Prospects for SUSY at LHC in light of Dark Matter

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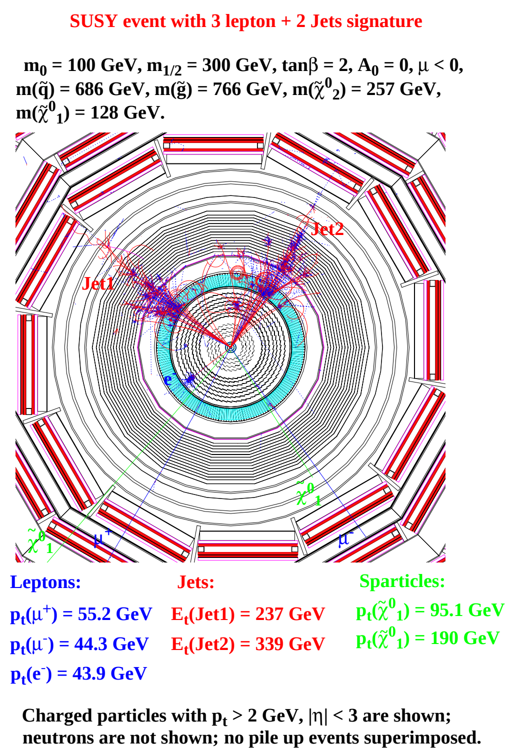
- ⋆ Supersymmetric models
- ⋆ WMAP allowed regions
- ⋆ SUSY at LHC in mSUGRA
- ⋆ Direct, indirect detection of neutralinos
- ⋆ Models with non-universal soft terms
  - – scalar mass non-universality
  - – gaugino mass non-universality
- ⋆ SUSY in the KKLT stringy model



The Standard Model of Particle Physics

Construction

- ⋆ gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y$
- ⋆ matter content: 3 generations quarks and leptons

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \; u_R,\; d_R; \quad \begin{pmatrix} \nu \\ e \end{pmatrix}_L ,\; e_R \tag{1}$$

- ⋆ Higgs sector ⇒ spontaneous electroweak symmetry breaking:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix} \tag{2}$$

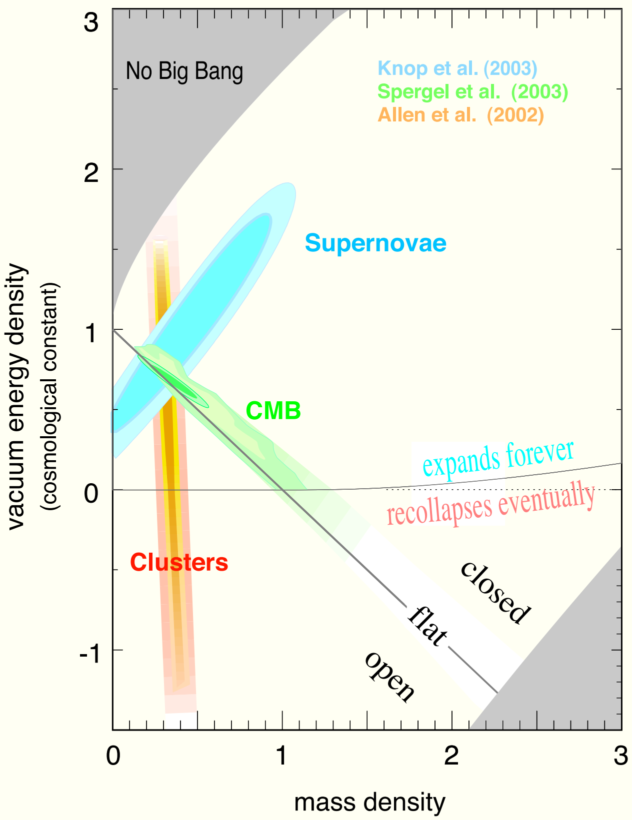
- ⋆ Yukawa interactions ⇒ massive quarks and leptons
- ⋆ 19 parameters
- ⋆ **good-to-excellent description of (almost)** *all* **accelerator data!**

Data *not* described by the SM

- neutrino masses and mixing
- baryogenesis $n_B/n_\gamma \sim 10^{-10}$
  - (matter anti-matter asymmetry)
- cold dark matter
- dark energy

★ Note: astro/cosmo origin of all discrepancies!

★ We will adopt the WMAP result
  - $\Omega_{CDM}h^2 = 0.113 \pm 0.009$
  - as a guide to prospects for SUSY discovery



Supersymmetric models

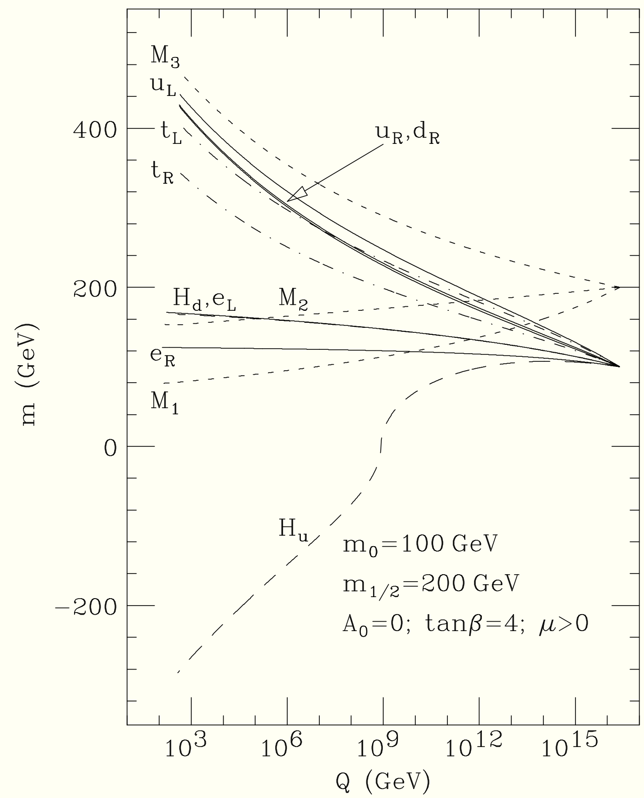
- ⋆ We will assume the MSSM is the correct effective theory at $Q < M_{GUT}$
- ⋆ We will focus on models with gravity-mediated SUSY breaking since these most naturally give rise to thermal relics which can describe the CDM needed in the universe
- ⋆ Soft SUSY breaking boundary conditions usually stipulated at $Q = M_{GUT}$
- ⋆ lots of possibilities depending on SUSY breaking/ GUTs/ compactification $\cdots$ (all unknown physics)
- ⋆ minimal choice: single scalar mass m_0, gaugino mass $m_{1/2}$, trilinear term A_0, bilinear term B
- ⋆ evolve couplings/soft terms to M_{weak} via RG evolution
- ⋆ EWSB radiatively due to large m_t
- ⋆ parameter space: $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$

⋆ this is simplest choice and a baseline model, but **many** other possibilities depending on high scale physics

- non-universal scalar masses
- non-universal gaugino masses
- FC soft SUSY breaking terms
- large CP violating phases
- additional fields beyond MSSM below M_{GUT}?
- $\cdots$

Sparticle mass spectra

- ⋆ Mass spectra codes
- ⋆ RGE running: $M_{GUT} \rightarrow M_{weak}$
  - Isajet (HB, Paige, Protopopescu, Tata)
    - $*$ $\geq$7.72: Isatools
  - SuSpect (Djouadi, Kneur, Moultaka)
  - SoftSUSY (Allanach)
  - Spheno (Porod)
- ⋆ Comparison (Belanger, Kraml, Pukhov)
- ⋆ Website: `http://kraml.home.cern.ch/kraml/comparison/`



Constraints on SUSY models

- ⋆ LEP2:
  - $m_h > 114.4$ GeV for SM-like h
  - $m_{\widetilde{W}_1} > 103.5$ GeV
  - $m_{\tilde{e}_{L,R}} > 99$ GeV for $m_{\tilde{\ell}} - m_{\widetilde{Z}_1} > 10$ GeV
- ⋆ $BF(b \to s\gamma) = (3.25 \pm 0.54) \times 10^{-4}$ (BELLE, CLEO, ALEPH)
  - SM theory: $BF(b \to s\gamma) \simeq 3.3 - 3.7 \times 10^{-4}$
- ⋆ $a_\mu = (g-2)_\mu/2$ (Muon $g-2$ collaboration)
  - $\Delta a_\mu = (27.1 \pm 9.4) \times 10^{-10}$ (Davier et al. e^+e^-)
  - $\Delta a_\mu^{SUSY} \propto \frac{m_\mu^2 \mu M_i \tan\beta}{M_{SUSY}^4}$
- ⋆ $BF(B_s \to \mu^+\mu^-) < 1.5 \times 10^{-7}$ (CDF-new!)
  - constrains at very large $\tan\beta \gtrsim 50$
- ⋆ $\Omega_{CDM} h^2 = 0.113 \pm 0.009$ (WMAP)

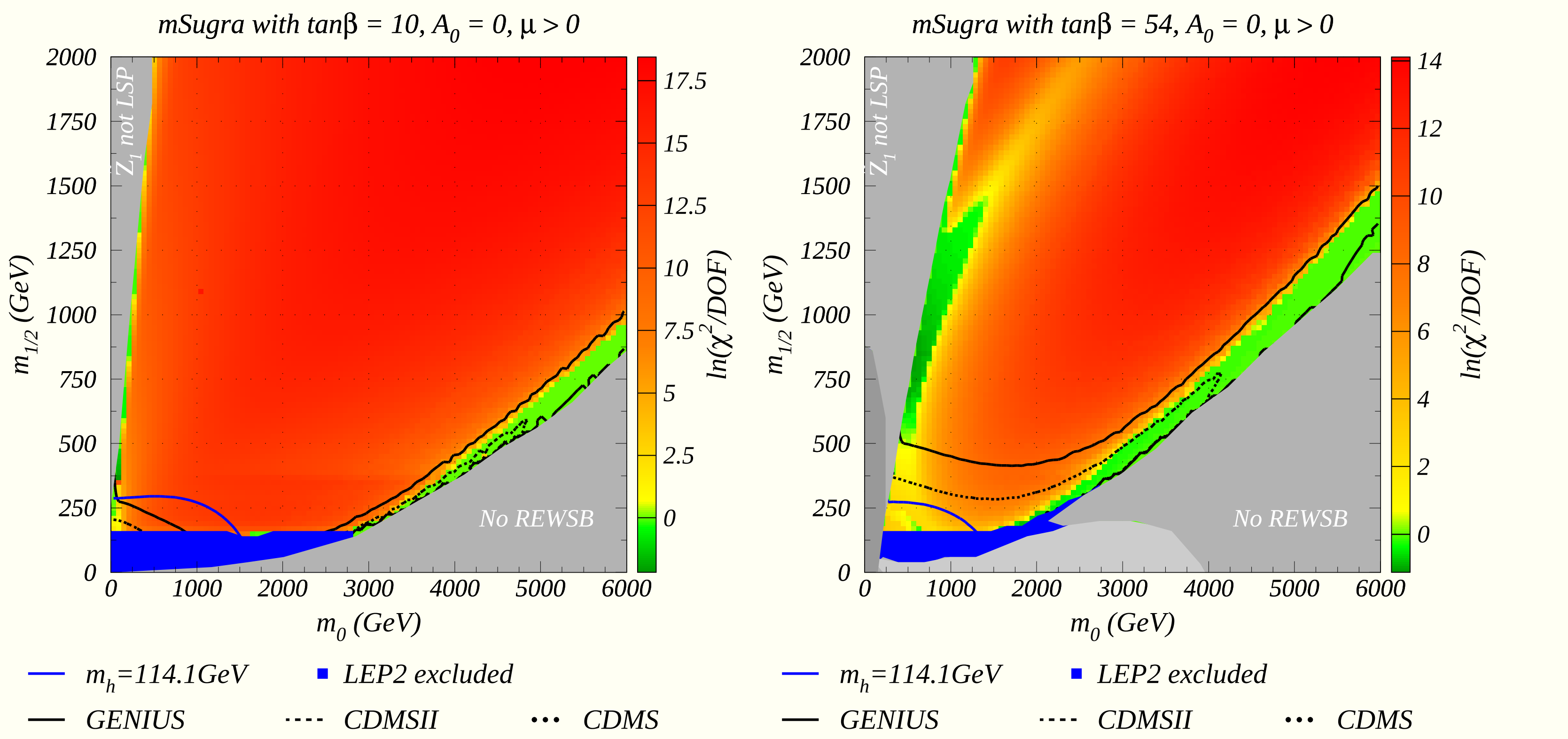
Neutralino dark matter

- ⋆ Why R-parity? natural in $SO(10)$ SUSYGUTS if properly broken, or broken via compactification (Mohapatra, Martin, Kawamura, $\cdots$)
- ⋆ In thermal equilibrium in early universe
- ⋆ As universe expands and cools, freeze out
- ⋆ Number density obtained from Boltzmann eq'n
  - $dn/dt = -3Hn - \langle \sigma v_{rel} \rangle (n^2 - n_0^2)$
  - depends critically on thermally averaged annihilation cross section times velocity
- ⋆ many thousands of annihilation/co-annihilation diagrams
- ⋆ equally many computer codes
  - DarkSUSY, Micromegas, IsaReD, $\cdots$

Main mSUGRA regions consistent with WMAP

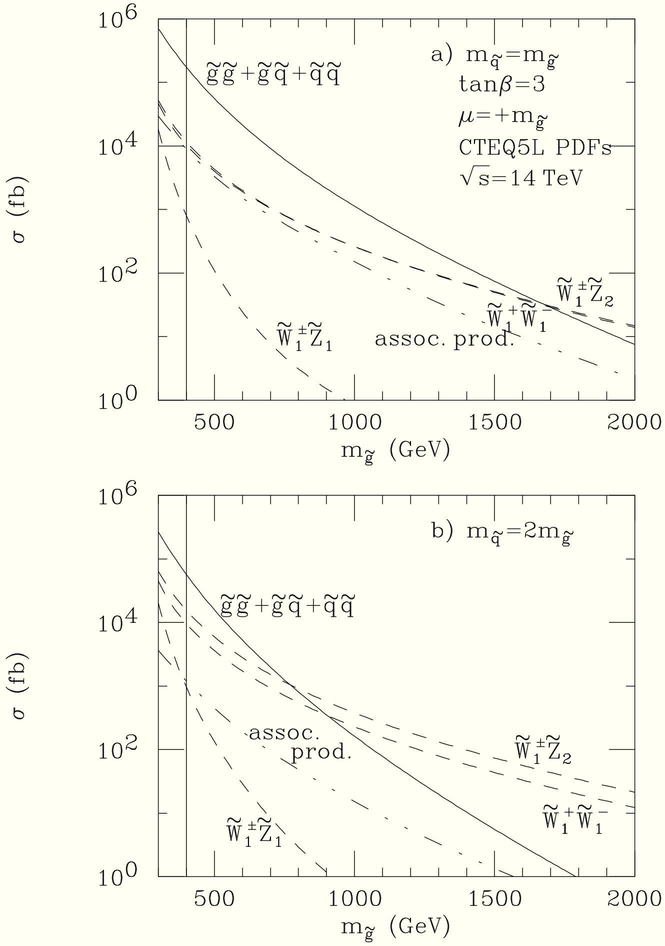
- ⋆ bulk region (low m_0, low $m_{1/2}$)
- ⋆ stau co-annihilation region ($m_{\tilde{\tau}_1} \simeq m_{\widetilde{Z}_1}$)
- ⋆ HB/FP region (large m_0 where $|\mu| \to small$)
- ⋆ A-funnel ($2m_{\widetilde{Z}_1} \simeq m_A,\ m_H$)
- ⋆ h corridor ($2m_{\widetilde{Z}_1} \simeq m_h$)
- ⋆ stop co-annihilation region (particular A_0 values $m_{\tilde{t}_1} \simeq m_{\widetilde{Z}_1}$)

Results of χ^2 fit using τ data for a_μ:

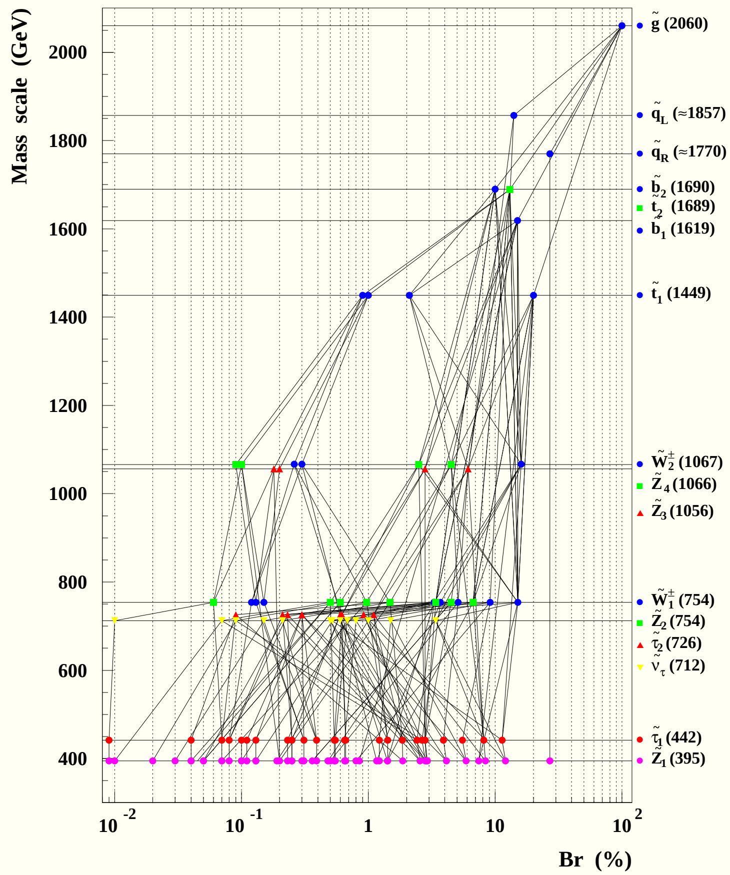


HB, C. Balazs: JCAP 0305, 006 (2003)

Production of sparticles at LHC

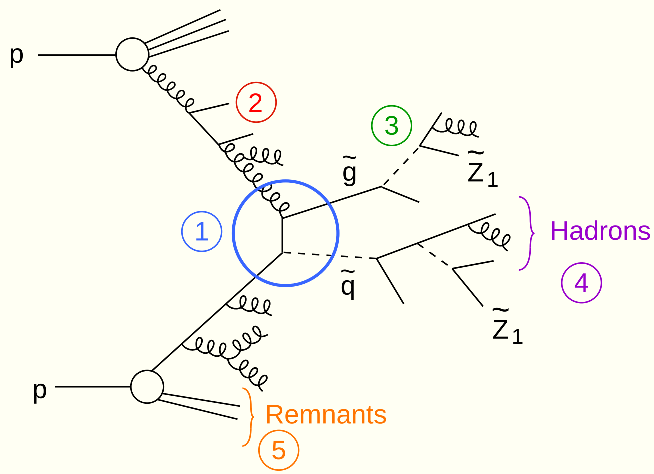


Sparticle cascade decays



$\tilde{Z}_1$ qq	(27.0 %)	$\tilde{Z}_1$ τνWWWbb	(4.1 %)
$\tilde{Z}_1$ τνWbb	(12.1 %)	$\tilde{Z}_1$ ττbb	(2.9 %)
$\tilde{Z}_1$ ττWWbb	(8.4 %)	$\tilde{Z}_1$ ττqq	(2.9 %)
$\tilde{Z}_1$ WWbb	(7.4 %)	$\tilde{Z}_1$ τνZWbb	(2.8 %)
$\tilde{Z}_1$ τνqq	(5.9 %)	$\tilde{Z}_1$ τνhWbb	(2.6 %)

Event generation for sparticles



Event generation in LL - QCD

1) Hard scattering / convolution with PDFs

2) Intial / final state showers

3) Cascade decays

4) Hadronization

5) Beam remnants

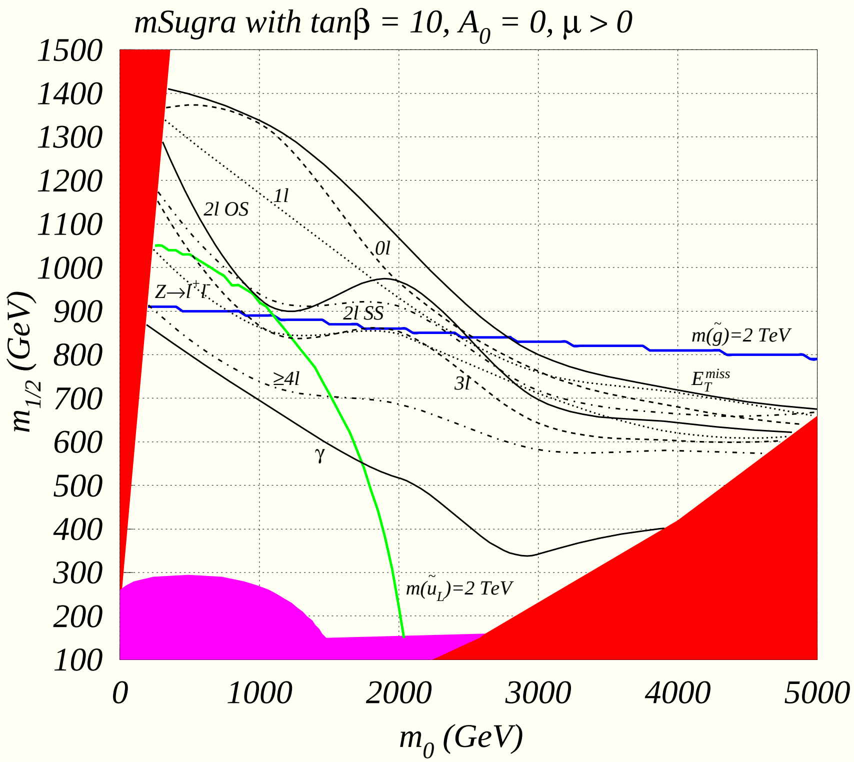
Search for SUSY at CERN LHC

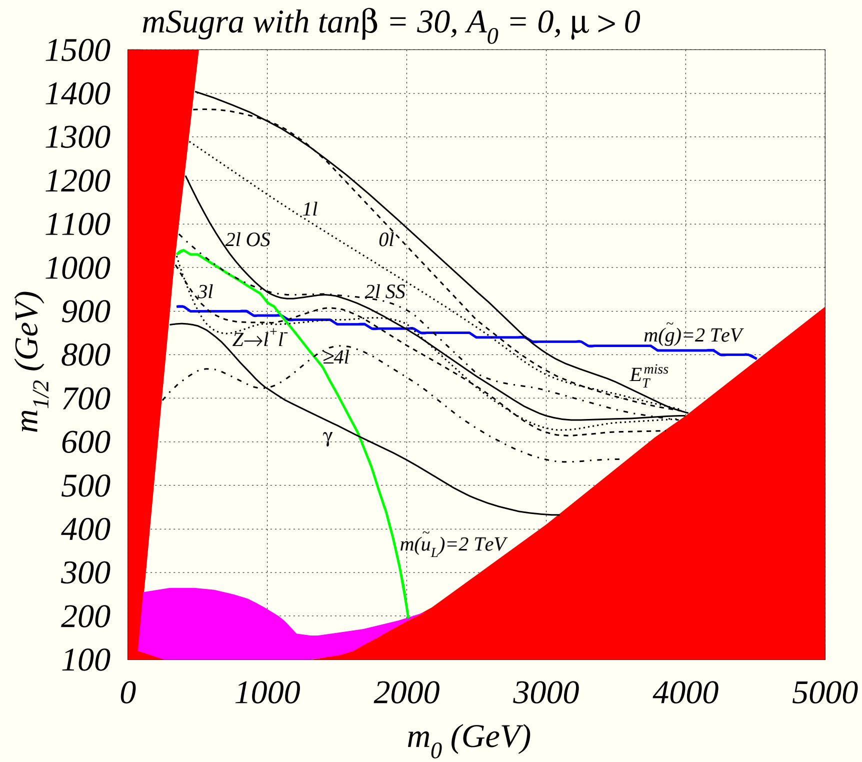
- ⋆ $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV
- ⋆ lengthy cascade decays are likely
  - $\not{E}_T +$ jets
  - $1\ell + \not{E}_T +$ jets
  - $OS\ 2\ell + \not{E}_T +$ jets
  - $SS2\ell + \not{E}_T +$ jets
  - $3\ell + \not{E}_T +$ jets
  - $4\ell + \not{E}_T +$ jets
- ⋆ BG: $W + jets$, $Z + jets$, $t\bar{t}$, $b\bar{b}$, WW, $4t$, $\cdots$
- ⋆ Grid of cuts gives optimized S/B

Pre-cuts and cuts

- ⋆ $\not{E}_T > 200$ GeV
- ⋆ $N_j \geq 2$ (where $p_T(jet) > 40$ GeV and $|\eta(jet)| < 3$
- ⋆ Grid of cuts for optimized S/B:
  - $N_j \geq 2 - 10$
  - $\not{E}_T > 200 - 1400$ GeV
  - $E_T(j1) > 40 - 1000$ GeV
  - $E_T(j2) > 40 - 500$ GeV
  - $S_T > 0 - 0.2$
  - muon isolation
- ⋆ $S > 10$ events for 100 fb^{-1}
- ⋆ $S > 5\sqrt{B}$ for optimal set of cuts

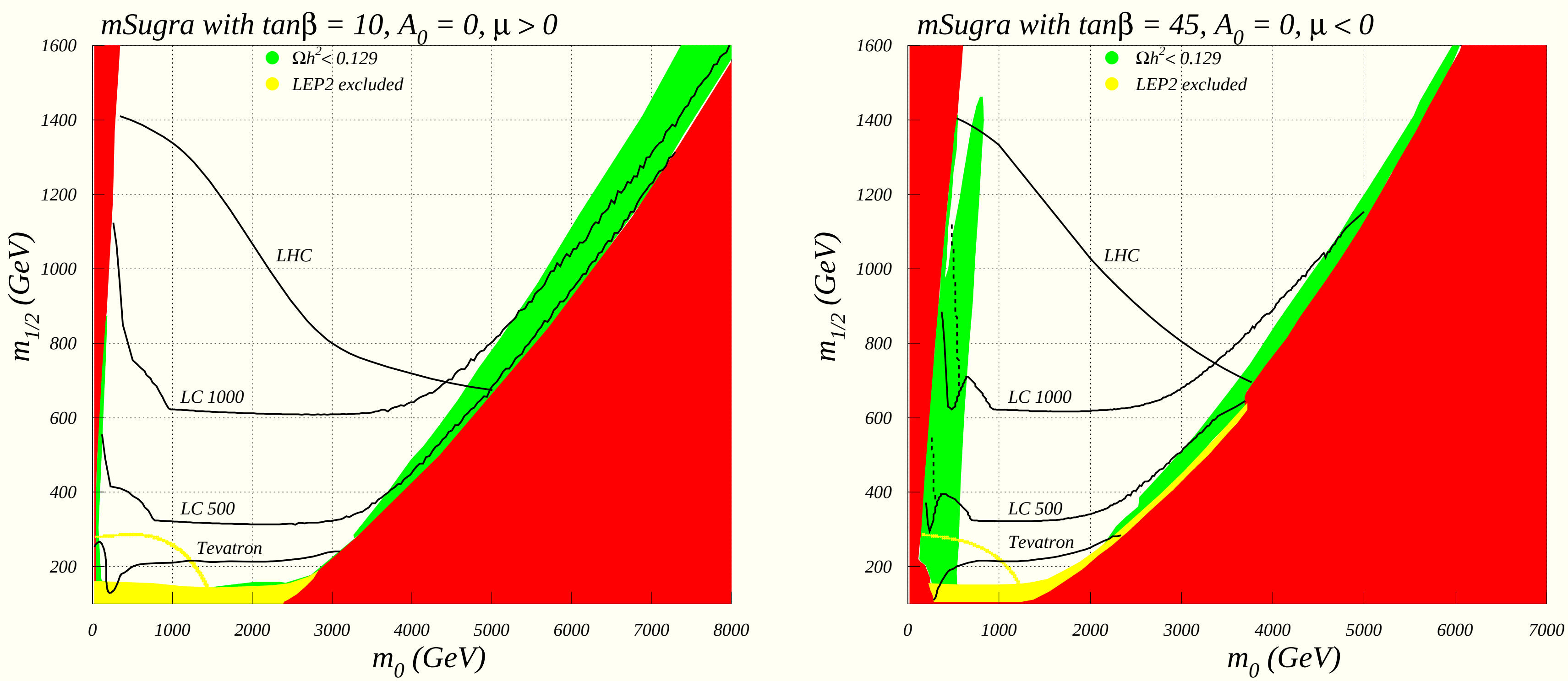
Sparticle reach of LHC for 100^{-1} fb





HB, Balazs, Belyaev, Krupovnickas, Tata: JHEP 0306, 054 (2003)

Sparticle reach of all colliders and relic density



HB, Belyaev, Krupovnickas, Tata: JHEP 0402, 007 (2004)

Precision measurements at LHC

- $M_{eff} = \not{E}_T + E_T(j1) + \cdots + E_T(j4)$ sets overall $m_{\tilde{g}},\ m_{\tilde{q}}$ scale
- $m(\ell\bar{\ell}) < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ mass edge
- $m(\ell\bar{\ell})$ distribution shape
- combine $m(\ell\bar{\ell})$ with jets to gain $m(\ell\bar{\ell}j)$ mass edge: info on $m_{\tilde{q}}$
- further mass edges possible *e.g.* $m(\ell\bar{\ell}jj)$
- Higgs mass bump $h \to b\bar{b}$ likely visible in $\not{E}_T + jets$ events
- in favorable cases, may overconstrain system for a given model

⋆ methodology very p-space dependent

⋆ some regions are very difficult *e.g.* HB/FP

Focus on the Focus Point region

⋆ Can reach be extended in HB/FP region? Three approaches

- Mercadante, Mizukoshi, Tata, PRD72 (2005) 035009
  - use also b-jet tag; increase of reach by 15%
- HB, Krupovnickas, Profumo, Ullio: JHEP 0510, 020 (2005)
  - search for $pp \to \widetilde{W}_1 \widetilde{Z}_2 \to 3\ell + \not{E}_T$: similar reach as BBBKT mSUGRA
- Belyaev et al (forthcoming)
  - ≥ 9 jets+ leptons $+ \not{E}_T$: much greater reach claimed

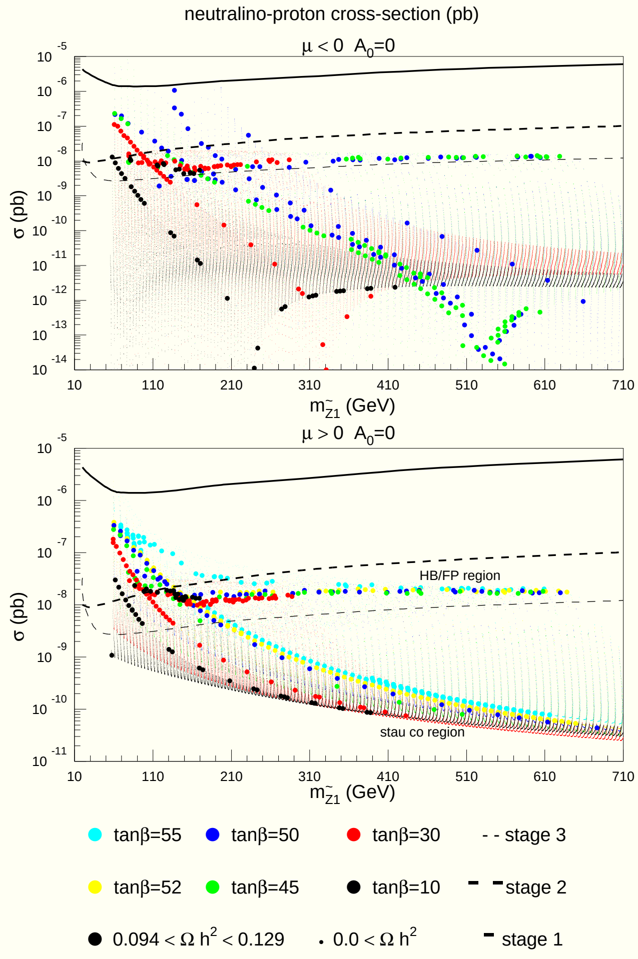
Direct and indirect detection of SUSY DM

- ⋆ Direct search via neutralino-nucleon scattering
- ⋆ Indirect search for SUSY DM: (HB, J. O'Farrill)
  - $\tilde{Z}_1\tilde{Z}_1 \to b\bar{b}, etc.$ in core of sun (or earth): $\Rightarrow \nu_\mu \to \mu$ in ν telescopes
    - Amanda, Icecube, Antares
  - $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \gamma$ in galactic core or halo
  - $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to e^+$ in galactic halo
  - $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \bar{p}$ in galactic halo
  - $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \bar{D}$ in galactic halo
    - $\bar{D}$ recently detected (BESS)
    - future: Gaseous Antiparticle Spectrometer (GAPS)-
      - slow $\bar{D}$; look for x-rays after capture on atoms
      - HB and Profumo, JCAP 0512, 008 (2005)

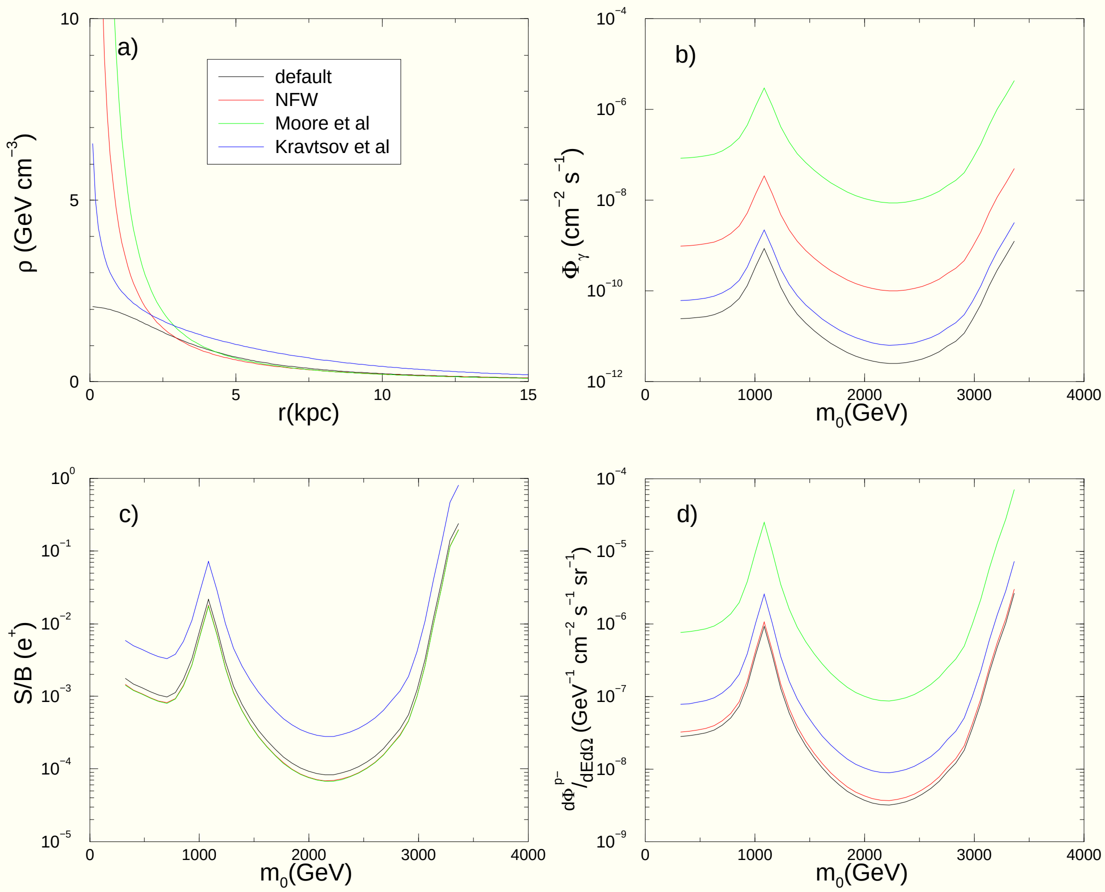
Direct detection of SUSY DM

scan over mSUGRA space :

- ⋆ Stage 1:
  - • CDMS1, Edelweiss, Zeplin1
- ⋆ Stage 2:
  - – CDMS2, CRESST2, Zeplin2, Edelweiss2
- ⋆ Stage 3:
  - – SuperCDMS, Zeplin4, Xenon, WARP

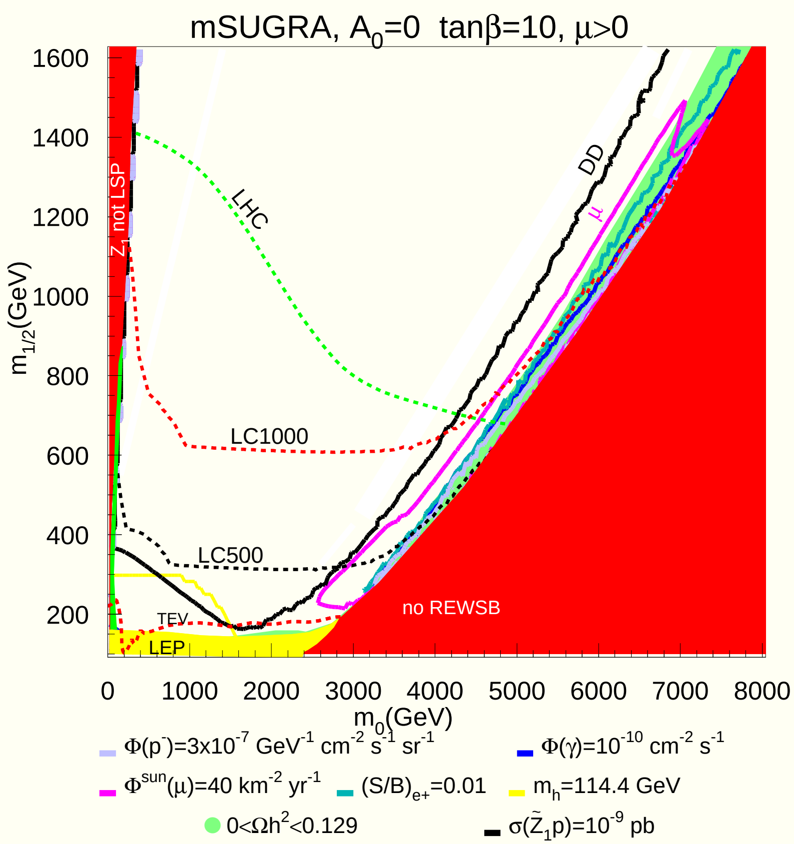


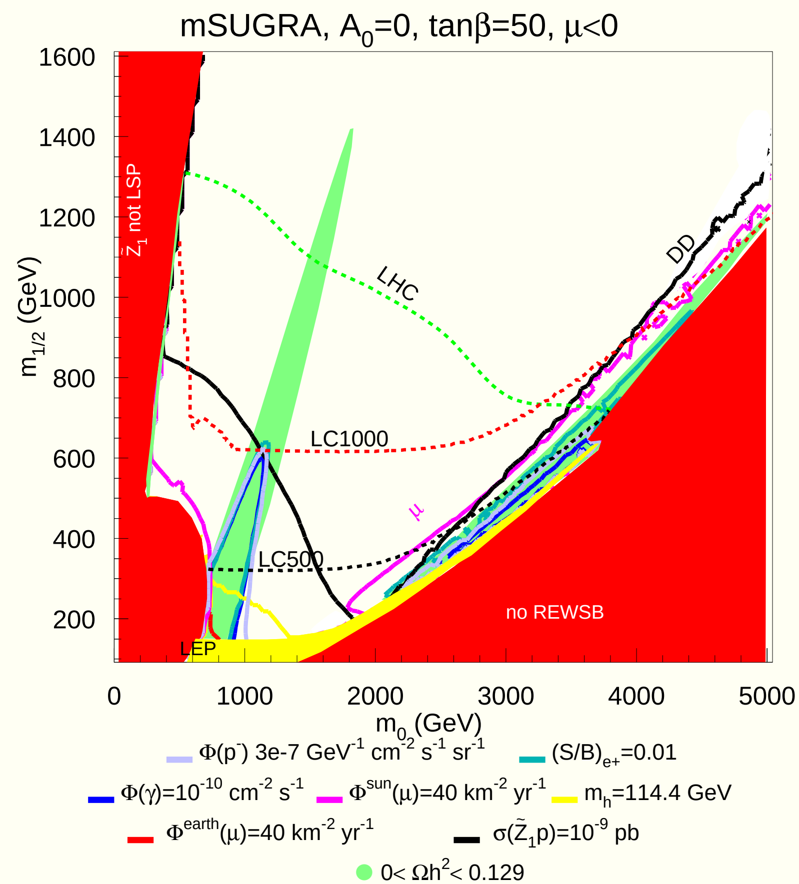
Rates for γs, e^+s, $\bar{p}$s vs. m_0 for fixed $m_{1/2} = 550$ GeV, $\tan\beta = 50$



- HB, Belyaev, Krupovnickas and O' Farrill
- rates enhanced in A-funnel and HB/FP region (MHDM)

Direct and indirect detection of neutralino DM

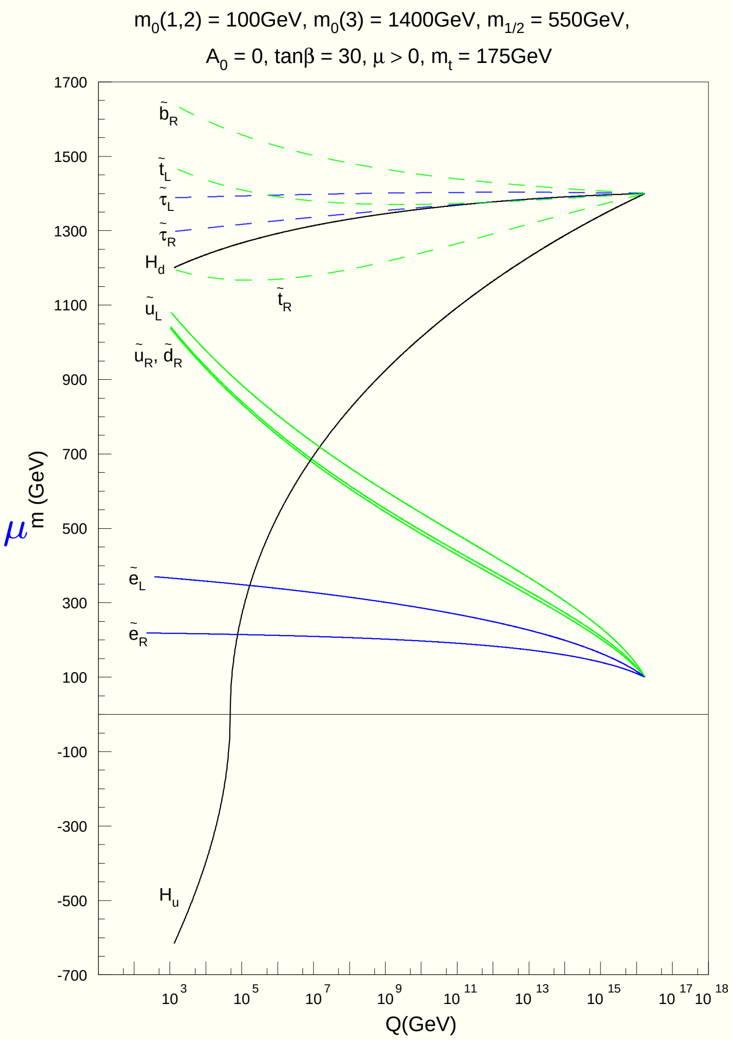




HB, Belyaev, Krupovnickas, O'Farrill: JCAP 0408, 005 (2004)

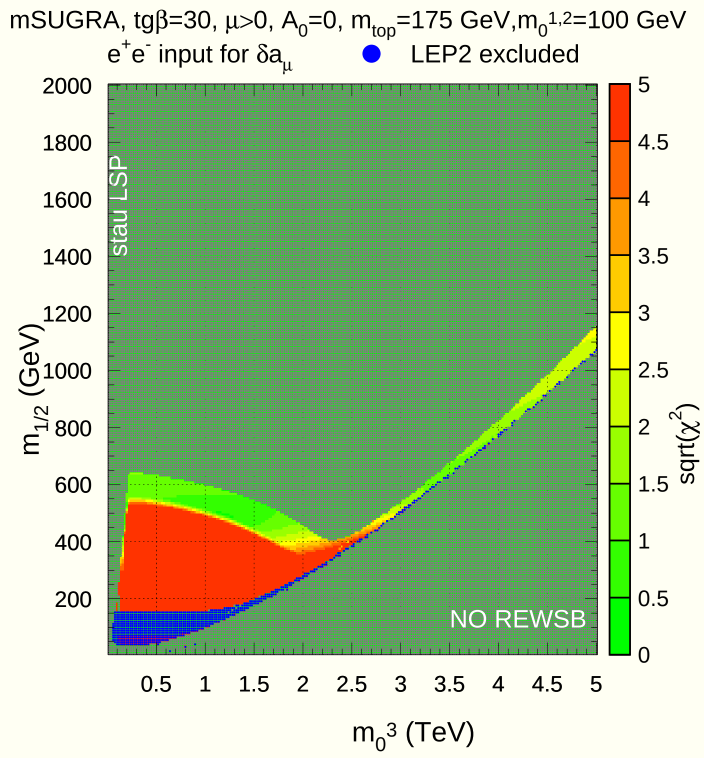
SUGRA models with non-universal scalars

- Normal scalar mass hierarchy (NMH):
- $BF(b \to s\gamma)$ prefers heavy 3rd gen. squarks
- $(g-2)_\mu$ prefers light 2nd gen. sleptons
- $m_0(1) \simeq m_0(2) \ll m_0(3)$
  - (preserve FCNC bounds)
- motivation: reconcile $BF(b \to s\gamma)$ with $(g-2)_\mu$
  - HB, Belyaev, Krupovnickas, Mustafayev
  - JHEP 0406, 044 (2004)



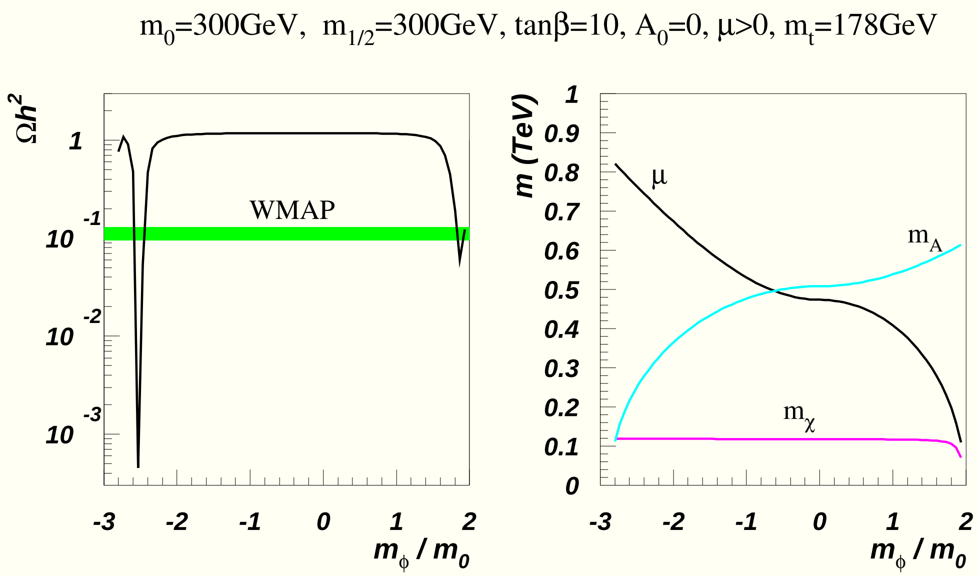
Normal scalar mass hierarchy: parameter space

- $m_0(1) \simeq m_0(2) \ll m_0(3)$
- LHC: light sleptons, enhanced leptonic cascade decays
- ILC: first two gen. sleptons likely accessible; squarks/staus heavy



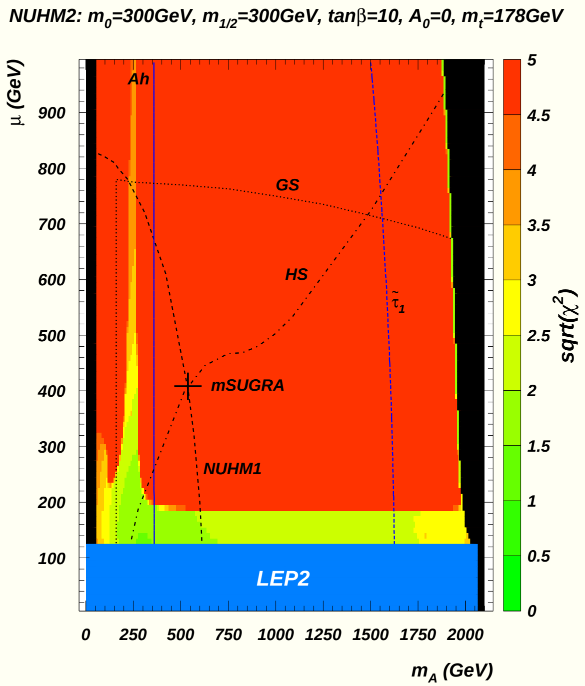
SUGRA models with non-universal Higgs mass (NUHM1)

- $m_{H_u}^2 = m_{H_d}^2 \equiv m_\phi^2 \neq m_0$: Drees; HB, Belyaev, Mustafayev, Profumo, Tata
- motivation: $SO(10)$ SUSYGUTs where $\hat{H}_{u,d} \in \phi(10)$ while matter $\in \psi(16)$
- $m_\phi^2 \gg m_0 \Rightarrow$higgsino DM for any $m_0,\ m_{1/2}$
- $m_\phi^2 < 0 \Rightarrow$ can have A-funnel for any $\tan\beta$



NUHM2 (2-parameter case)

- $m^2_{H_u} \neq m^2_{H_d} \neq m_0$: HB, Belyaev, Mustafayev, Profumo, Tata
- motivation: $SU(5)$ SUSYGUTs where $\hat{H}_u \in \phi(5)$, $\hat{H}_d \in \phi(\bar{5})$
- can re-parametrize $m^2_{H_u},\ m^2_{H_d} \leftrightarrow \mu,\ m_A$ (Ellis, Olive, Santoso)
- large S term in RGEs $\Rightarrow$ light $\tilde{u}_R,\ \tilde{c}_R$ squarks, $m_{\tilde{e}_L} < m_{\tilde{e}_R}$



Non-universal gaugino masses

★ SUGRA models where GKF transforms non-trivially (Snowmass '96)

★ Heterotic superstring models with orbifold compactification: SUSY breaking dominated by the moduli field

★ KKLT model of type IIB string compactification with fluxes

★ Extra-dimensional SUSY GUT models where SUSY breaking is communicated from the SUSY breaking brane to the visible brane via gaugino mediation (e.g. Dermisek-Mafi model)

★ ...

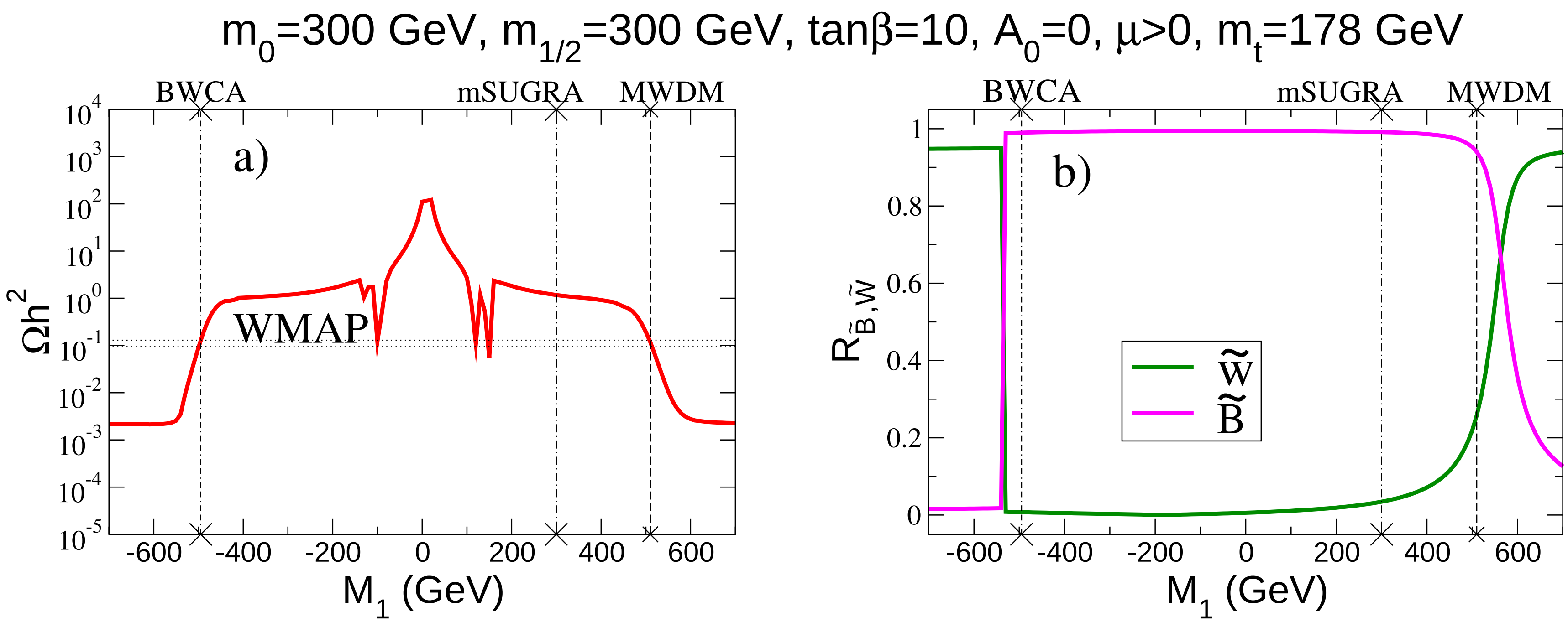
★ Here we adopt a phenomenological approach of independent M_1, M_2, M_3 but require consistency with WMAP

- MWDM: HB, Mustafayev, Park, Profumo, JHEP**0507**, 046 (2005)
- BWCA DM: HB, Krupovnickas, Mustafayev, Park, Profumo, Tata, JHEP**0512** (2005) 011.

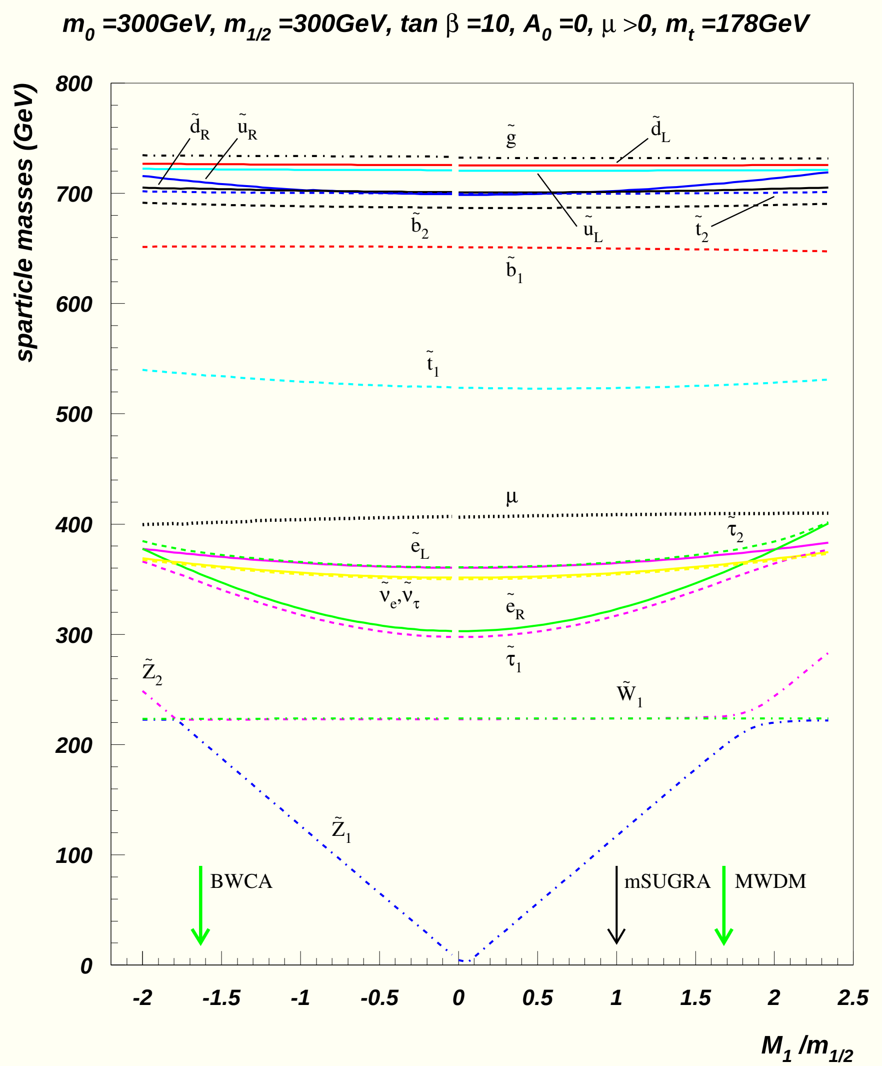
– LM3DM: HB, Mustafayev, Park, Profumo, Tata, JHEP**0604** (2006) 041.

⋆ Related work: Corsetti and Nath; Birkedal-Hansen and Nelson; Bertin, Nezri and Orloff; Bottino, Donato, Fornengo, Scopel; Belanger, Boudjema, Cottrant, Pukhov, Semenov; Mambrini, Munoz and Cerdeno; Auto, HB, Belyaev, Krupovnickas; Masiero, Profumo, Ullio

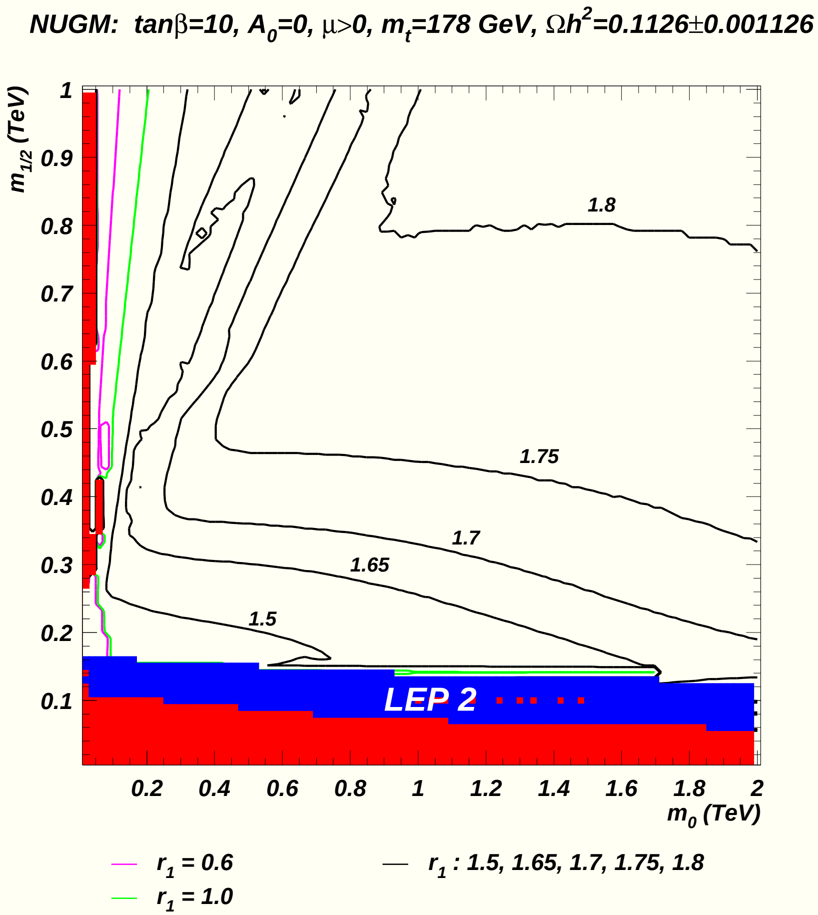
$\Omega_{\widetilde{Z}_1} h^2$ vs. M_1



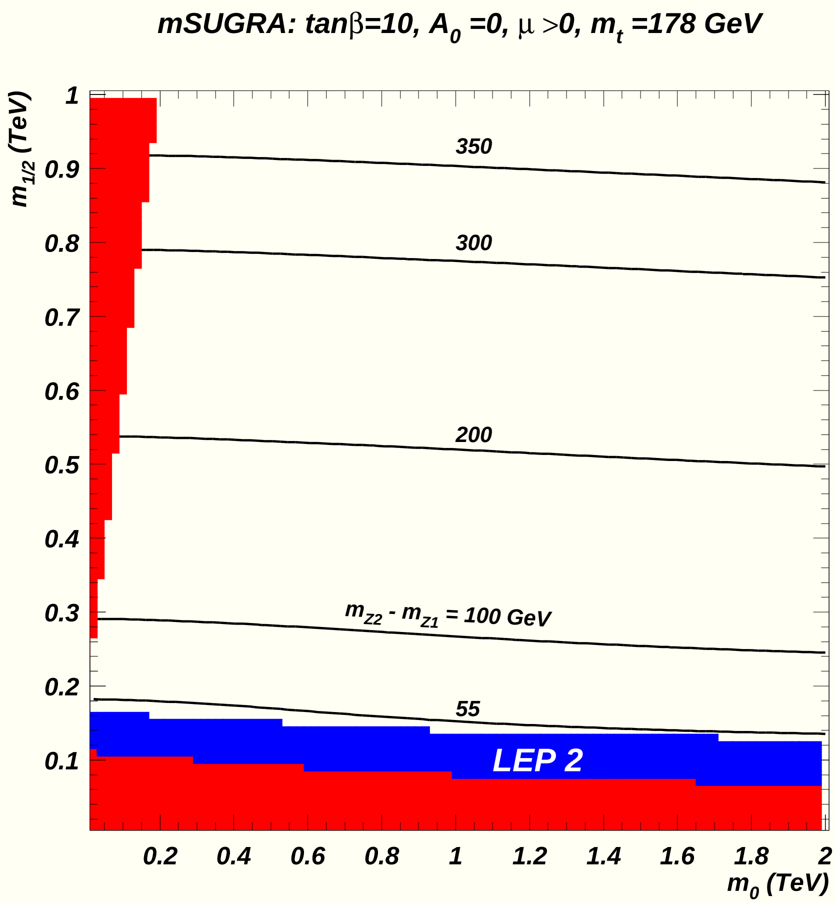
Sparticle mass spectra vs M_1

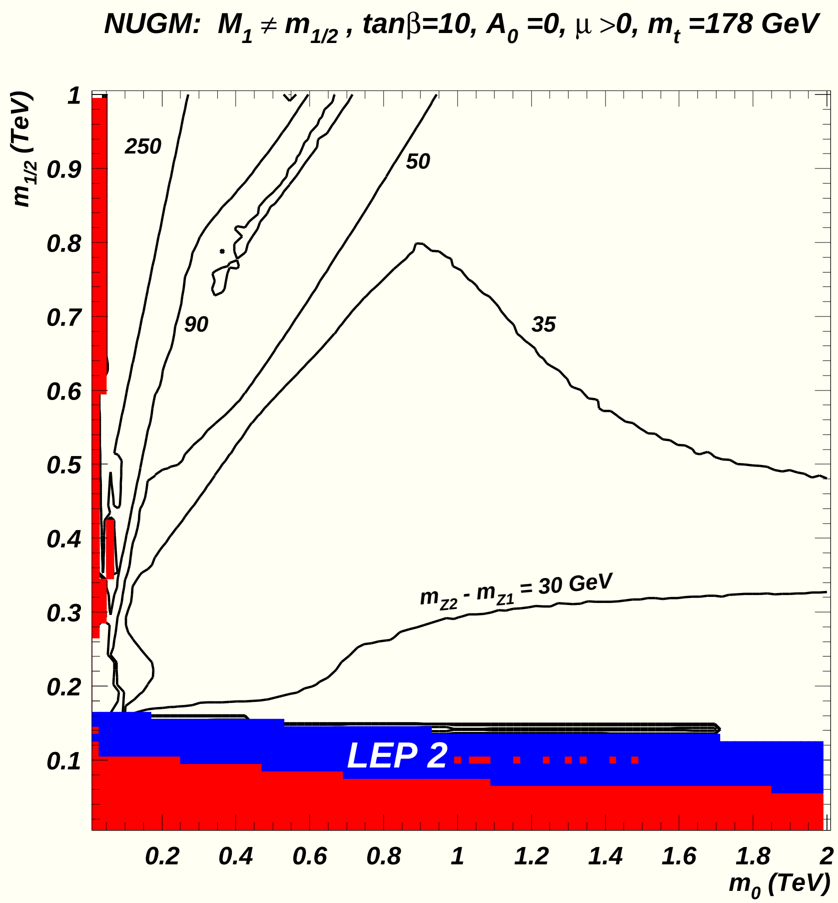


MWDM: Any point in m_0-$m_{1/2}$ plane can be WMAP allowed

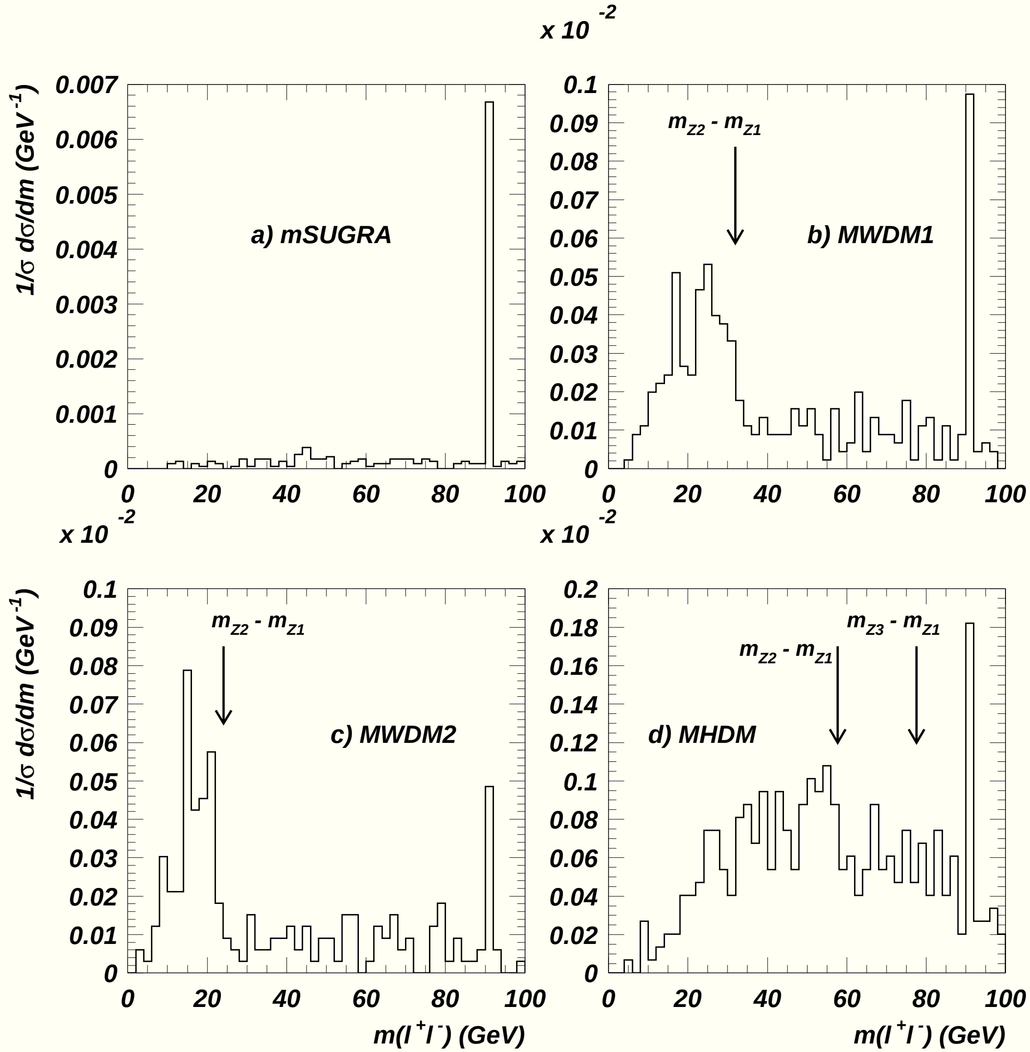


MWDM: small $\widetilde{Z}_2 - \widetilde{Z}_1$ mass gap



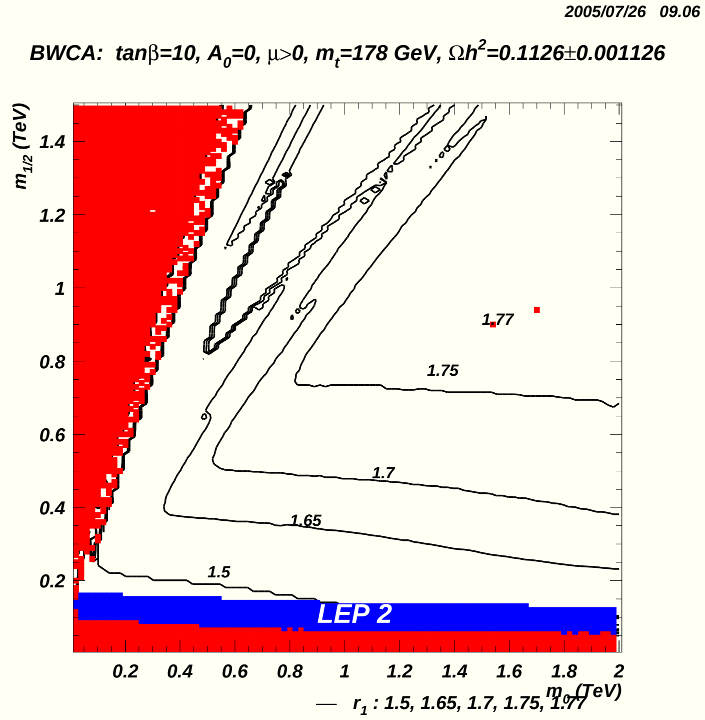


$m(\ell^+\ell^-)$: mass gap observable at LHC for MWDM

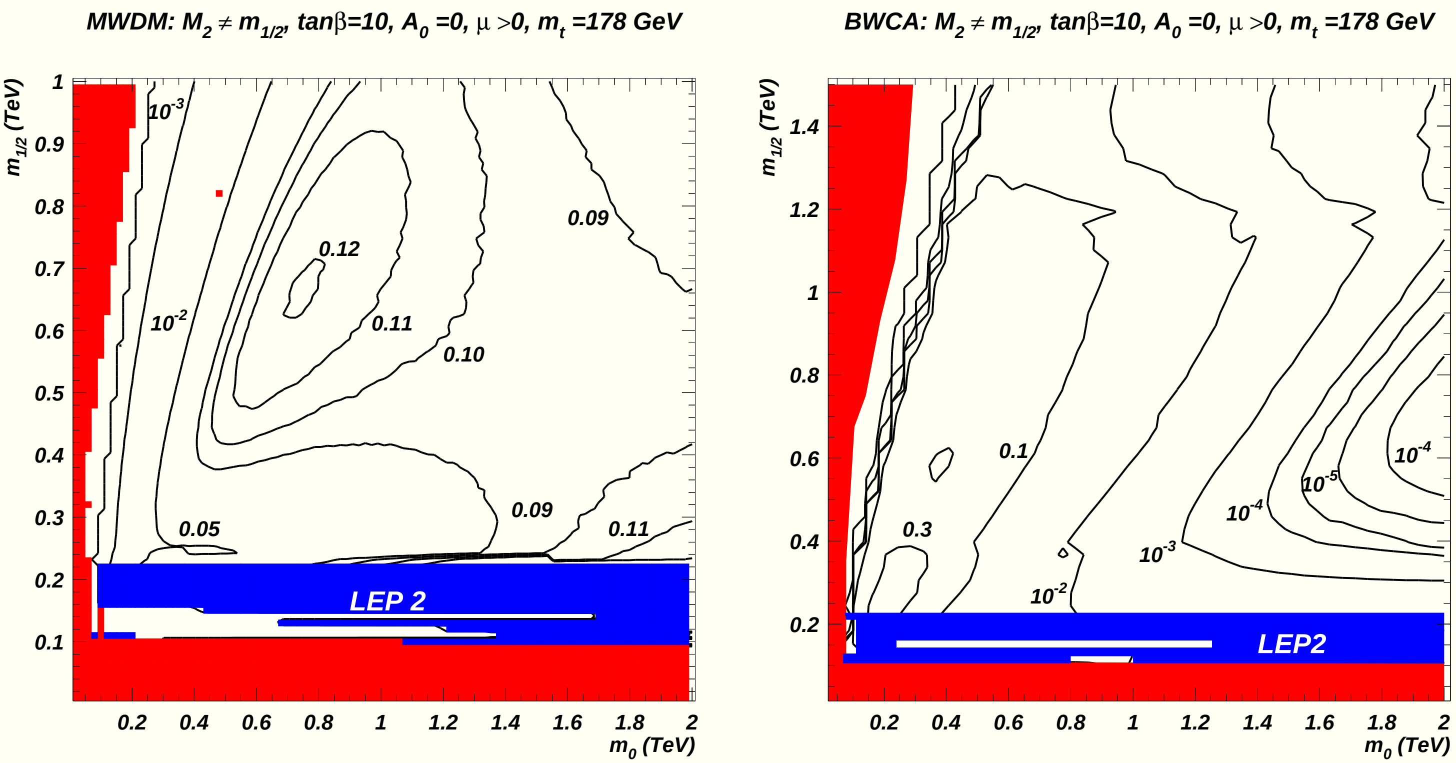


Bino-wino co-annihilation (BWCA) scenario

- If $M_1/M_2 < 0$, then no mixing between bino-wino
- Can only reduce relic density via bino-wino co-annihilation when $M_1 \simeq -M_2$ at $Q = M_{weak}$

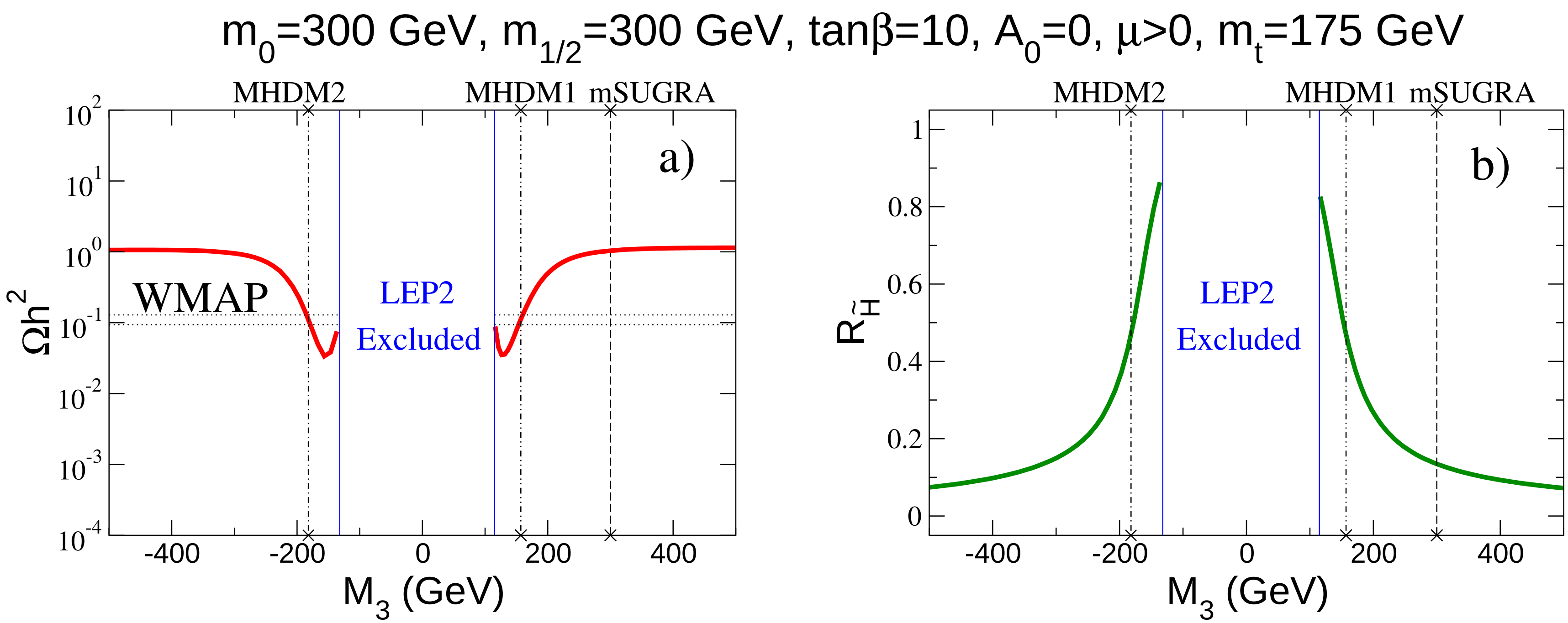


In BWCA at $m_0 \lesssim 500$ GeV, $BF(\widetilde{Z}_2 \to \widetilde{Z}_1\gamma)$ enhanced!



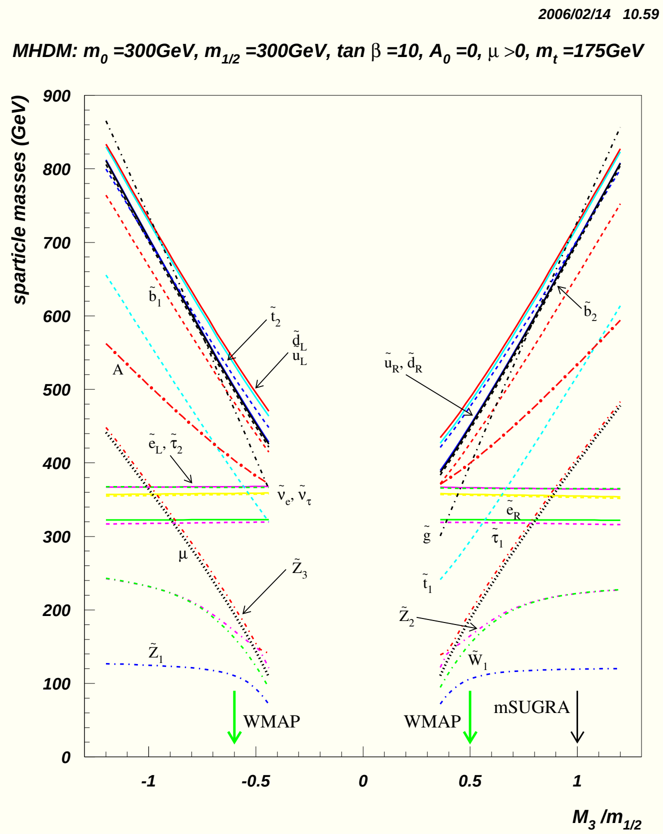
Haber+Wyler; Ambrosanio+Mele; Baer+Krupovnickas: JHEP 0209, 038 (2002)

Mixed higgsino DM from a low M_3 (LM3DM)



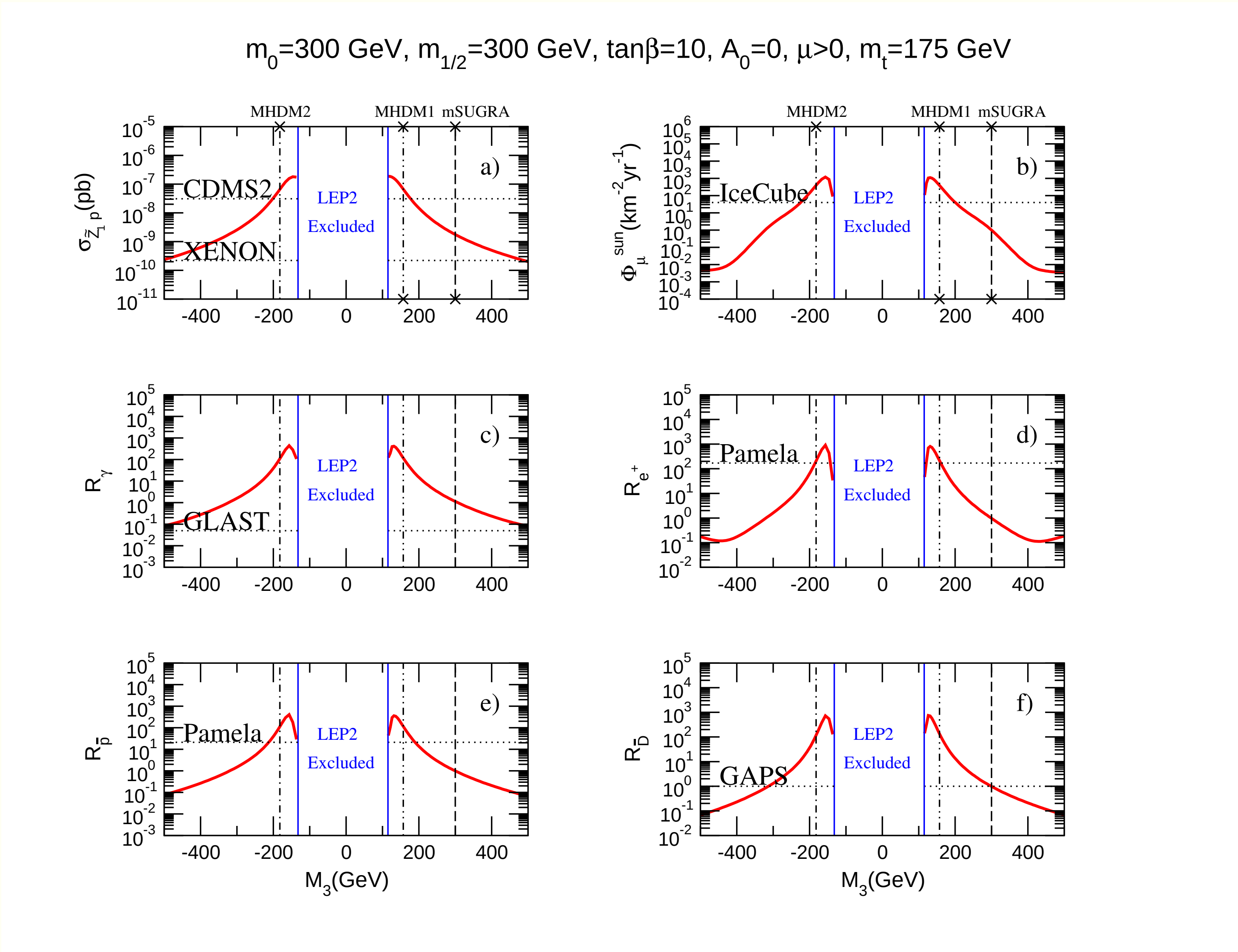
- low $M_3 \Rightarrow$ low $m_{\tilde{g}},\ m_{\tilde{q}},\ \mu$

Sparticle mass spectra for LM3DM

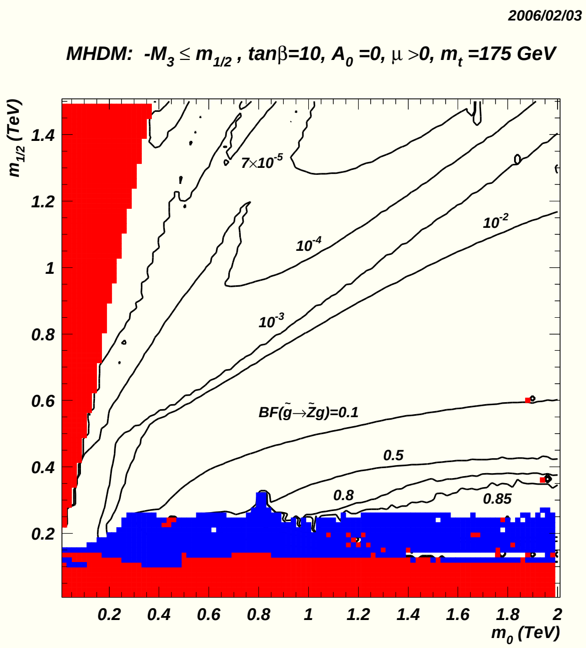


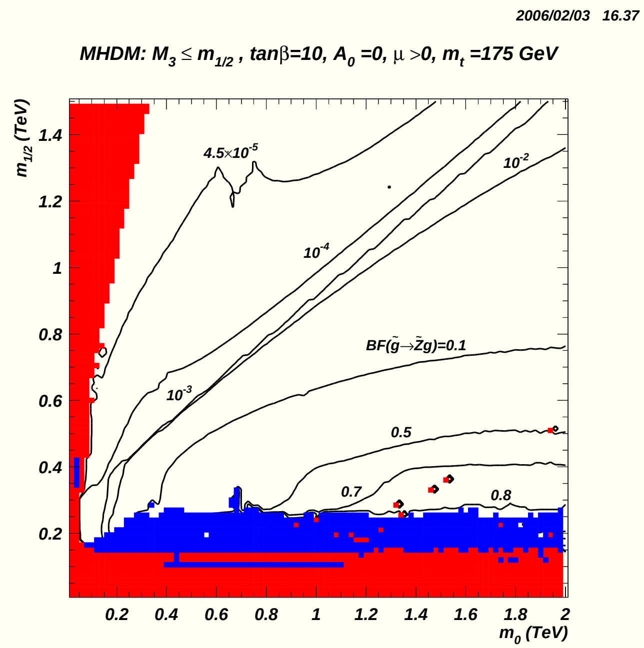
- low $m_{\tilde{g}},\ m_{\tilde{q}},\ \mu \Rightarrow$ huge DM detection rates!

Direct/indrct DM rates greatly enhanced for LM3DM



In LM3DM, $BF(\tilde{g} \to \widetilde{Z}_i)$ loop decay enhanced!





Baer, Tata, Woodside: PRD**42** (1990) 1568.

Mixed modulus-AMSB models

⋆ KKLT model: type IIB superstring compactification with fluxes

- stabilize moduli/dilaton via fluxes and e.g. gaugino condensation on $D7$ brane
- introduce anti-$D3$ brane (uplifting potential; de Sitter universe with $\Lambda > 0$
- small SUSY breaking due to $\overline{D3}$ brane
- mass hierarchy: $m_{moduli} \gg m_{3/2} \gg m_{SUSY}$

⋆ MSSM soft terms calculated by Choi, Falkowski, Nilles, Olechowski, Pokorski

⋆ phenomenology: Choi, Jeong, Okumura, Falkowski, Lebedev, Mambrini,Kitano, Nomura

⋆ see also: HB, E. Park, X. Tata, T. Wang, hep-ph/0604253

Parameter Space

MSSM sparticle mass scale $\sim \frac{m_{3/2}}{16\pi^2} \equiv M_s$

Ratio of modulus-mediated and anomaly-mediated contributions set by a phenomenological parameter α

Modulus-mediated contributions depend on location of fields in extra dimensions. These contributions depend on "modular weights" of the fields, determined by where these fields are located.

modular weights n_i= 0 (1) (($\frac{1}{2}$)) for D7 (D3) ((intersection))
Gauge kinetic function indices l_a= 1 (0) on $D7$ ($D3$) branes.

Model completely specified by

$$m_{3/2},\ \alpha,\ \tan\beta,\ sign(\mu),\ n_i,\ l_a$$

Radiative EWSB determines μ^2 as usual.

Soft SUSY Breaking Terms

The soft terms renormalized at $Q \sim M_{\rm GUT}$ are given by,

$$
\begin{aligned}
M_a &= M_s\left(\ell_a\alpha + b_a g_a^2\right), \\
A_{ijk} &= M_s\left(-a_{ijk}\alpha + \gamma_i + \gamma_j + \gamma_k\right), \\
m_i^2 &= M_s^2\left(c_i\alpha^2 + 4\alpha\xi_i - \dot{\gamma}_i\right),
\end{aligned}
$$

with

$$c_i = 1 - n_i,$$

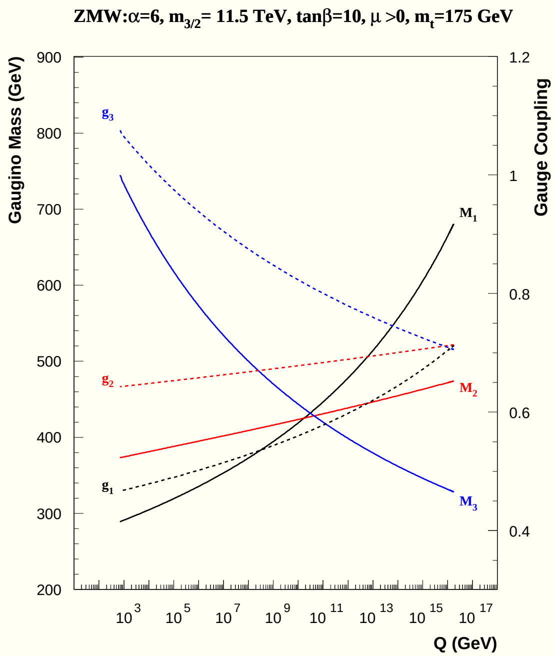
$$a_{ijk} = 3 - n_i - n_j - n_k,$$

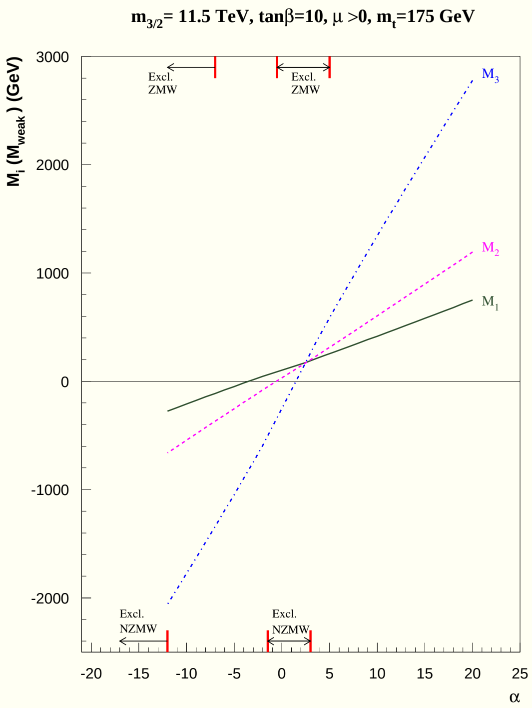
$$\xi_i = \sum_{j,k} a_{ijk}\frac{y_{ijk}^2}{4} - \sum_a l_a g_a^2 C_2^a(f_i), \text{and } \dot{\gamma}_i = 8\pi^2\frac{\partial\gamma_i}{\partial\log\mu}$$

We will always fix $l_a = 1$ and examine two cases:

- ⋆ $n_i = 0$; Zero Modular Weight (ZMW).
- ⋆ $n_{\rm matter} = 1/2$, $n_{\rm Higgs} = 1$, Non-Zero Modular Weight (NZMW).

True Unification and Mirage Unification

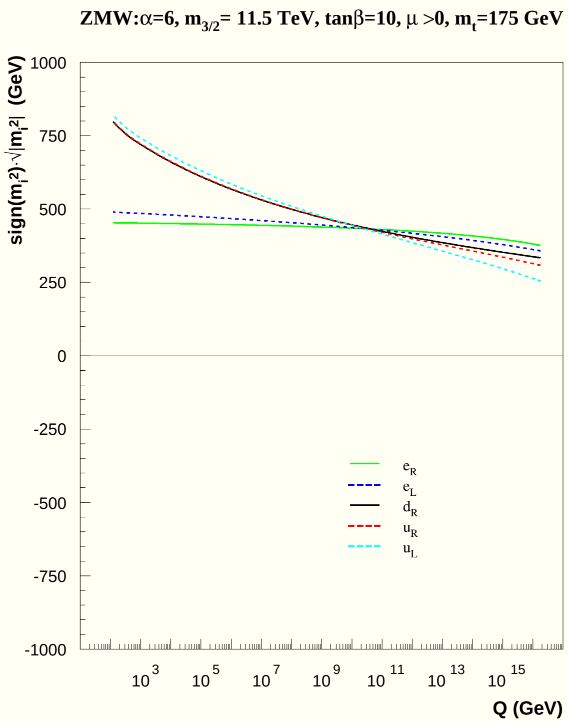


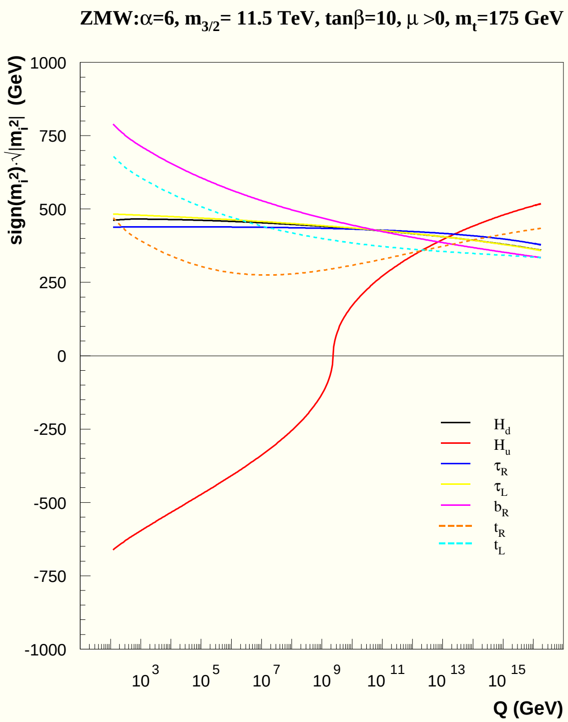


Low mirage unification scale

If $M_1\text{weak} = \pm M_2\text{weak}$, potential for agreement with relic density via Mixed Wino DM (MWDM) / Bino-Wino Coannihilation (BWCA).

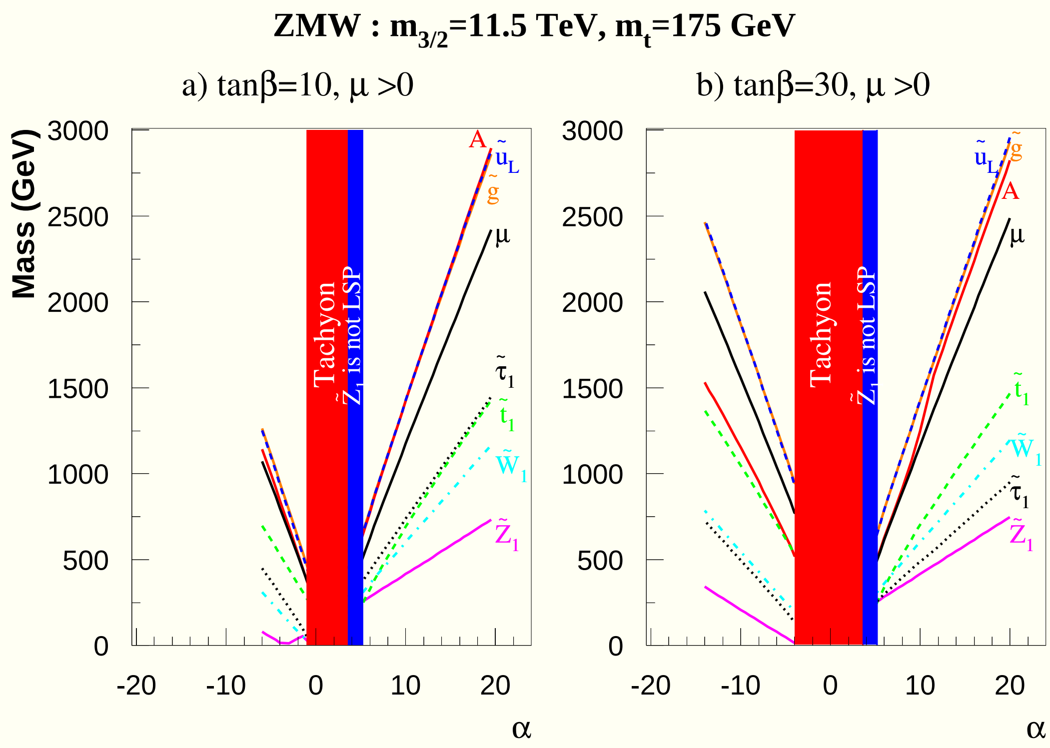
ZMW Model



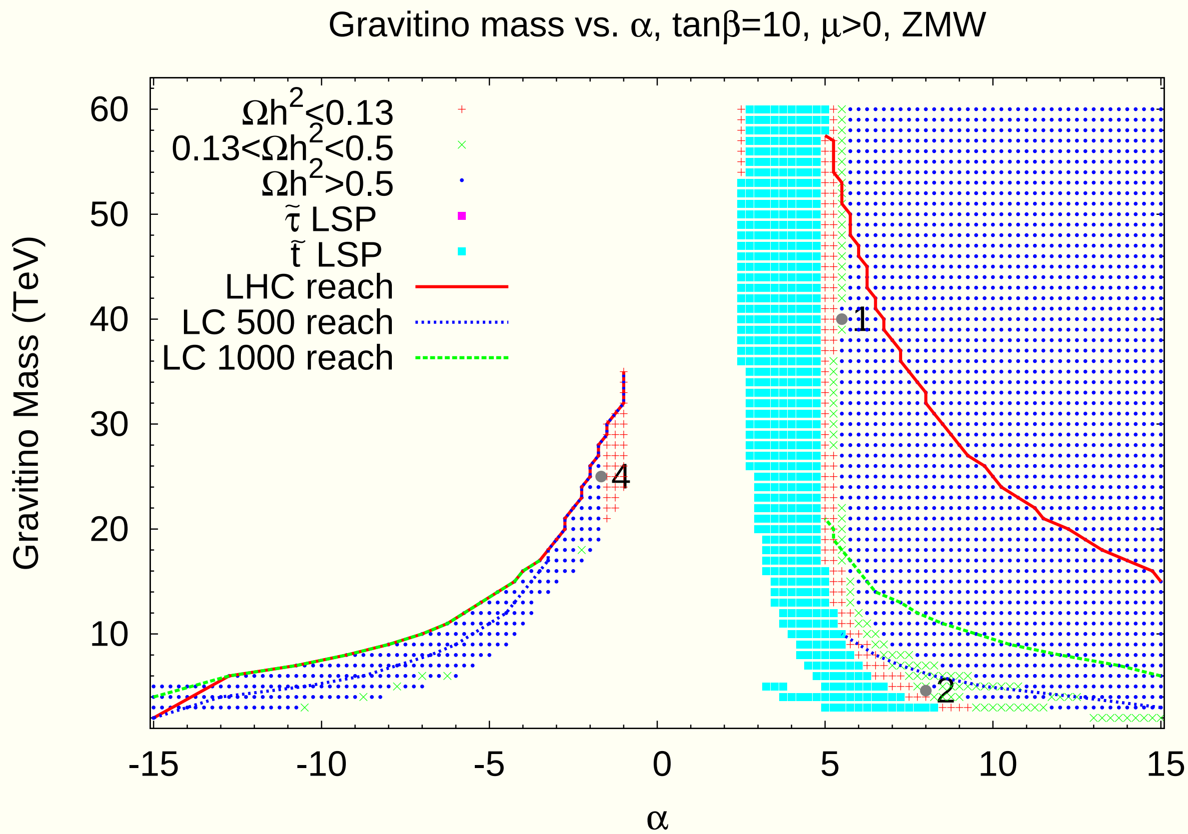


Mirage unification for scalar masses also, but spoiled by Yukawa couplings (NZMW model is an exception). Note low value of $m_{\tilde{t}_R}$. Anticipate light $\tilde{t}_1$.

ZMW Model Mass Spectrum



For low positive α, $m_{\tilde{t}_1} \sim m_{\widetilde{Z}_1}$, and for large $\tan\beta$ $m_{\tilde{\tau}_1} \sim m_{\widetilde{Z}_1}$ also. Stop and stau co-annihilation mechanisms operative. For negative α in first frame, we have BWCA. No MWDM possible as for the required α, $\tilde{t}_1 =$ LSP.



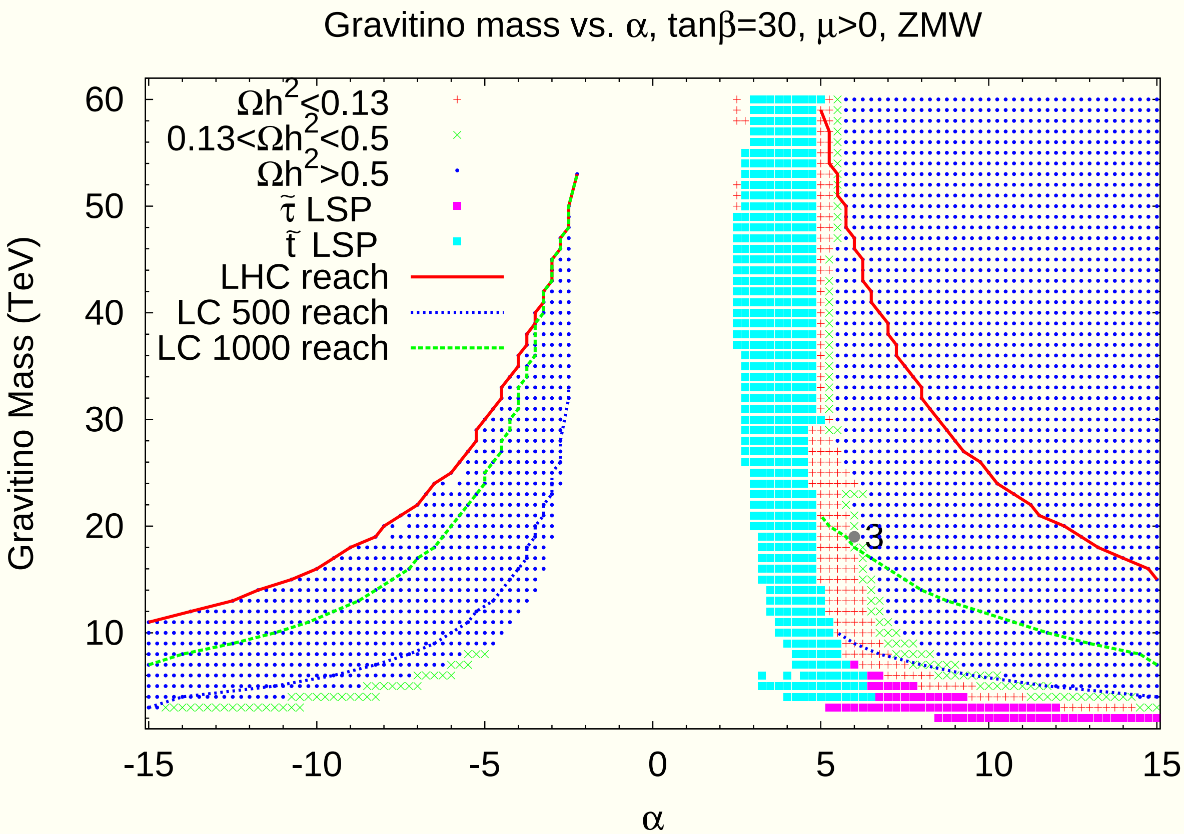
Stop coannihilation region.

Mixed higgsino region at low positive alpha.

BWCA for $\alpha < 0$. No MWDM region.

In the neighbourhood of Point 2, $m_{\tilde{t}_1} < m_t$, $m_h \lesssim 120$ GeV

$\Rightarrow$ Electroweak baryogenesis? (Carena, Quiros, Wagner; Balázs, Carena, Wagner)



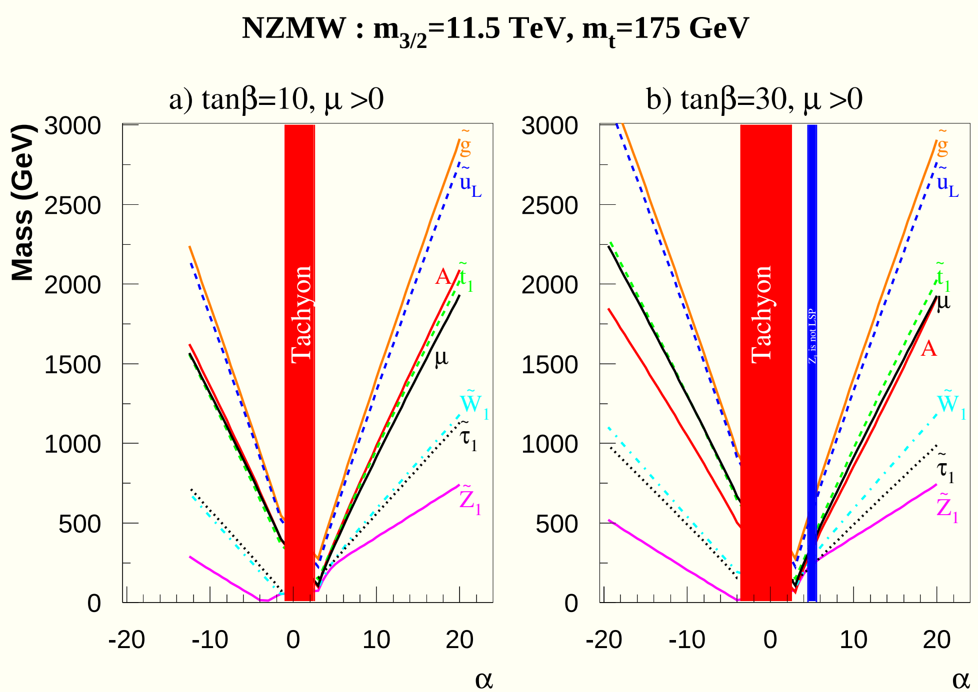
Stop and stau coannihilation regions.

BWCA region disappears.

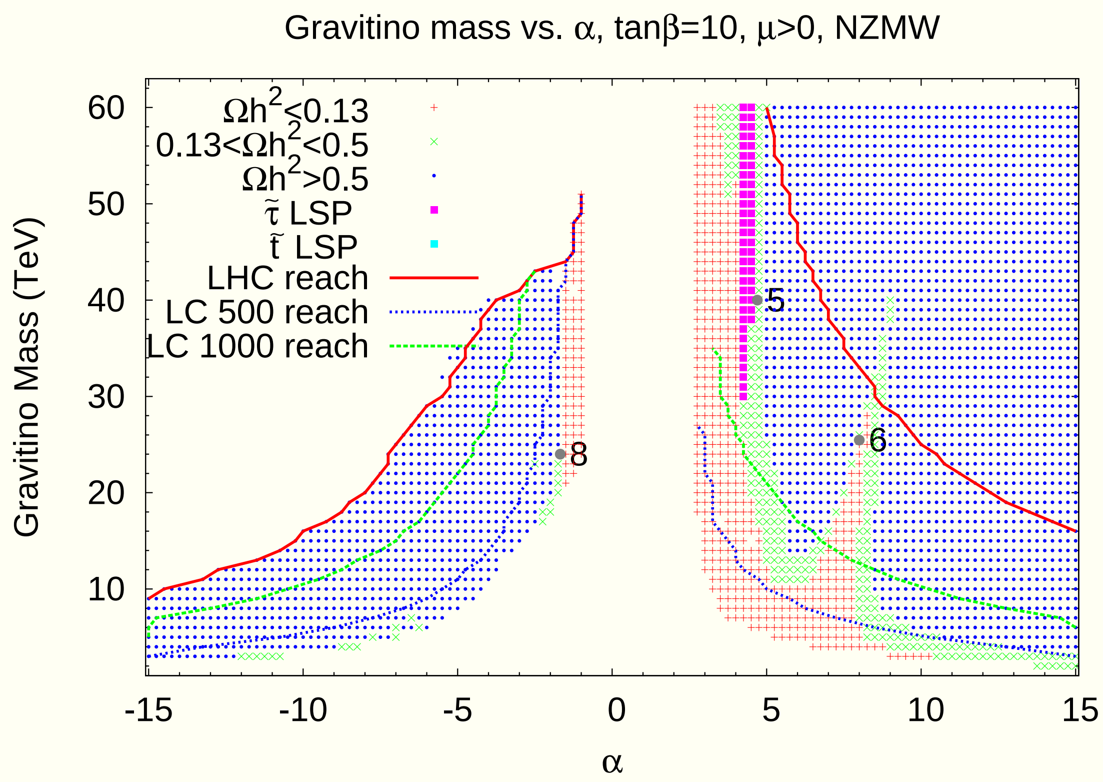
LHC Covers most of the WMAP allowed planes except for large $m_{3/2}$ near $\alpha \sim 5 - 6$.

NZMW Model

Now the modulus-mediated contribution to $A(\mathrm{GUT}) \sim M_s$, so stop is not as light as in ZMW case.



Stau NLSP $\Longrightarrow$ Stau co-annihilation; Higgs funnel annihilation
Also, BWCA for $\alpha < 0$, $\tan\beta \sim 10$.



Stau coannihilation, Higgs funnel and BWCA regions clearly seen.

Also, mixed bino-wino-higgsino region (via low $|M_3|$).

Bulk region at low $m_{3/2}$.

LHC reach qualitatively similar to ZMW case.

Conclusions

- ⋆ SUSY is standard way beyond the SM
- ⋆ SUGRA models most naturally encompass DM: thermal WIMPS
- ⋆ WMAP bound $\Omega_{\widetilde{Z}_1}h^2 = 0.113 \pm 0.009$ especially constraining
  - bulk, $\tilde{\tau}$ coann., HB/FP, A-funnel, h-funnel, $\tilde{t}_1$ coann.
- ⋆ Various regions $\Rightarrow$ distinct collider/DM signatures
- ⋆ Non-universality
  - normal scalar mass hierarchy (NMH)
  - NUHM1, NUHM2 models
  - mixed wino DM
  - bino-wino co-annihilation DM
  - mixed higgsino DM if M_3 reduced
- ⋆ MM-AMSB (KKLT) phenomenology

Weak Scale Supersymmetry

HB and X. Tata

Spring, 2006; Cambridge University Press

- ★ Part 1: superfields/Lagrangians
  - 4-component spinor notation for exp'ts
  - master Lagrangian for SUSY gauge theories
- ★ Part 2: models/implications
  - MSSM, SUGRA, GMSB, AMSB, $\cdots$
- ★ Part 3: SUSY at colliders
  - production/decay/event generation
  - collider signatures
  - R-parity violation