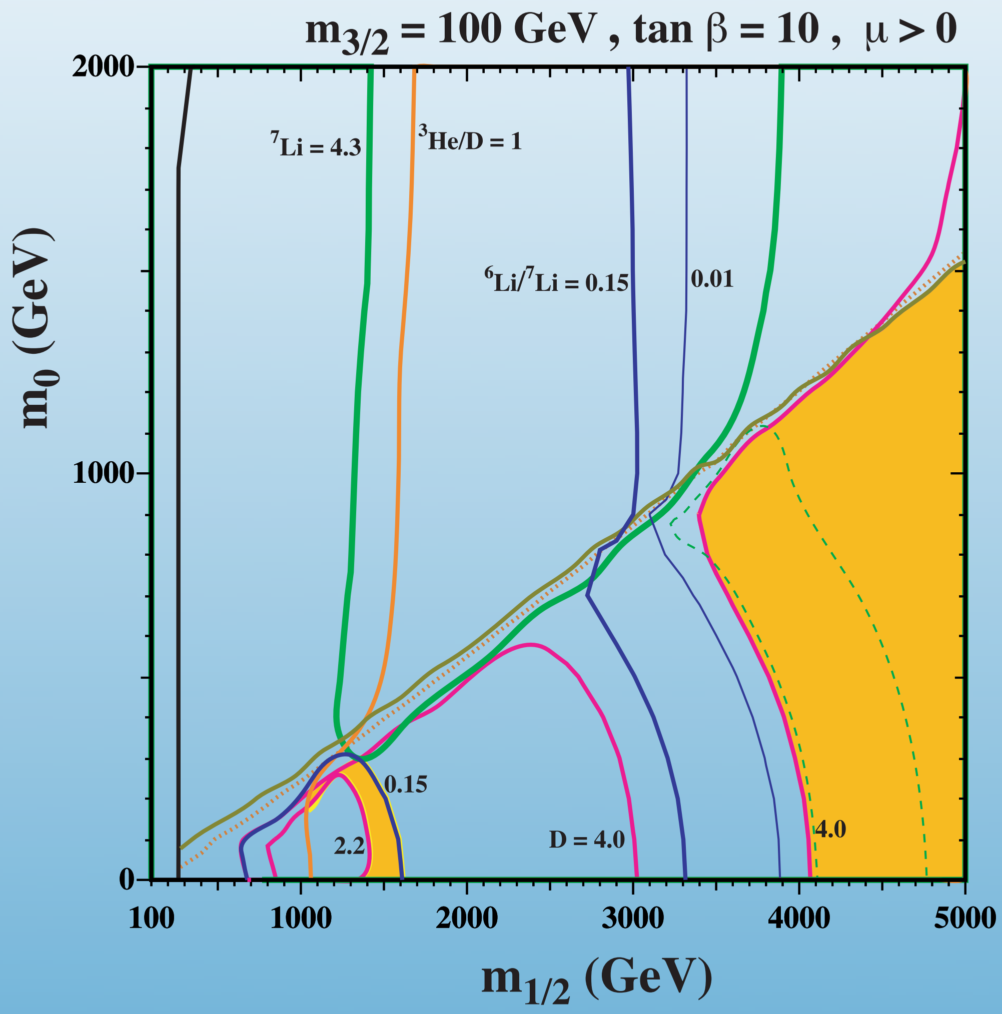




The Very CMSSM (mSUGRA):

- Add $B_0 = A_0 - m_0$: Select tan β

Ellis, Olive, Santoso, Spanos



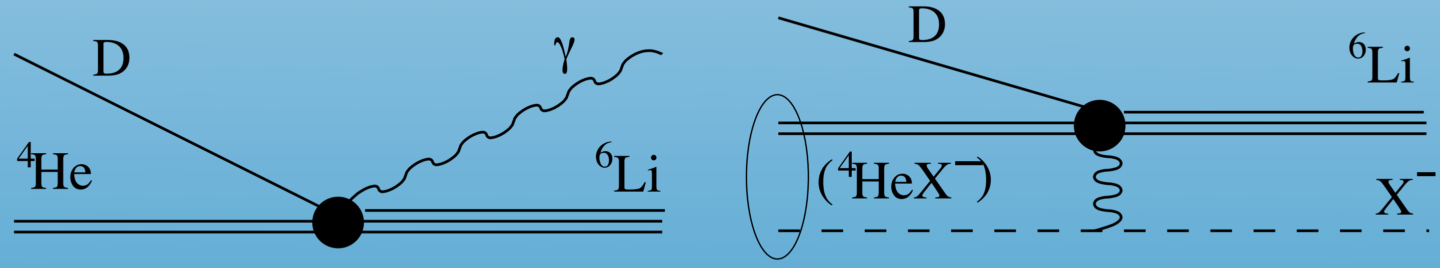
Cyburt, Ellis, Fields, KO, Spanos

Effects of Bound States

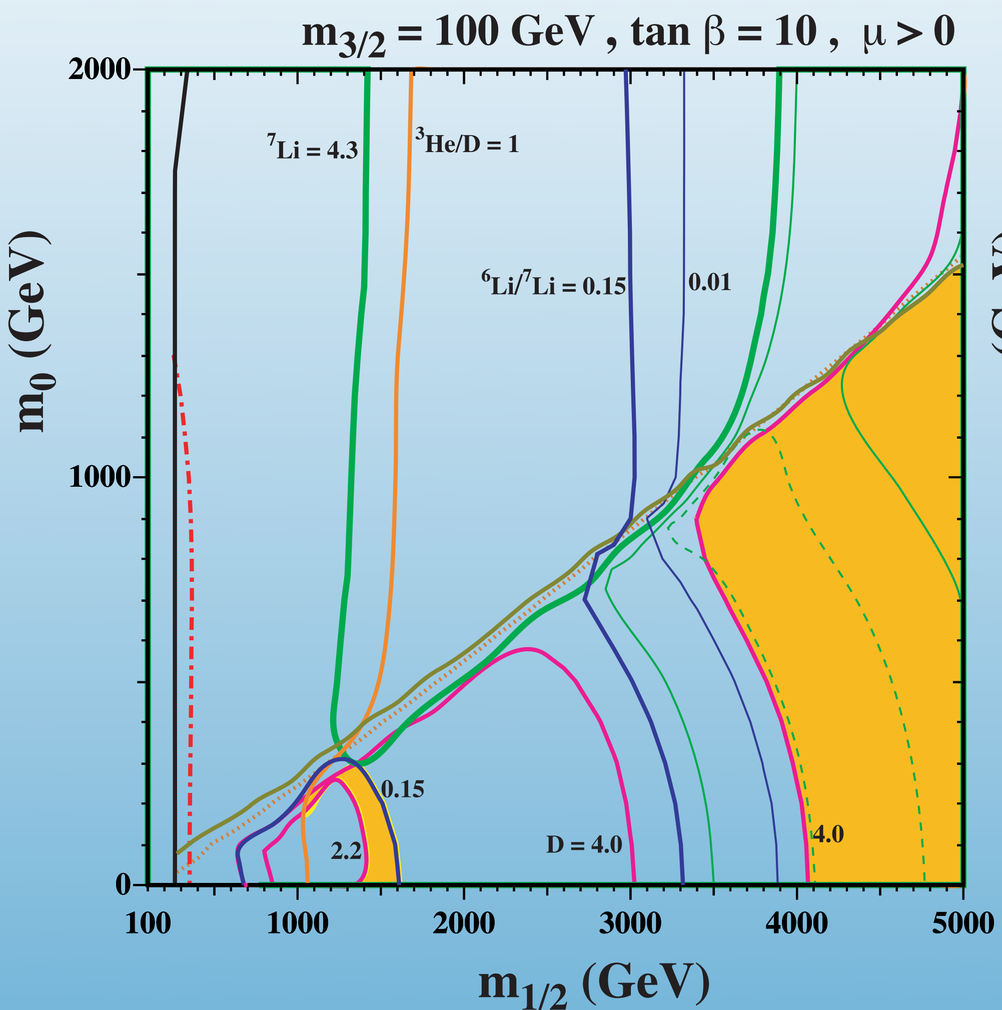
- In SUSY models with a $\tilde{\tau}$ NLSP, bound states form between ^4He and $\tilde{\tau}$

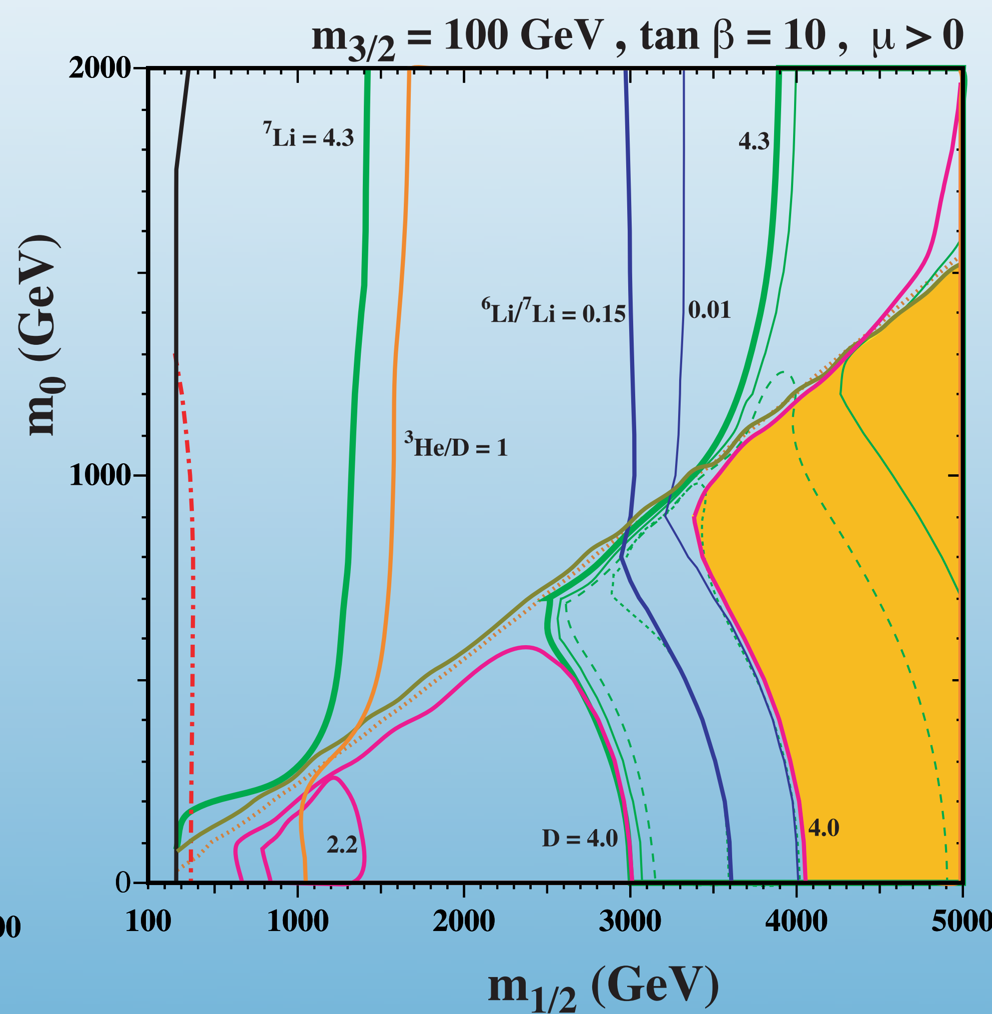
- The ^4He (D, γ) ^6Li reaction is normally highly suppressed (production of low energy γ)

- Bound state reaction is not suppressed

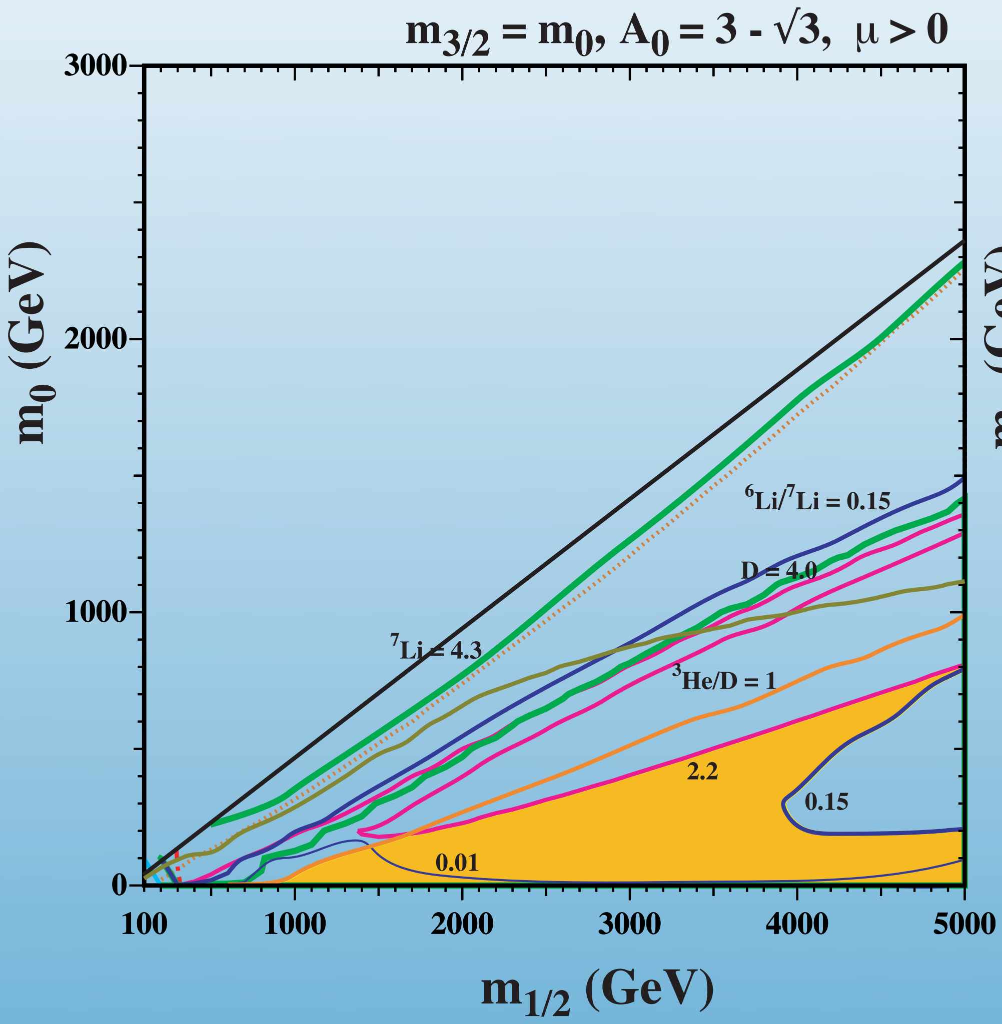


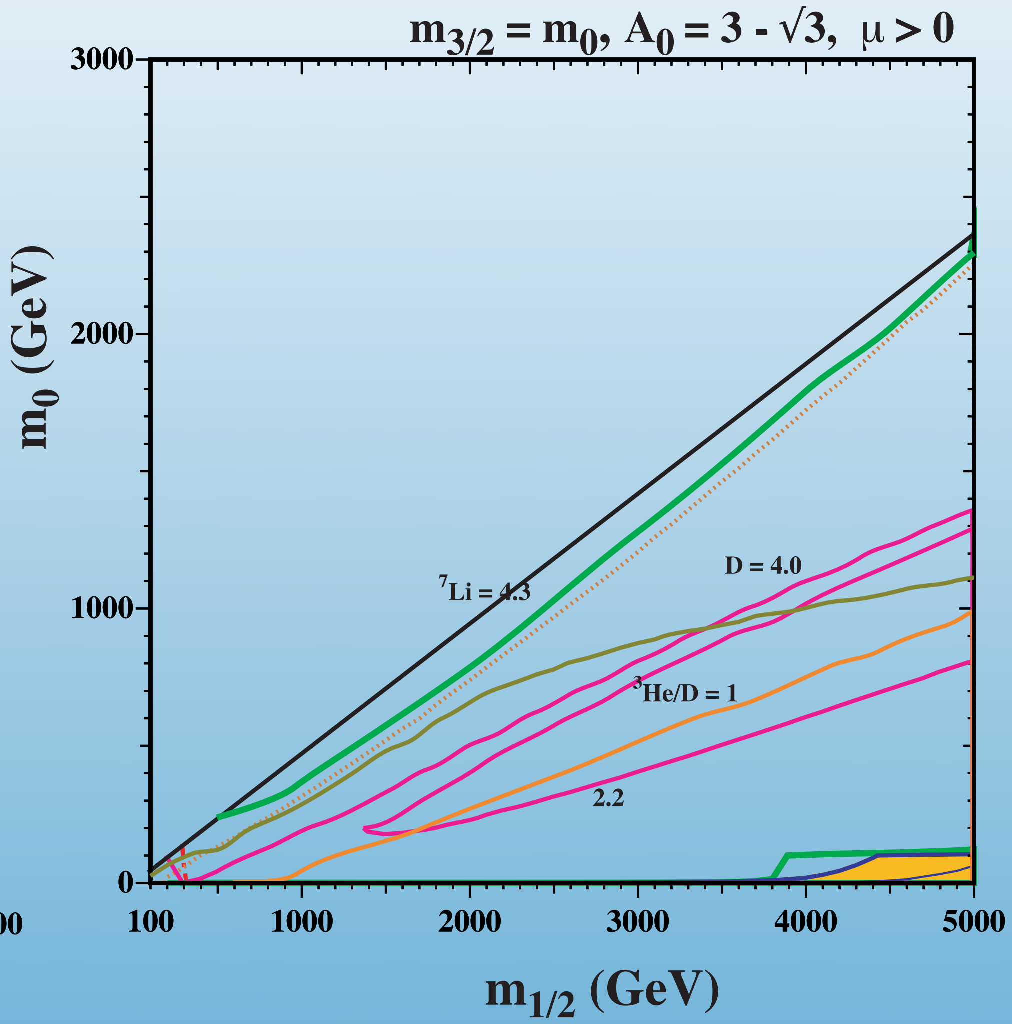
Pospelov





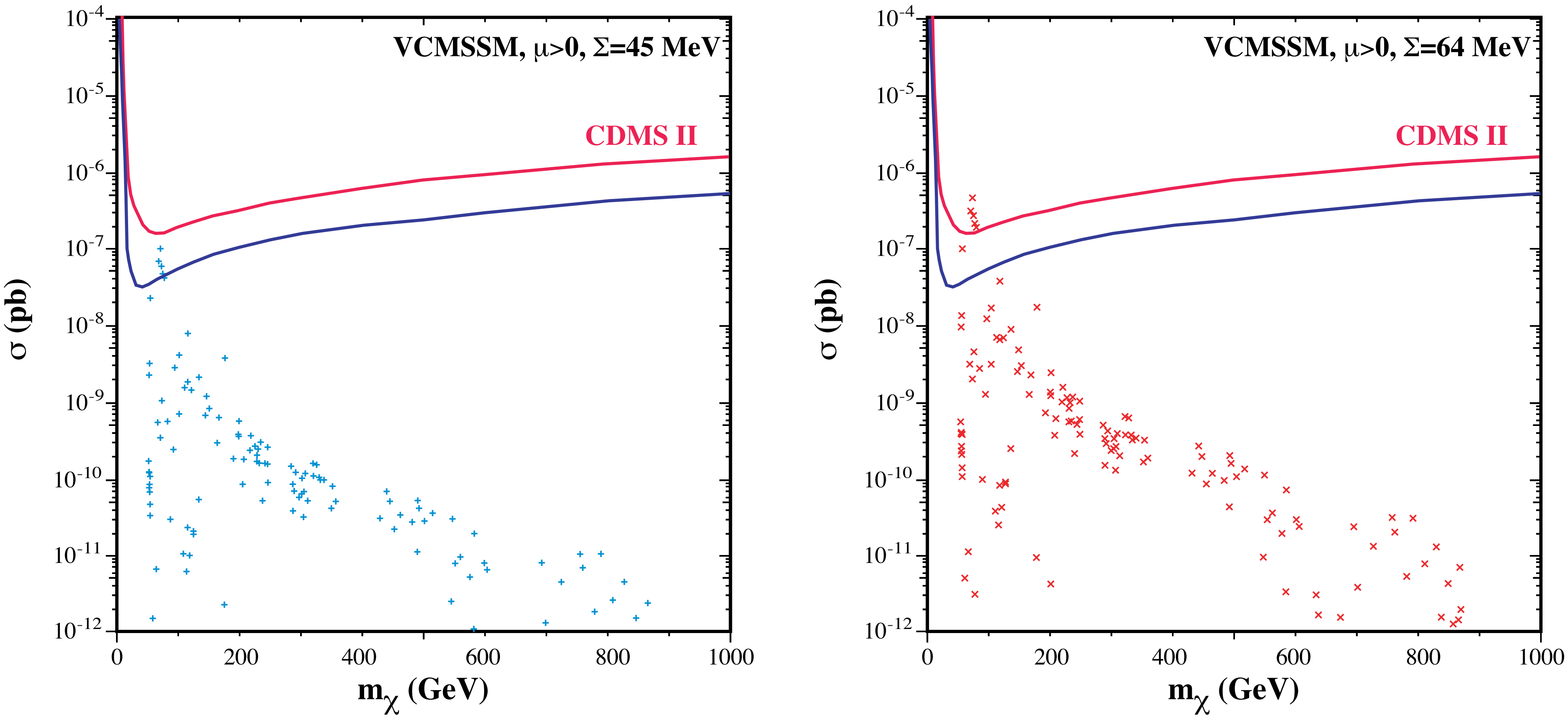
Cyburt, Ellis, Fields, KO, Spanos





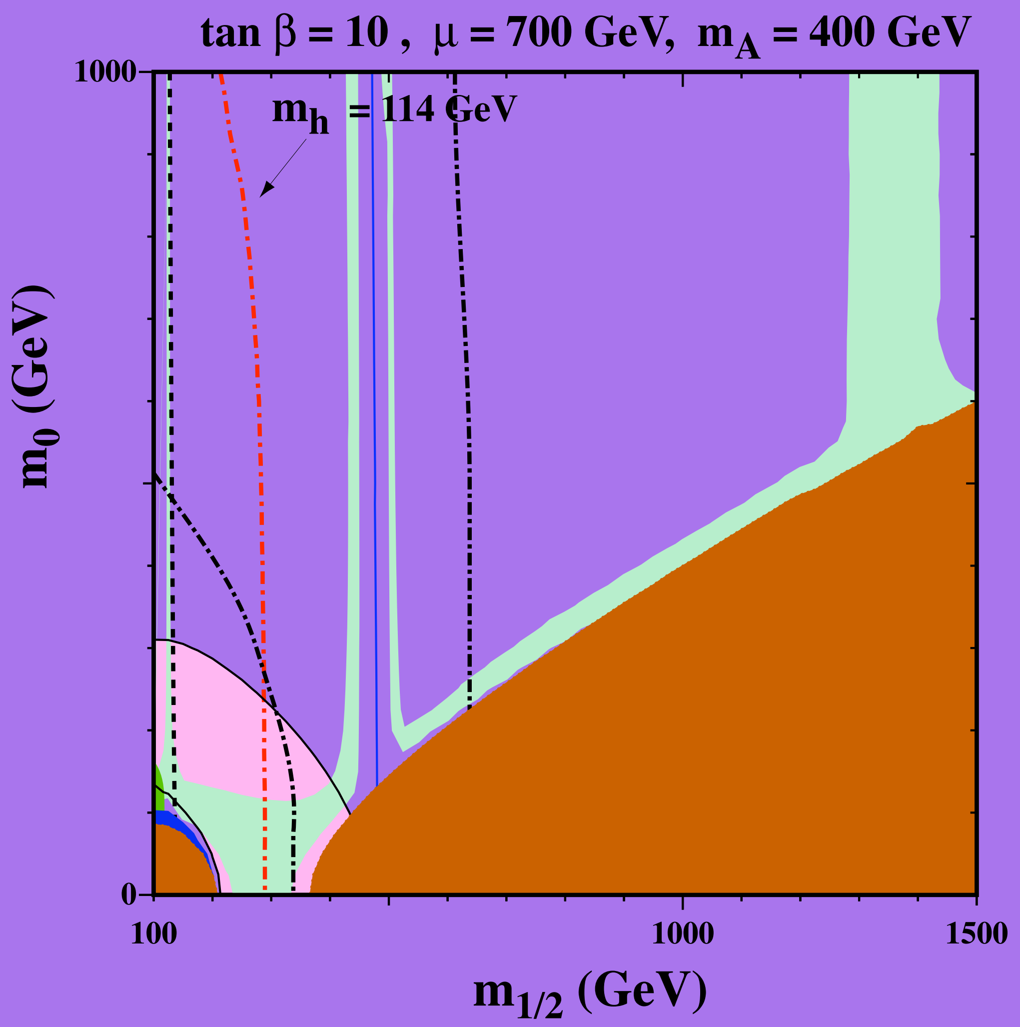
Cyburt, Ellis, Fields, KO, Spanos

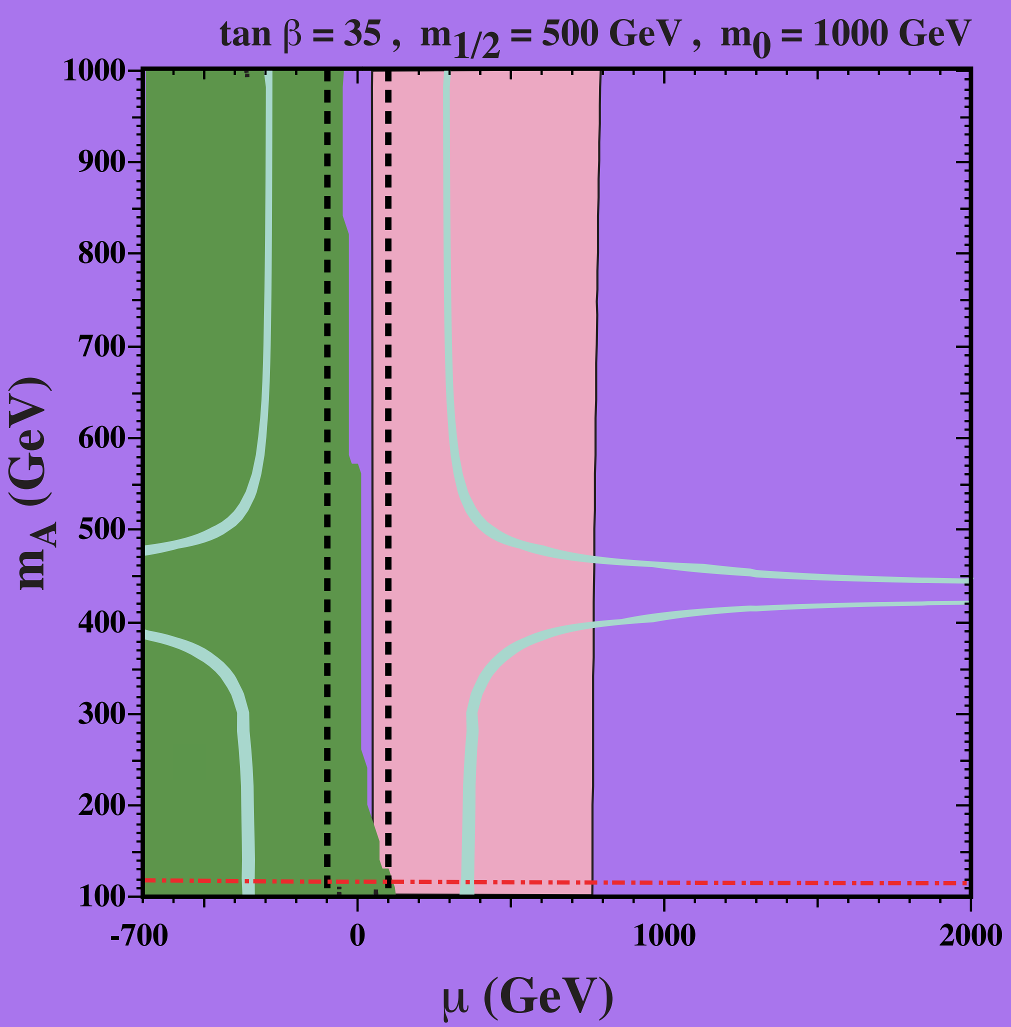
Direct Detection of NDM in the mSugra models



NUHM

- Drop unification of scalar masses
- All Higgs soft masses, m_1 and m_2, to be chosen independently of m_0
- Allows μ and m_A to be free parameters





The $m_0 - m_{1/2}$ plane

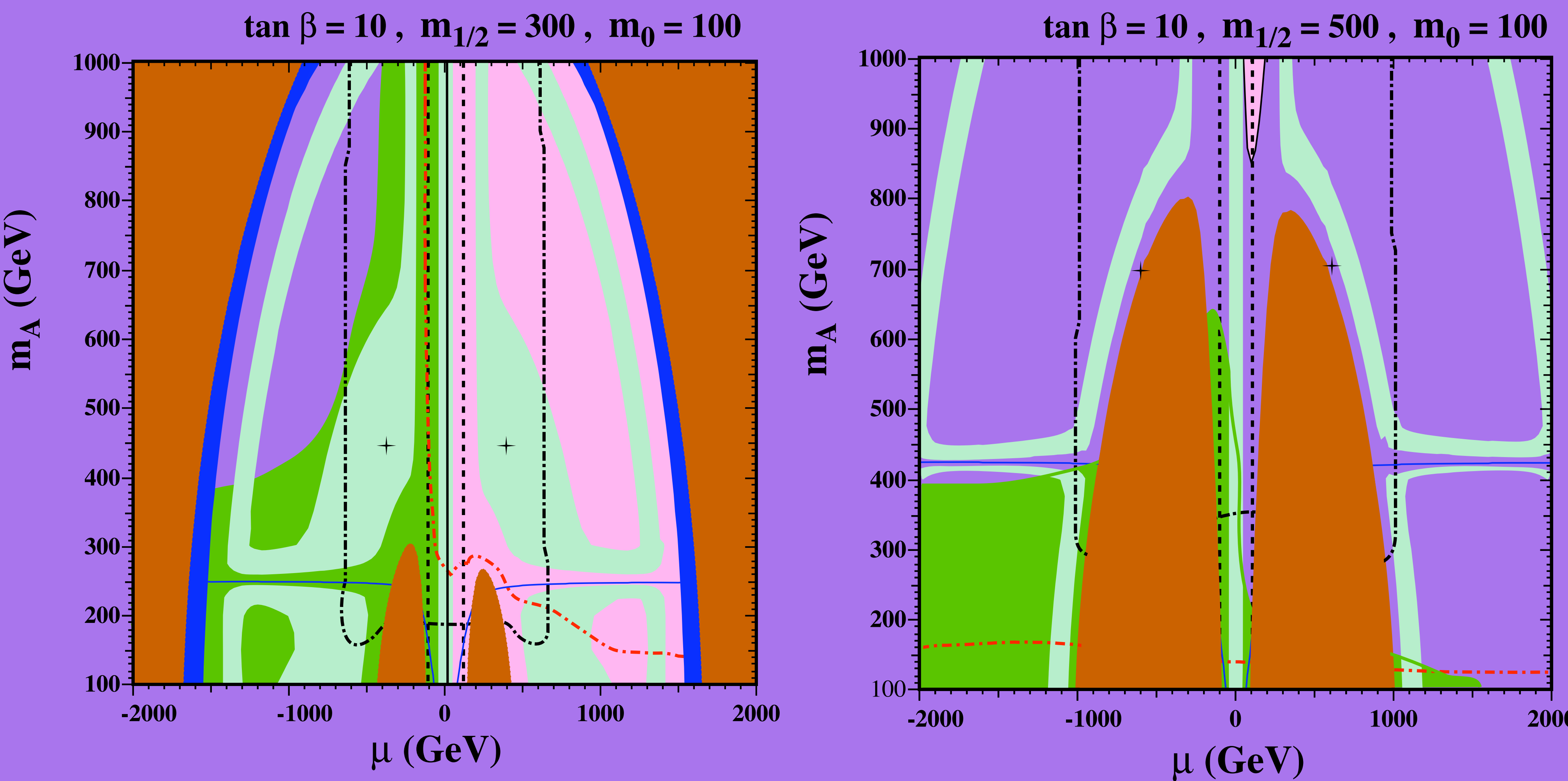
+ CMSSM value

Ellis, Falk, Olive, Santoso

The $m_A - \mu$ plane

+ CMSSM value

Ellis, Olive, Santoso, Spanos

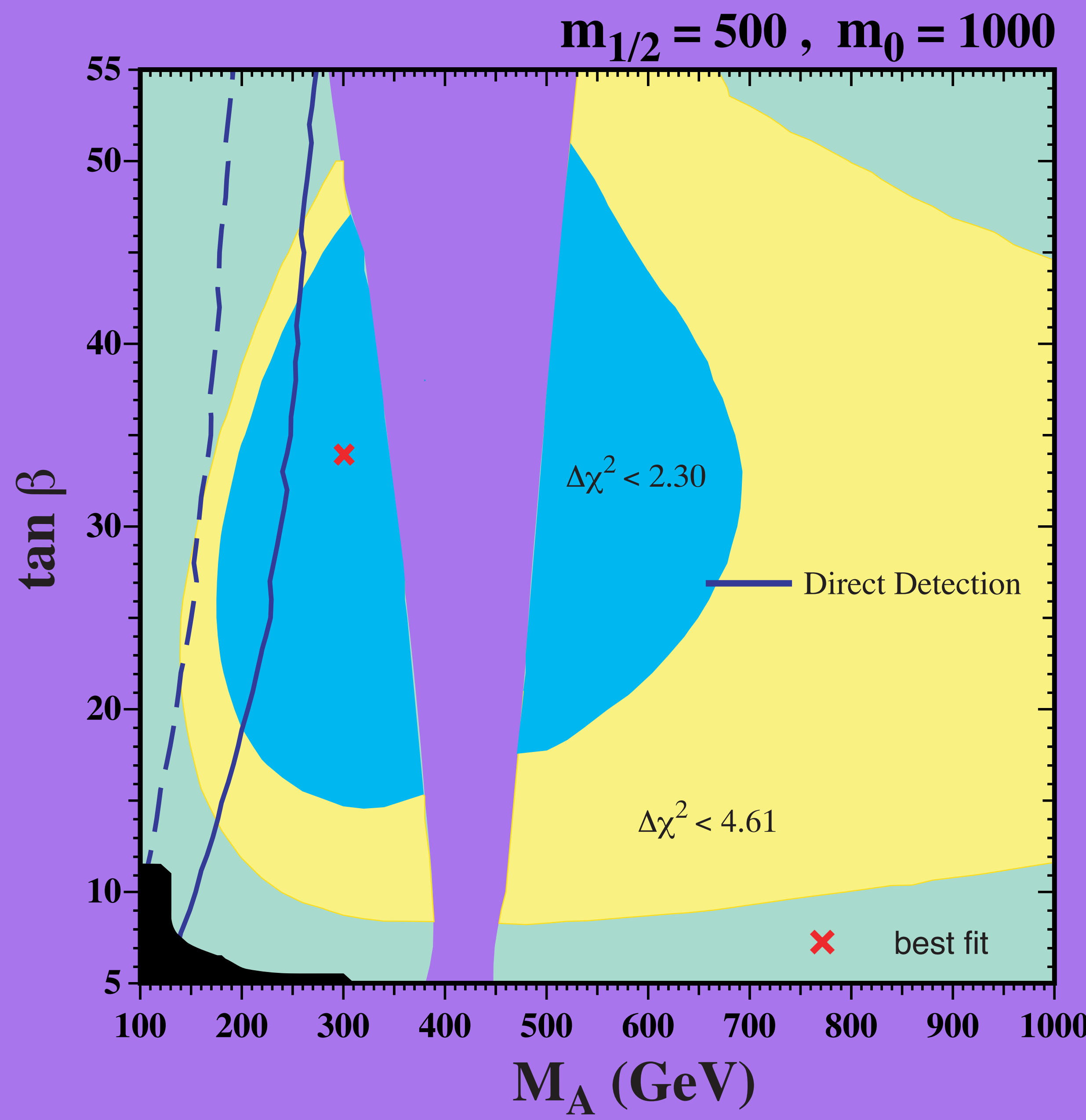


The $m_A - \mu$ plane

+ CMSSM value

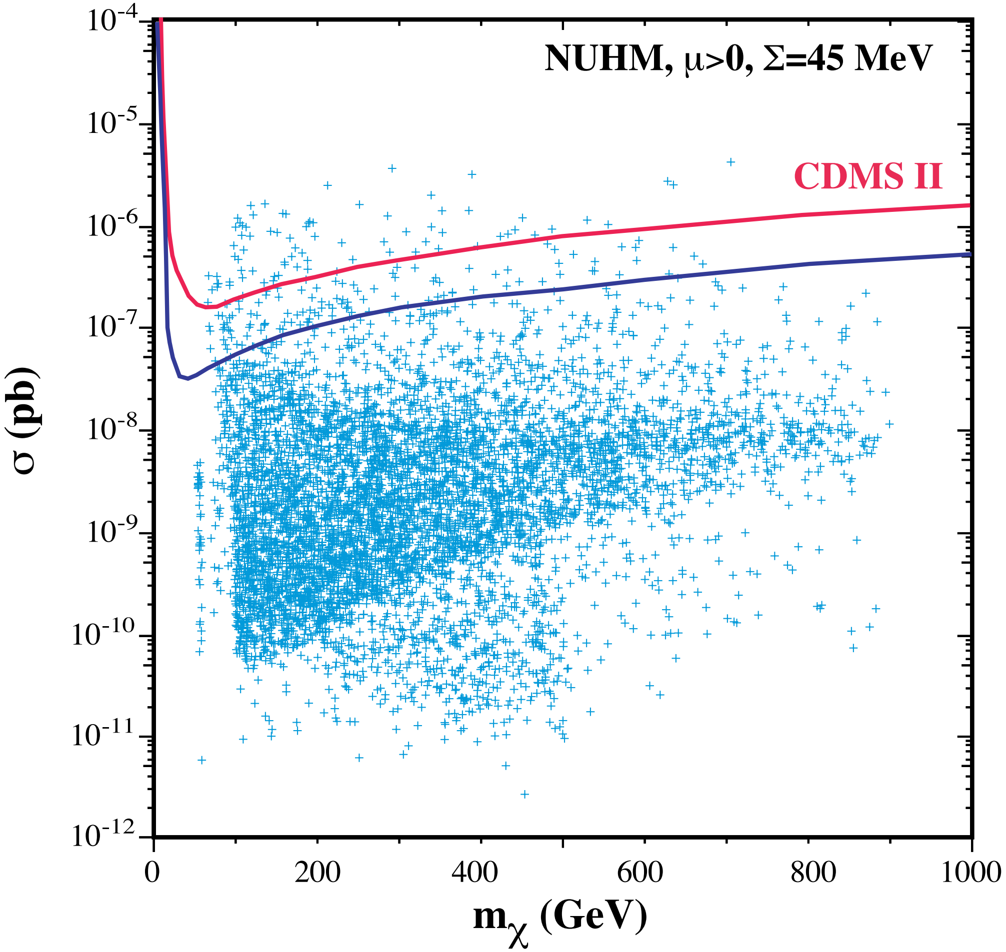
Ellis, Olive, Santoso

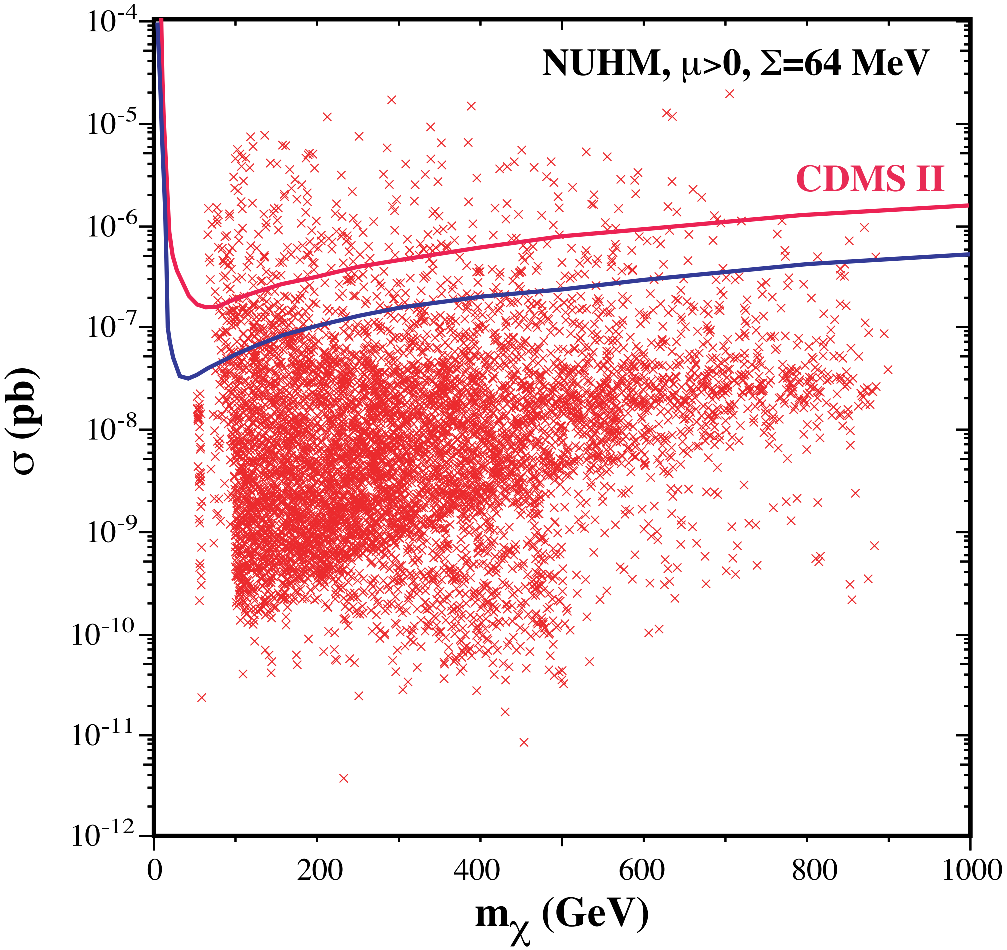
CDM-consistent M_A-tan β planes



Ellis, Hahn, Heinemeyer, Olive, Weiglein

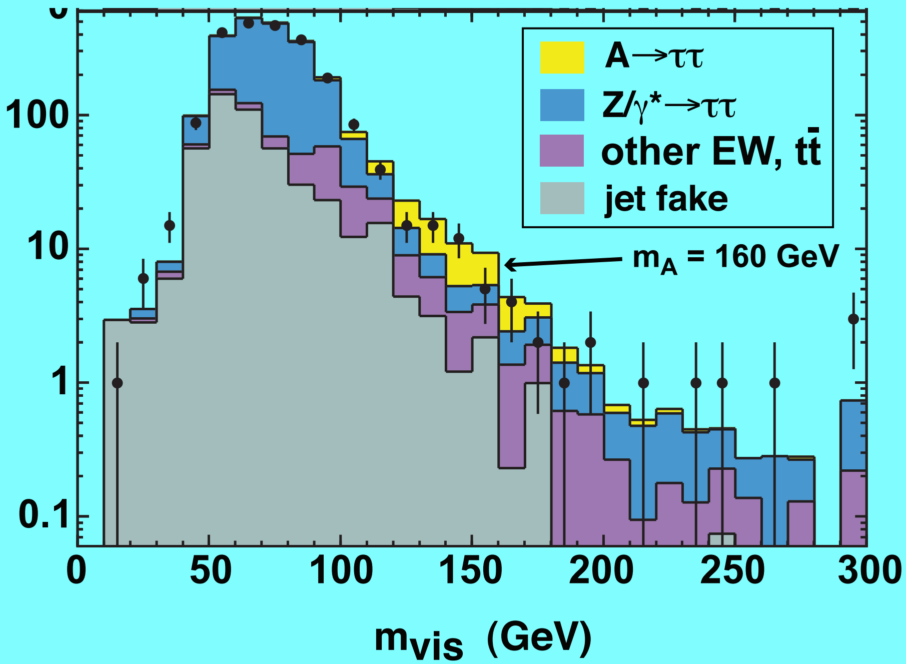
Direct Detection in the NUHM

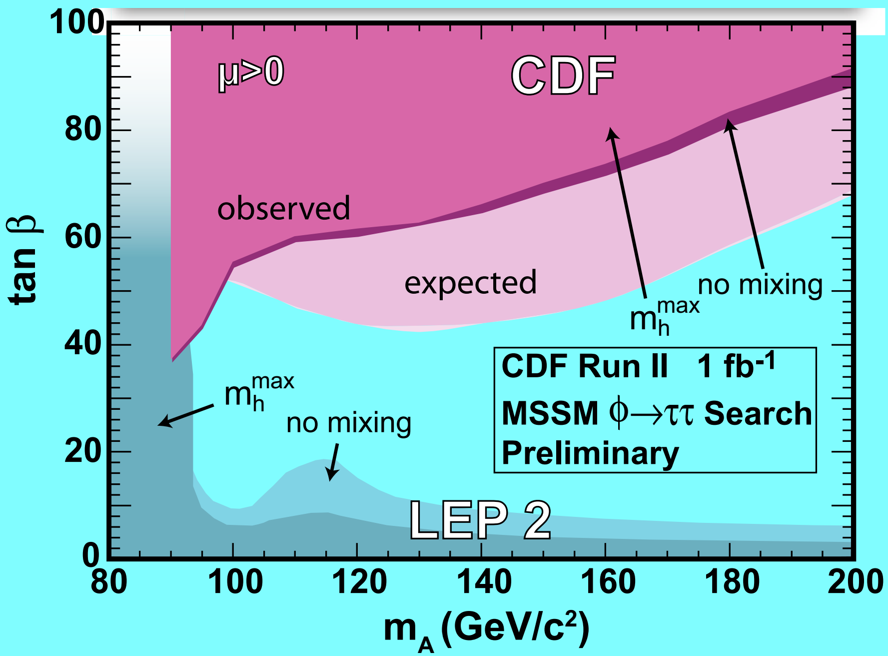




EOSS

Hint of Higgs?





Not possible in CMSSM (light Higgs)
but barely possible in NUHM

Higgs Production/Detection

Dominant Production Mode: gluon or $b\,\bar{b}$ fusion

Dominant Detection Channel: $b\,\bar{b}$ or $\tau^+\,\tau^-$

$\tau^+\,\tau^-$ cleaner signal

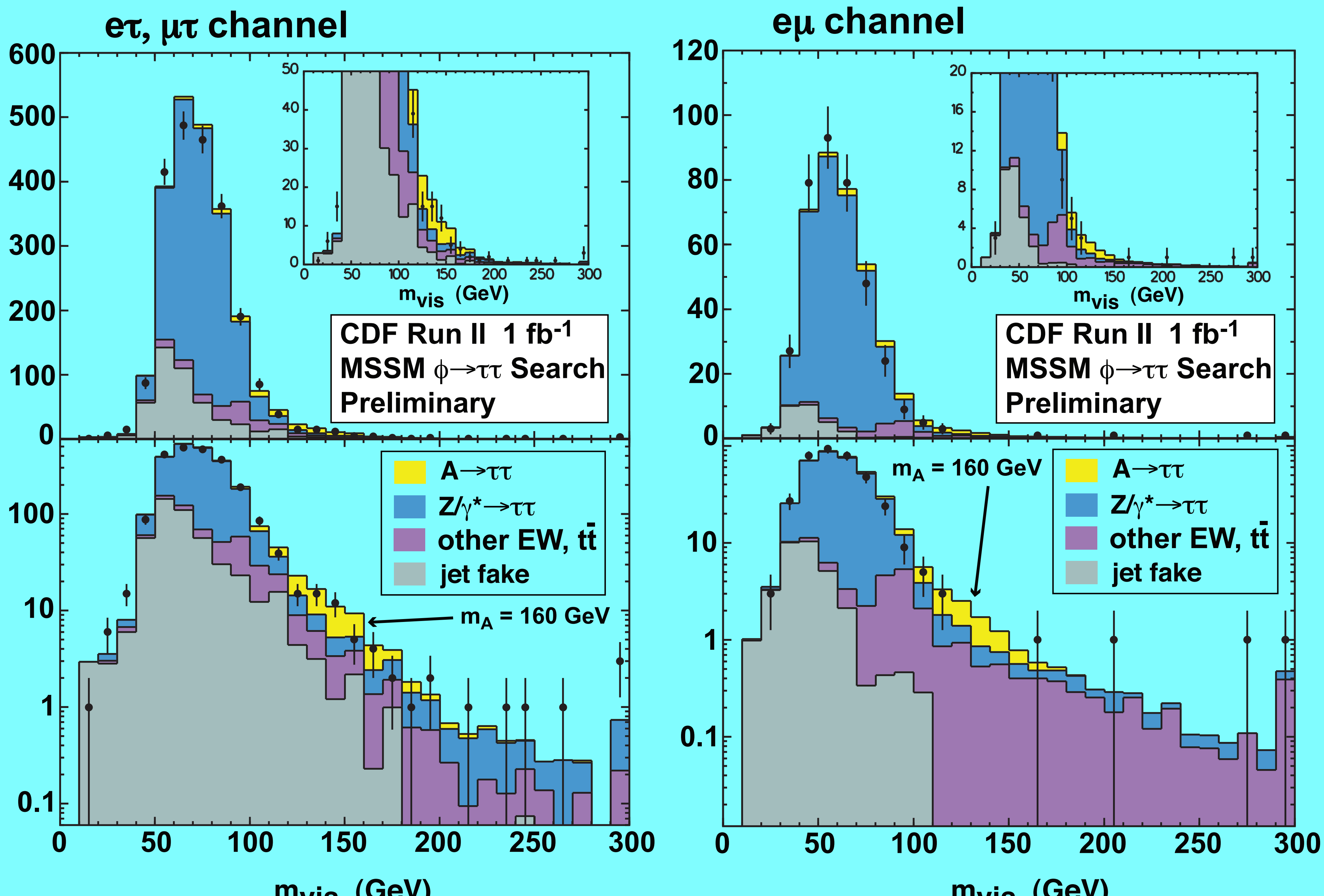
CDF Search for $H \rightarrow \tau^+\,\tau^-$

$\tau \longrightarrow e\nu_e\nu_\tau$, $\tau \longrightarrow \mu\nu_\mu\nu_\tau$, and $\tau \longrightarrow hadrons\ \nu_\tau$

Enhanced by $\tan^2\beta\,/((1+\Delta_b)^2+9)$ relative to SM

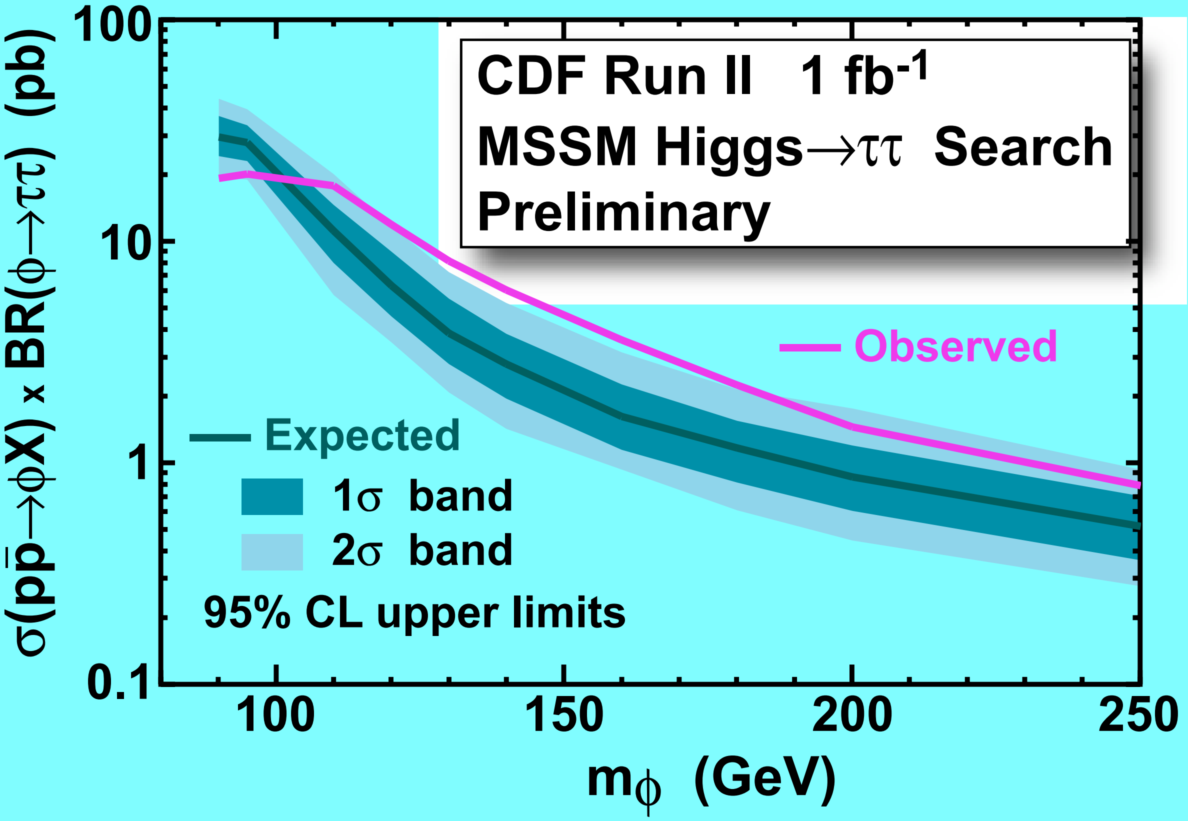
Background

source	$\tau_e\tau_{had}$	$\tau_\mu\tau_{had}$	$\tau_e\tau_\mu$
$Z \to \tau\tau$	793.0 ± 4.7	796.6 ± 4.6	312.4 ± 2.9
$Z \to ee, \mu\mu$	68.3 ± 1.9	63.2 ± 1.8	11.9 ± 0.8
di-boson events	1.5 ± 0.02	1.2 ± 0.02	6.1 ± 0.1
$t\bar{t}$	1.3 ± 0.03	1.1 ± 0.03	4.7 ± 0.07
jet fakes	331.7 ± 18.2	139.4 ± 11.4	33.5 ± 3.2
Sum BG	1195.9 ± 18.9	1001.5 ± 12.5	368.6 ± 4.4
DATA	1215	1000	374

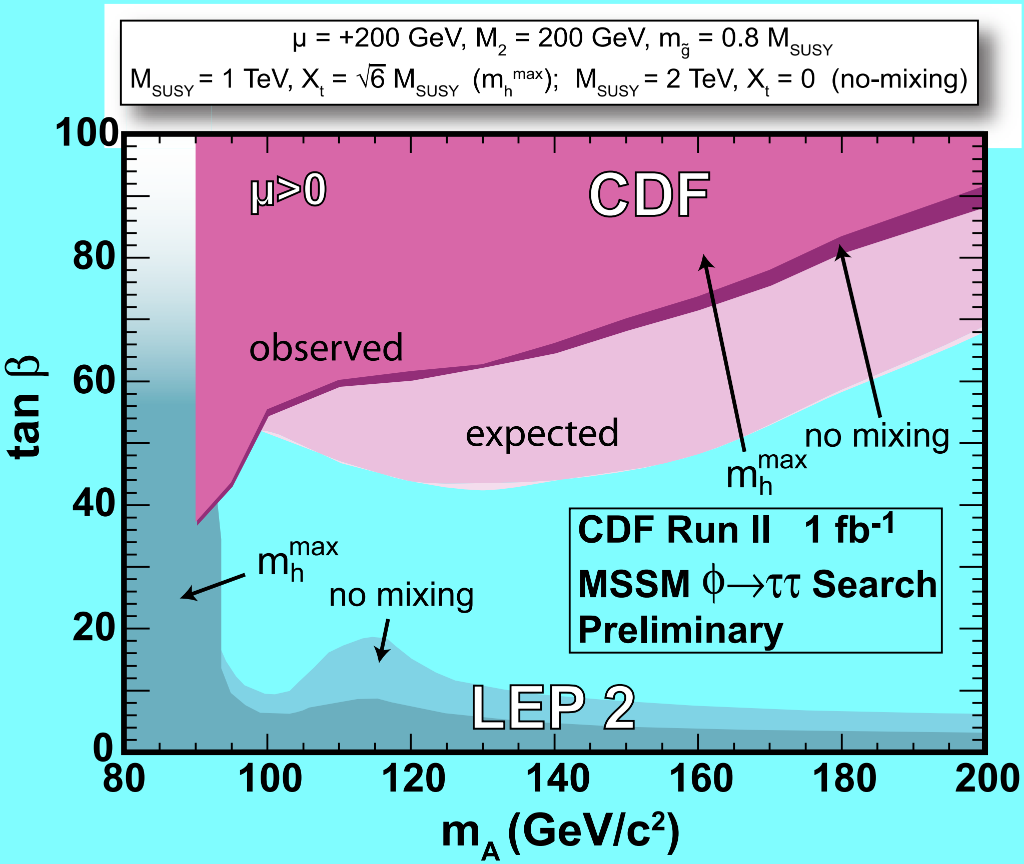


(a) $\tau_e\tau_{had}$ and $\tau_\mu\tau_{had}$ channels combined

(b) $\tau_e\tau_\mu$ channel

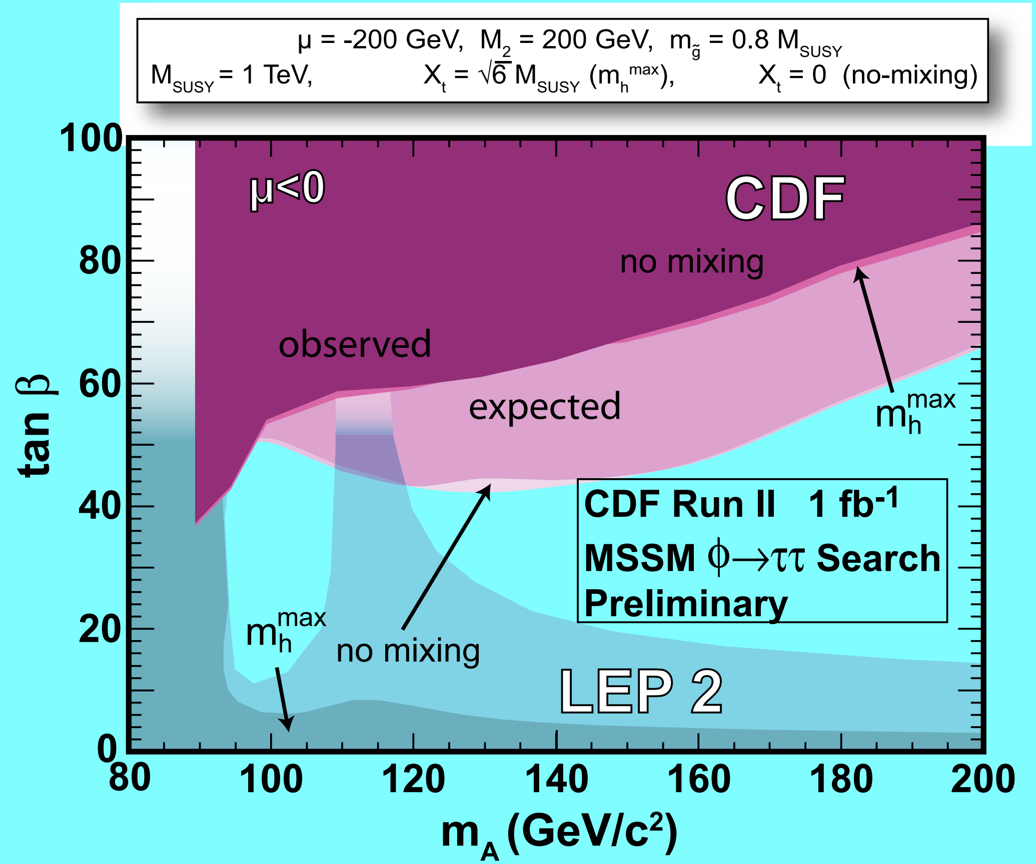


Observed limit is weaker than expected due to observed excess of events in the sample.



μ = +200 GeV, M2 = 200 GeV, mg̃ = 0.8 MSUSY
MSUSY = 1 TeV, Xt = √6 MSUSY (mhmax); MSUSY = 2 TeV, Xt = 0 (no-mixing)
μ>0
CDF
observed
expected
mhmax
no mixing
CDF Run II 1 fb-1
MSSM φ→ττ Search
Preliminary
LEP 2
tan β
mA (GeV/c²)

(a) $\mu > 0$



μ = -200 GeV, M2 = 200 GeV, mg̃ = 0.8 MSUSY
MSUSY = 1 TeV, Xt = √6 MSUSY (mhmax), Xt = 0 (no-mixing)
μ<0
CDF
no mixing
observed
expected
mhmax
CDF Run II 1 fb-1
MSSM φ→ττ Search
Preliminary
LEP 2
tan β
mA (GeV/c²)

(b) $\mu < 0$

Can this be accounted for in Supersymmetry

CMSSM?

NUHM?

CMSSM

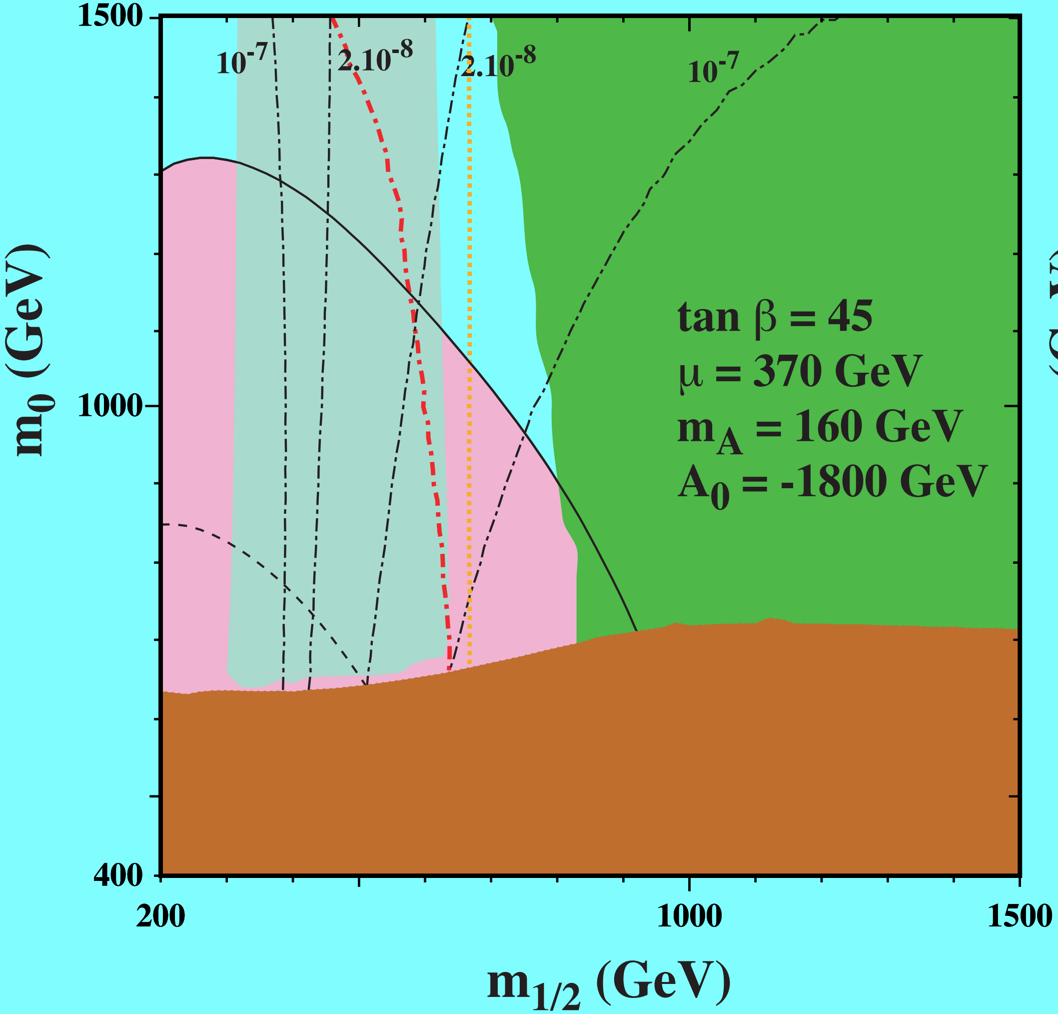
$M_A \sim 160$ GeV $\Rightarrow$ low $m_{1/2}$

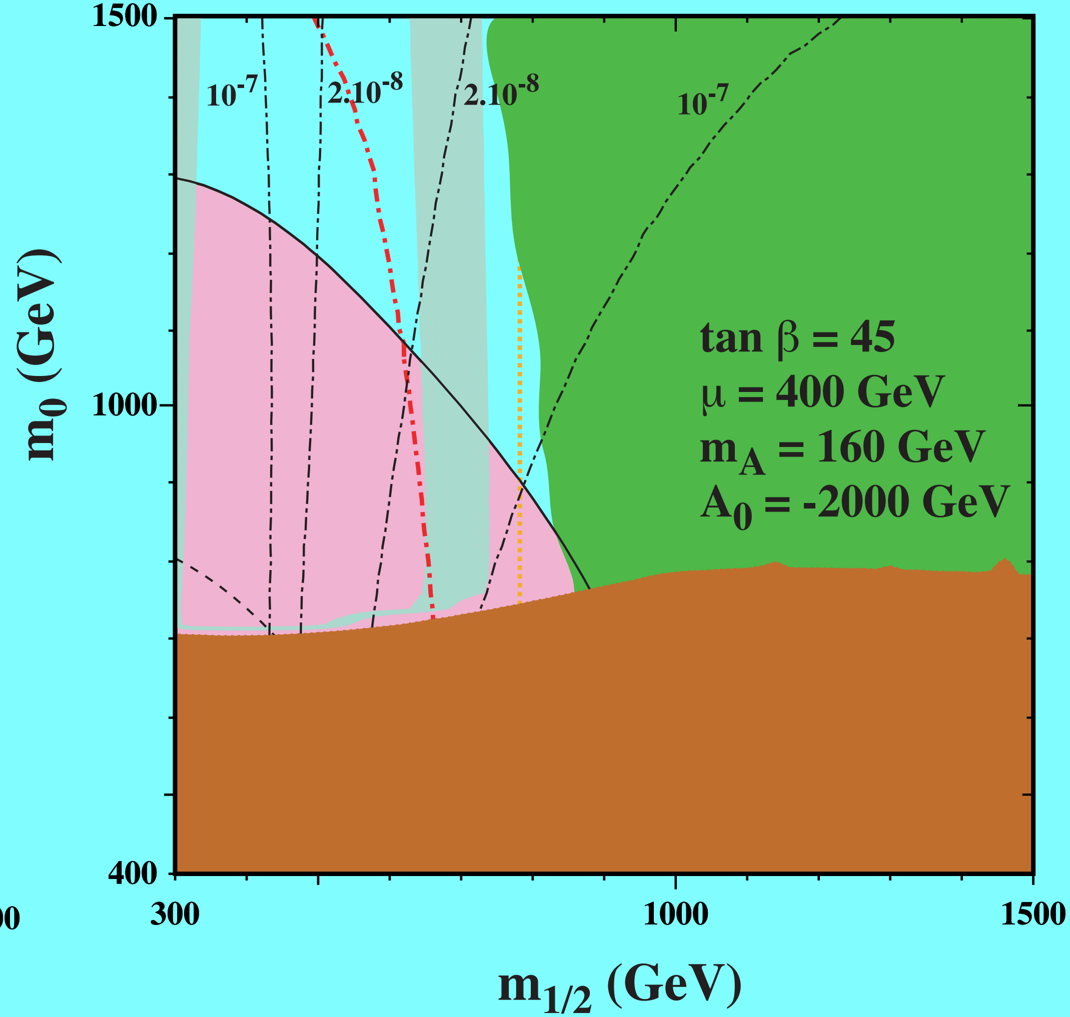
NUHM

- BR(b $\rightarrow$ s γ) - 2 main contributions - $H^{\pm}$ and $\chi^{\pm}$ exchange
- Light Higgs A $\Rightarrow$ Light $H^{\pm}$ $\Rightarrow$ Light $\chi^{\pm}$ $\Rightarrow$

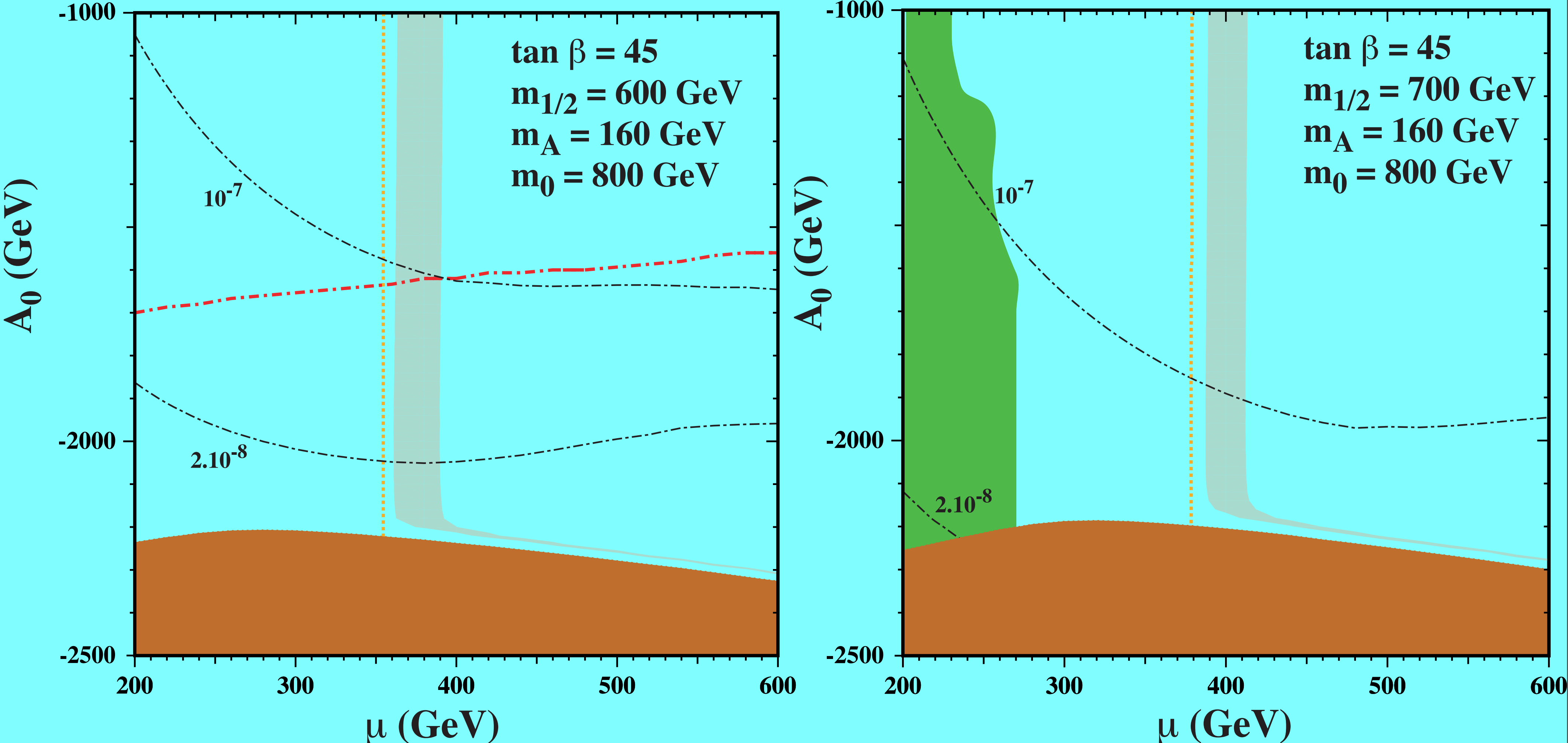
  Low $m_{1/2}$
- $\Rightarrow$ Light h, non-negligible g-2
- Relic density selects μ
- Large tan β + BR($B_s \rightarrow \mu^+ \mu^-$) selects A_0

NUHM Planes





EHOW



tan β = 45
m1/2 = 600 GeV
mA = 160 GeV
m0 = 800 GeV
10-7
2.10-8
-1000
-2000
-2500
A0 (GeV)
200
300
400
500
600
μ (GeV)
tan β = 45
m1/2 = 700 GeV
mA = 160 GeV
m0 = 800 GeV
10-7
2.10-8

EHOW

What's left?

($m_{1/2}$, m_0) in the range (500,1400), (700,700), (800,900)

$\mu \sim 400$ GeV

$A_0 \sim -1600 - -2400$ GeV

Hint of Higgs?

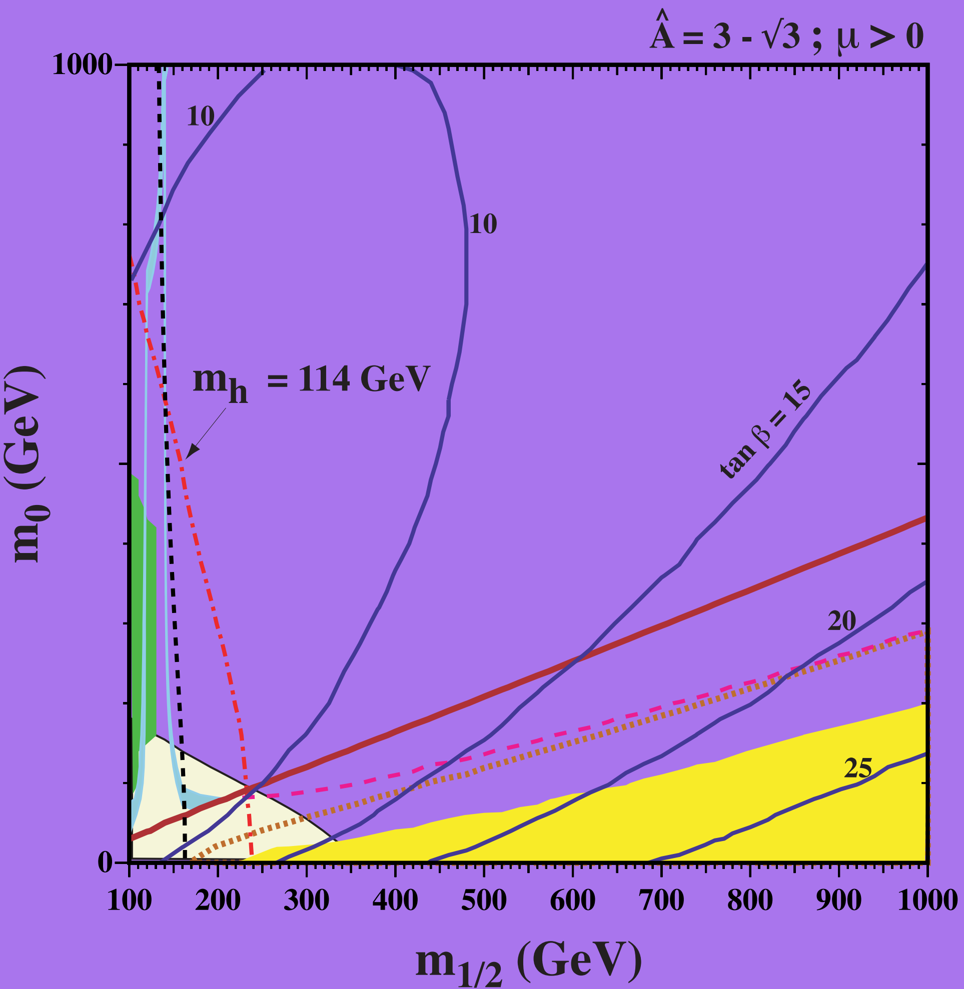
- Small M_A and large tan β possible but very constrained in the NUHM (not possible in the CMSSM)

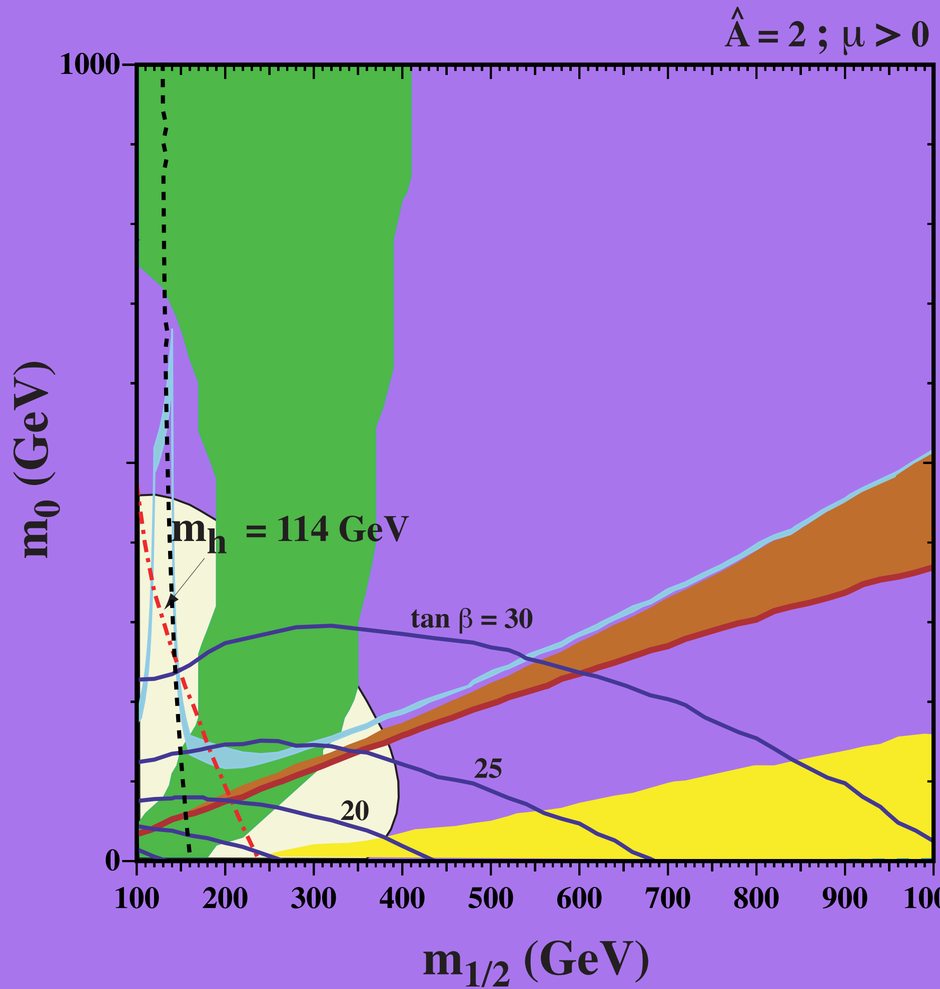
- BR($B_s \rightarrow \mu^+ \mu^-$) should be detected soon
- M_h close to LEP limit
- BR($b \rightarrow s \gamma$) should show deviations from SM
- g-2 discrepancy should be slightly less

- BR($B_u \rightarrow \tau \nu_\tau$) at 1/3 SM value
- Dark Matter should be detected by CDMS and XENON10

Summary

- mSugra models most difficult to access experimental esp. if GDM
- Good indication from indirect sensitivities for `low' energy signal for SUSY.
- Good prospect for Direct detection and $B \rightarrow \mu^{+} \mu^{-}$ particularly in non CMSSM models (unless GDM)





The Very CMSSM:

Ellis, Olive, Santoso, Spanos

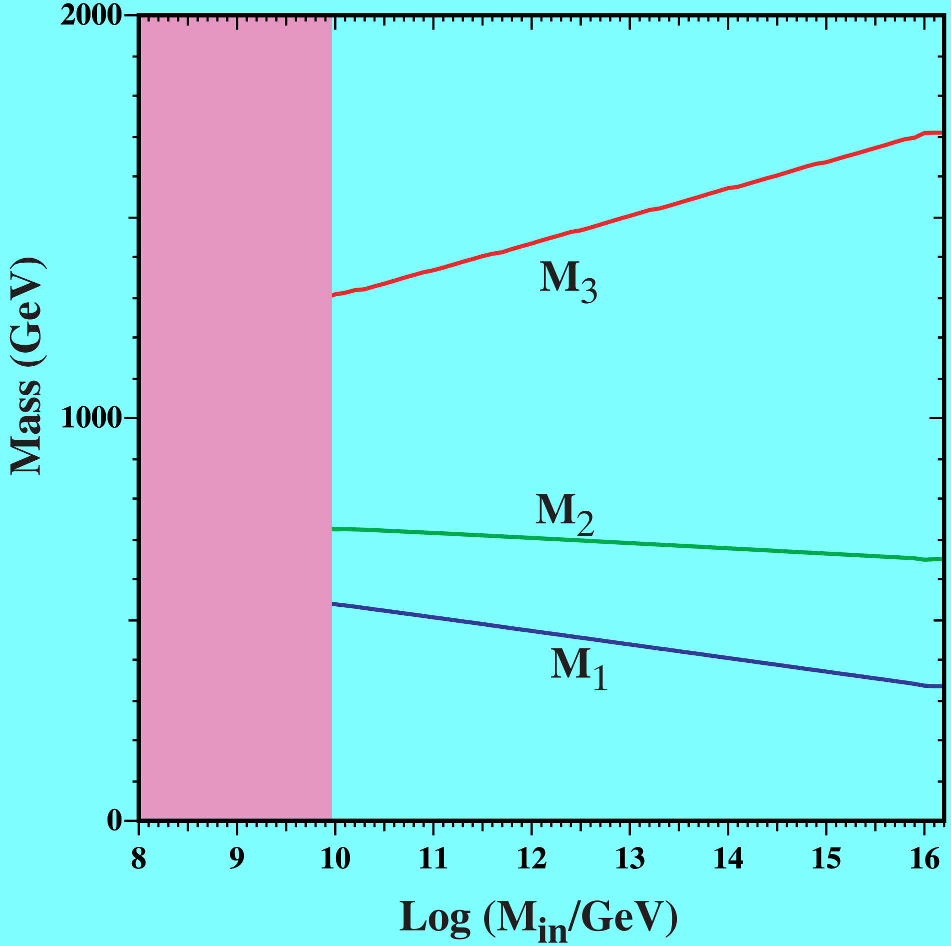
What do we expect?

Gaugino masses

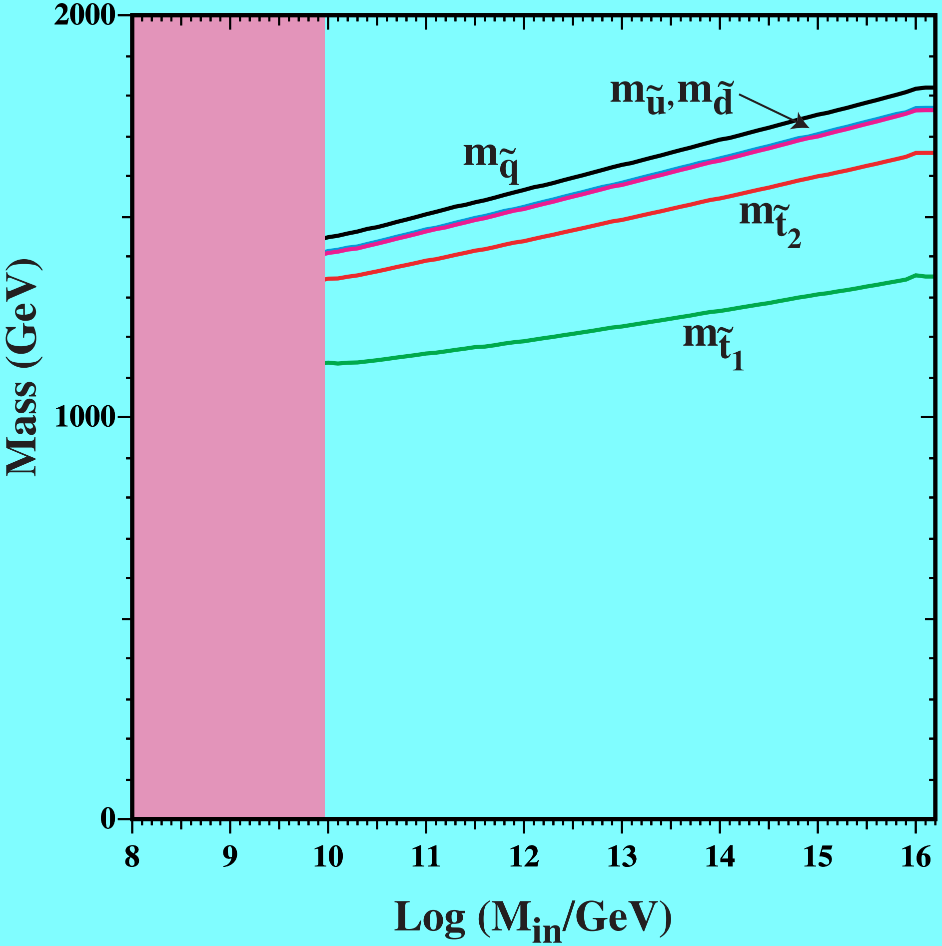
$$M_a(Q) = \frac{\alpha_a(Q)}{\alpha_a(M_{in})} m_{1/2}$$

Scalar masses

$$m^2_{0_i}(Q) = m^2_0(M_{in}) + C_i(Q, M_{in}) m^2_{1/2},$$



2000
1000
0
Mass (GeV)
M3
M2
M1
8 9 10 11 12 13 14 15 16
Log (Min/GeV)



2000
1000
0
Mass (GeV)
mũ,md̃
mq̃
mt̃2
mt̃1
8 9 10 11 12 13 14 15 16
Log (Min/GeV)

What do we expect?

Gaugino masses

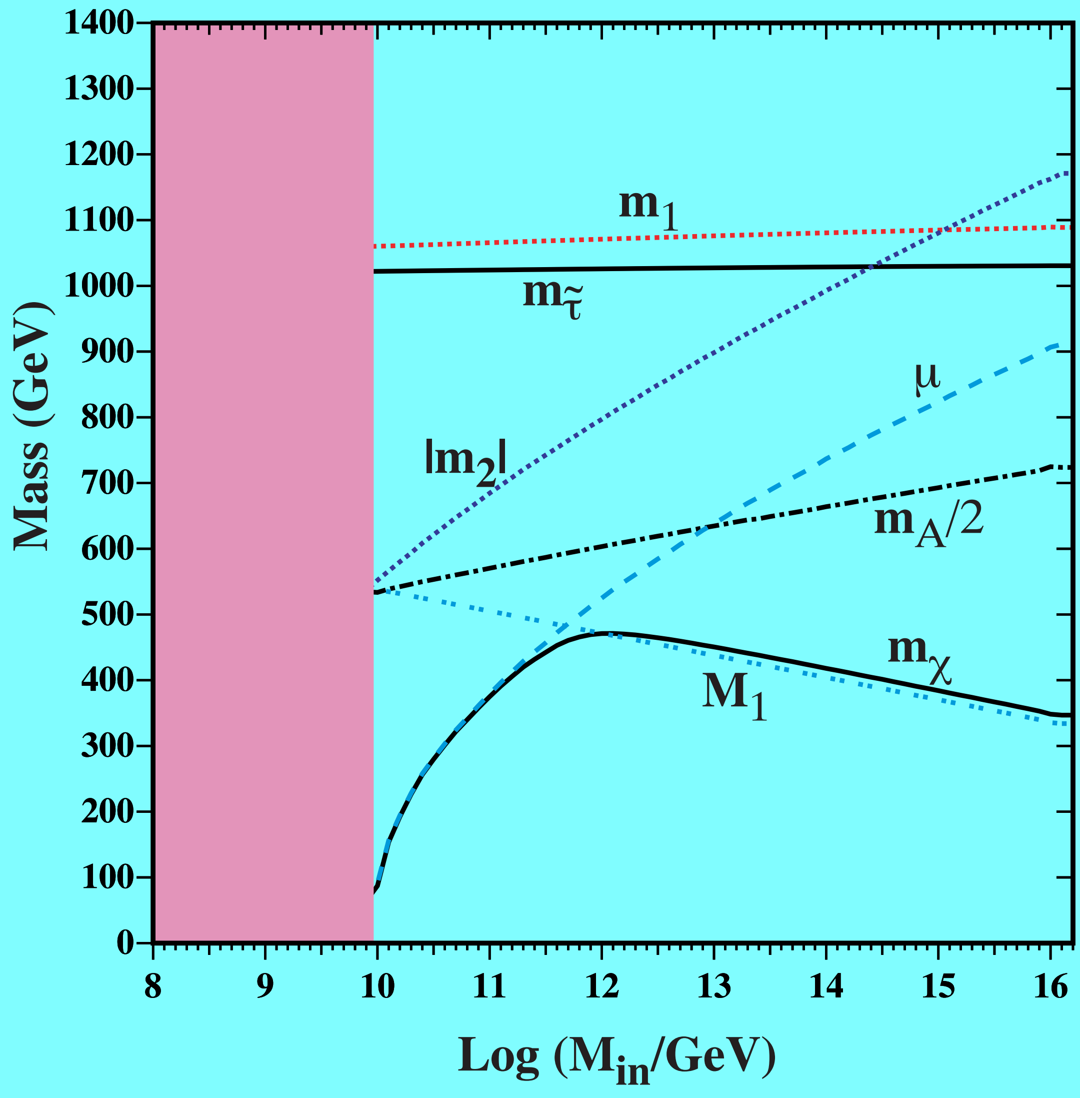
$$M_a(Q) = \frac{\alpha_a(Q)}{\alpha_a(M_{in})} m_{1/2}$$

Scalar masses

$$m_{0_i}^2(Q) = m_0^2(M_{in}) + C_i(Q, M_{in}) m_{1/2}^2,$$

The μ parameter

$$\mu^2 = \frac{m_1^2 - m_2^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{M_Z^2}{2},$$



$(m_{1/2}, m_0) = (700, 1000)$ GeV