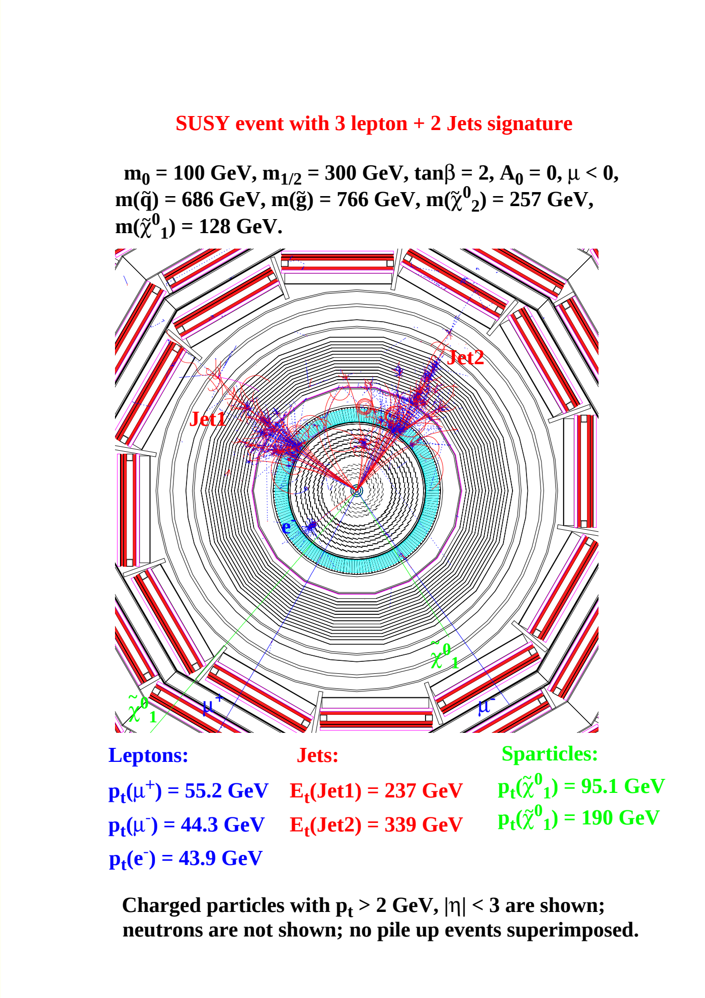
Direct, indirect and collider detection of SUSY dark matter

Howard Baer

Florida State University

- ⋆ 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



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

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

- ⋆ Higgs sector ⇒ spontaneous electroweak symmetry breaking:

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

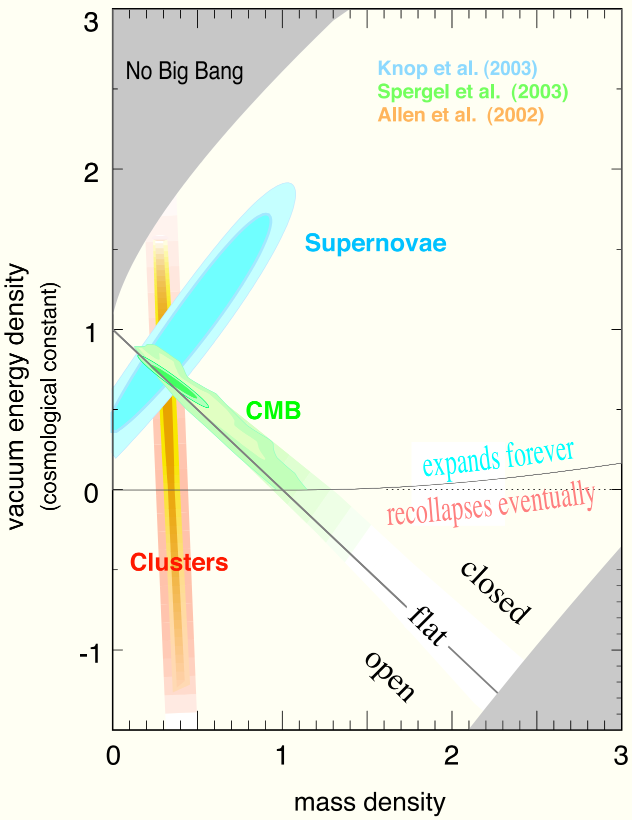
- ⋆ Yukawa interactions ⇒ massive quarks and leptons
- ⋆ 19 parameters
- ⋆ **good-to-excellent description of (almost)** ***all*** **accelerator data!**

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



Focus of this talk is on *supersymmetry*

"if we consider the main classes of new physics that are currently being contemplated$\cdots$, it is clear that (supersymmetry) is the most directly related to GUTs. SUSY offers a well defined model computable up to the GUT scale and is actually supported by the quantitative success of coupling unification in SUSY GUTs.For the other examples$\cdots$, all contact with GUTs is lost or at least is much more remote. $\cdots$ the SUSY picture$\cdots$ remains the standard way beyond the Standard Model"

G. Altarelli and F. Feruglio, hep-ph/0306265

Minimal Supersymmetric Standard Model: MSSM

- ⋆ Rules for Lagrangian of renormalizable globally supersymmetric Lagrangian
  - texts: Drees, Godbole, Roy (WS) ; HB and X. Tata (CUP, Spring '06)
- ⋆ Gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y$
- ⋆ Fields ⇒ superfields
  - fermions ⇒ (left) chiral scalar superfields
  - gauge fields ⇒ gauge superfields
  - *two* Higgs doublets are necessary
- ⋆ Superpotential: R_p conserving (RPC) or violating (RPV)?
- ⋆ Explicit soft SUSY breaking terms: scalar/ino masses, A_i, B
- ⋆ MSSM with RPC: 124 parameter model valid at M_{weak}?
- ⋆ MSSM with bi (tri)linear RPV: add 6 (45) more complex SP parameters

Models of SUSY breaking

- ⋆ Spontaneous breaking of SUSY phen. inconsistent within MSSM
- ⋆ Hidden sector models (HS)
- ⋆ HS is arena for SUSY breaking; how to communicate SUSY breaking to visible sector (VS)?
  - gravity mediation: supergravity (SUGRA) and local SUSY: minimal messenger sector: $m_{3/2} \sim$ TeV: LSP=bino/higgsino/wino/gravitino?
  - gauge mediation (GMSB): introduce messenger sector fields as intermediary between HS and VS: $m_{3/2} \ll$ TeV: LSP=gravitino
  - anomaly mediation (AMSB): $m_{3/2} >$ TeV: LSP=wino
- ⋆ role of extra dimensions? compactification? sequestered sector and AMSB; gaugino mediation; GUTs; $\cdots$

Gravity-mediated SUSY breaking models

- ⋆ $m_{3/2} \sim M_s^2/M_{Pl} \sim 10^3$ GeV for $M_s \sim 10^{11}$ GeV
- ⋆ theory below $Q = M_{GUT}$ usually assumed to be MSSM
- ⋆ 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

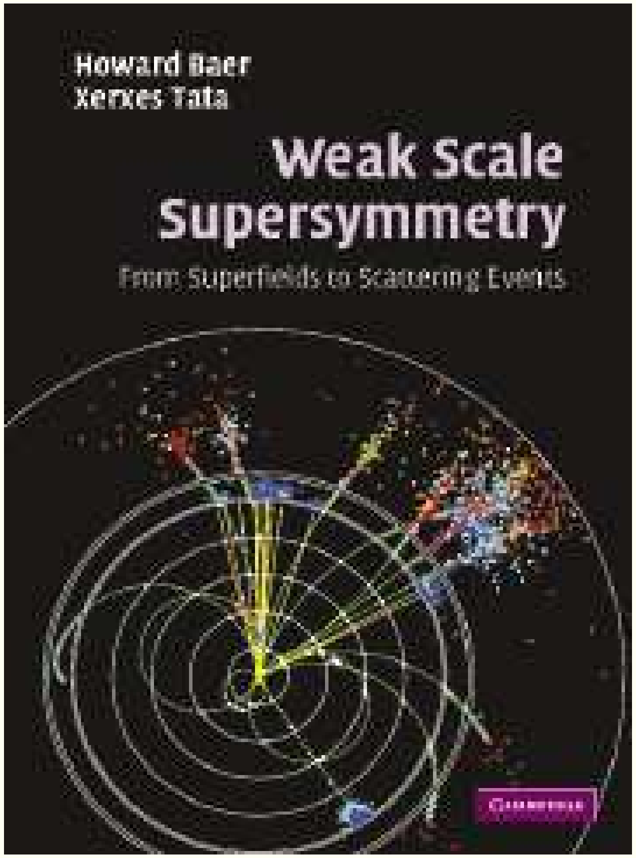
- non-universal scalar masses
- non-universal gaugino masses
- FC soft SUSY breaking terms
- large CP violating phases
- additional fields beyond MSSM below M_{GUT}?
- $\cdots$

Weak Scale Supersymmetry

HB and X. Tata

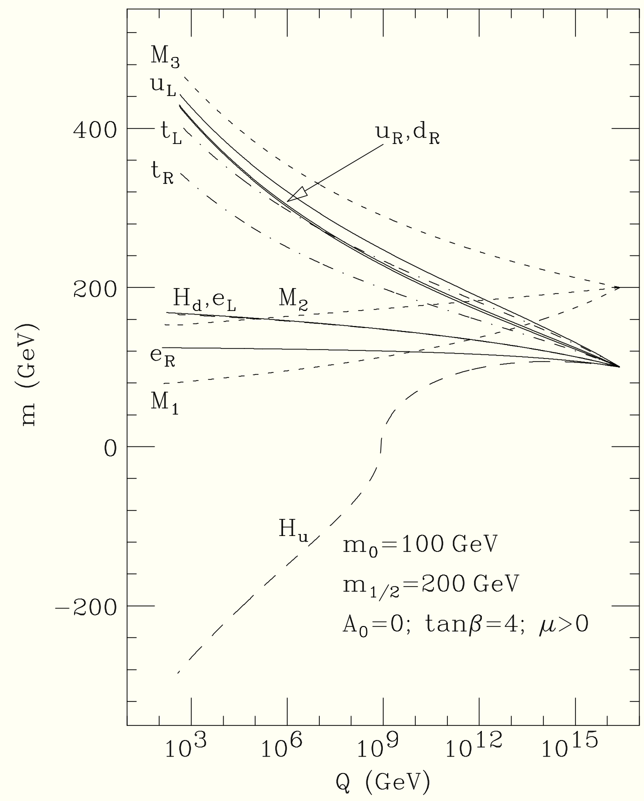
Spring, 2006; Cambridge University Press

- ⋆ 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



Sparticle mass spectra

- ⋆ Mass spectra codes
- ⋆ RGE running: $M_{GUT} \rightarrow M_{weak}$
  - Isajet (HB, Paige, Protopopescu, Tata)
    - $\ast$ $\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)

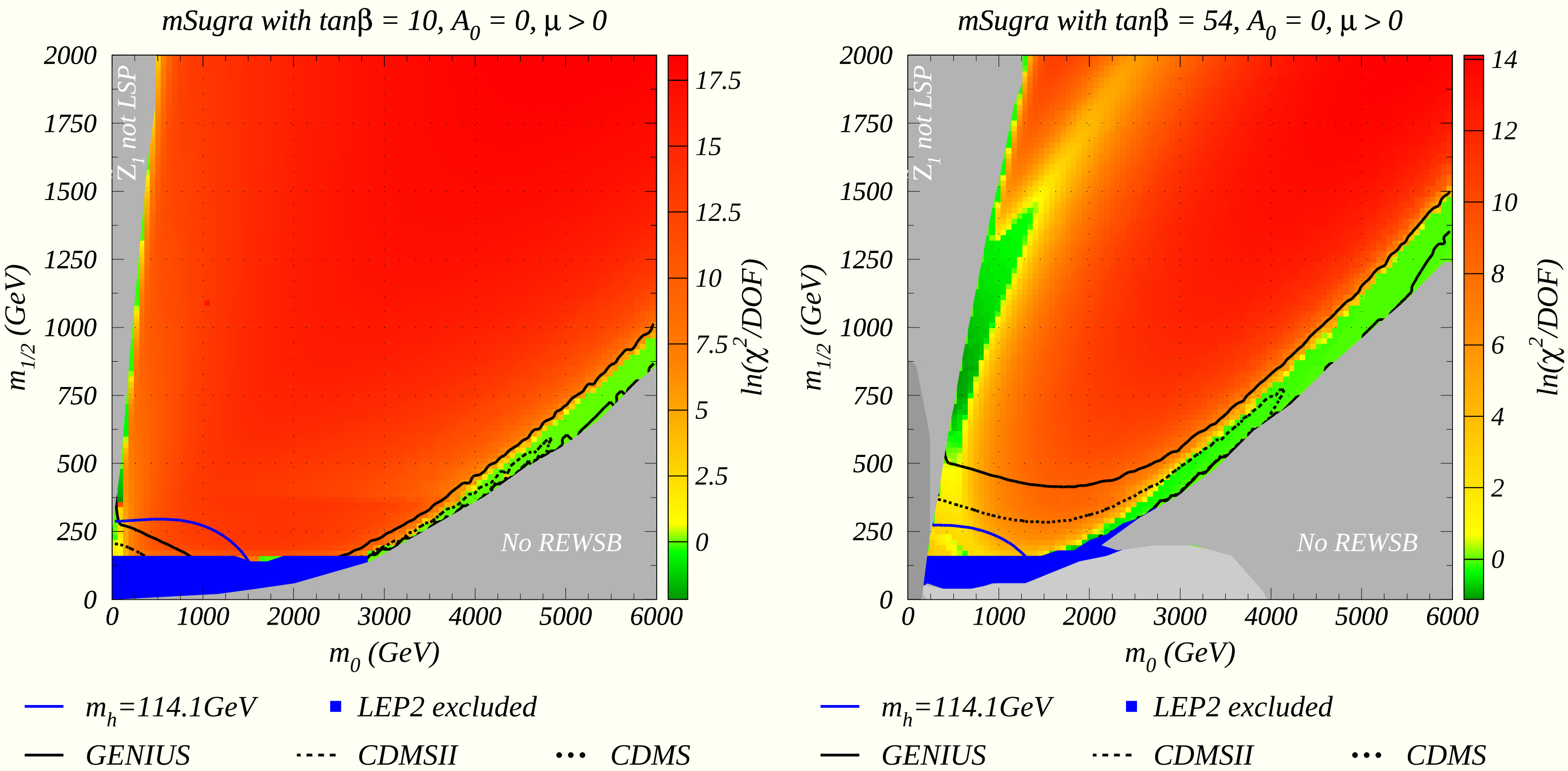
Neutralino dark matter

- ⋆ 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

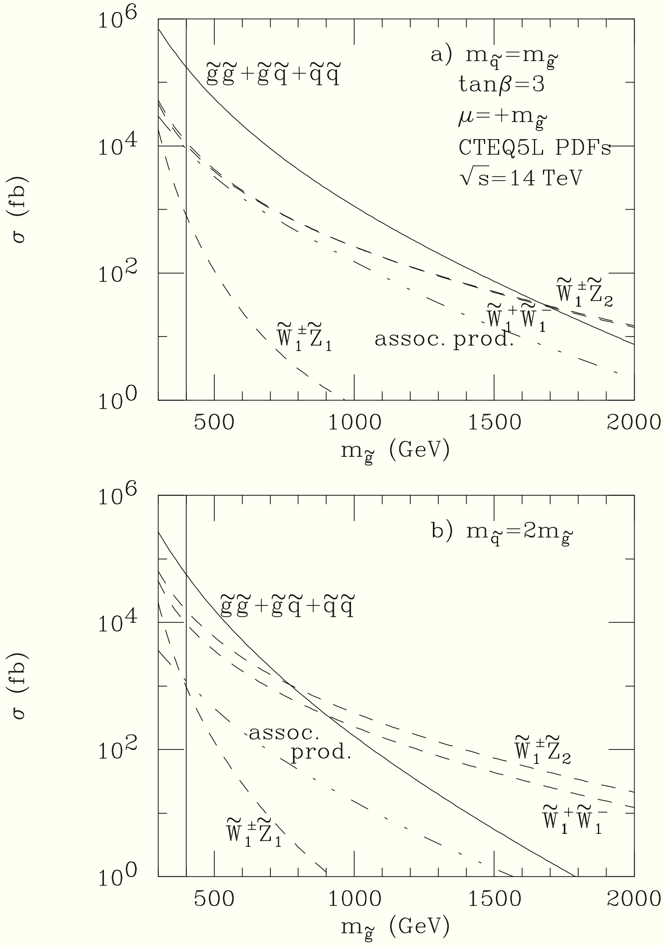
- ⋆ bulk region (low m_0, low $m_{1/2}$)
- ⋆ stau co-annihilation region ($m_{\tilde{\tau}_1} \simeq m_{\widetilde{Z}_1}$)
- ⋆ HB/FP region (large m_0 where $|\mu| \rightarrow small$)
- ⋆ A-funnel ($2m_{\widetilde{Z}_1} \simeq m_A,\ m_H$)
- ⋆ h corridor ($2m_{\widetilde{Z}_1} \simeq m_h$)
- ⋆ stop co-annihilation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

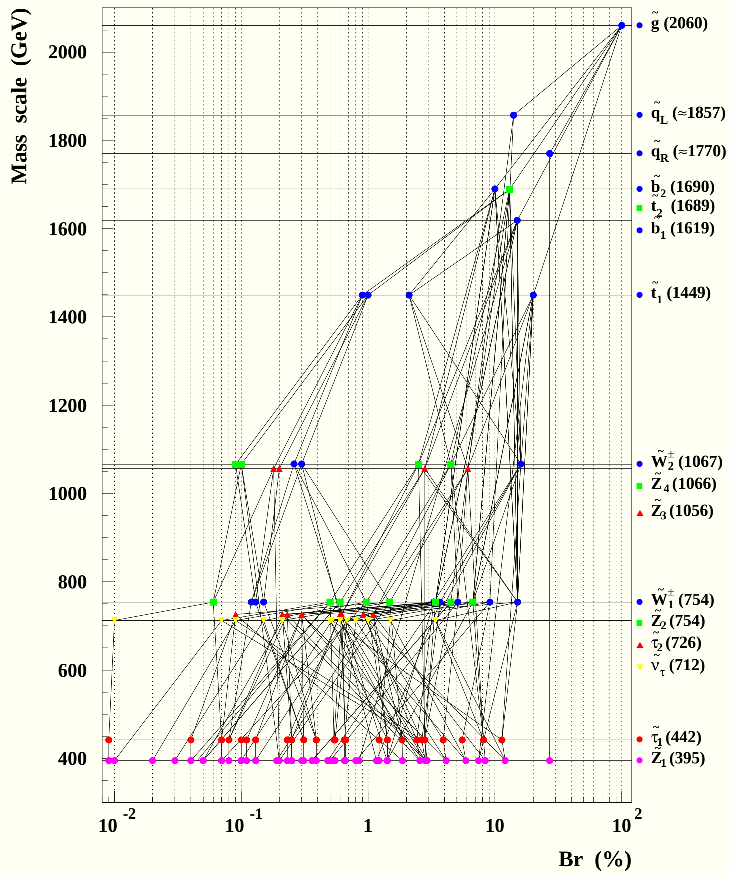


HB, C. Balazs: JCAP 0305, 006 (2003)

Production of sparticles at LHC

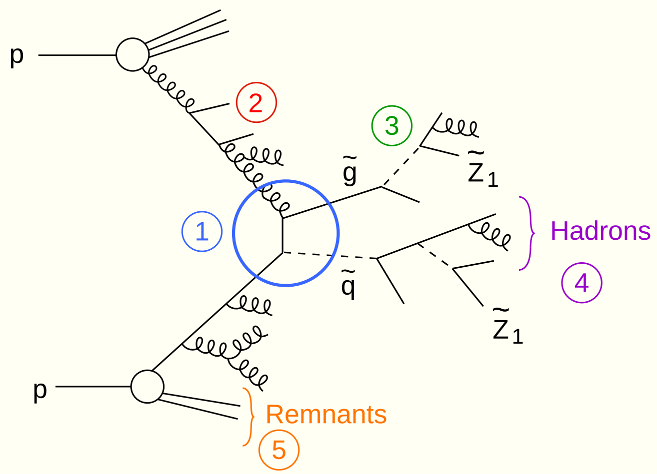


Sparticle cascade decays



$\tilde{Z}_1$ qq	(27.0 %)	$\tilde{Z}_1$ $\tau\nu$WWWbb	(4.1 %)
$\tilde{Z}_1$ $\tau\nu$Wbb	(12.1 %)	$\tilde{Z}_1$ $\tau\tau$bb	(2.9 %)
$\tilde{Z}_1$ $\tau\tau$WWbb	(8.4 %)	$\tilde{Z}_1$ $\tau\tau$qq	(2.9 %)
$\tilde{Z}_1$ WWbb	(7.4 %)	$\tilde{Z}_1$ $\tau\nu$ZWbb	(2.8 %)
$\tilde{Z}_1$ $\tau\nu$qq	(5.9 %)	$\tilde{Z}_1$ $\tau\nu$hWbb	(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

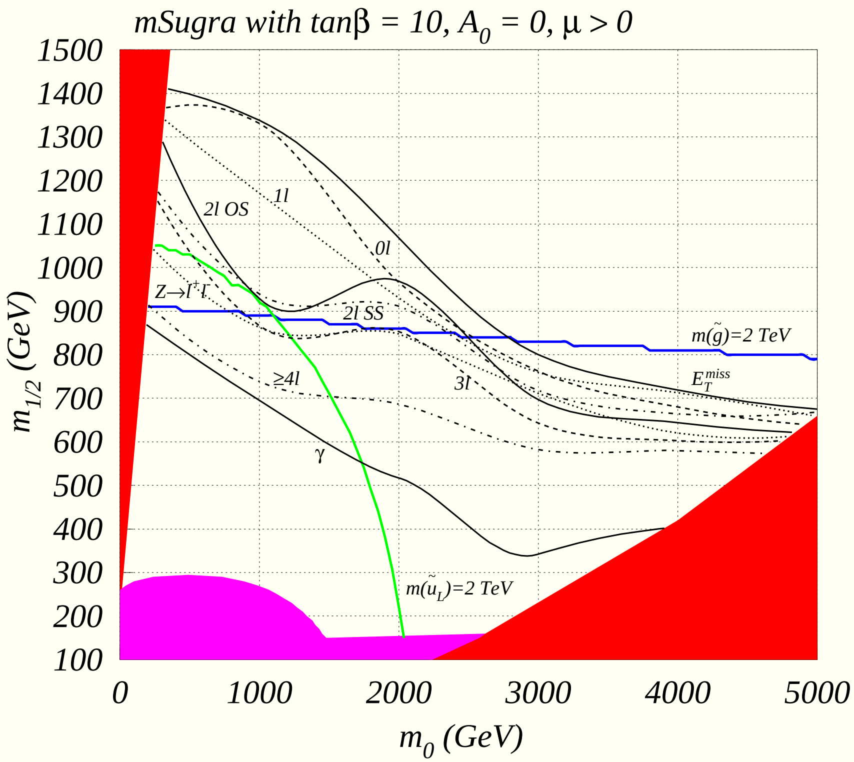
Search for SUSY at CERN LHC

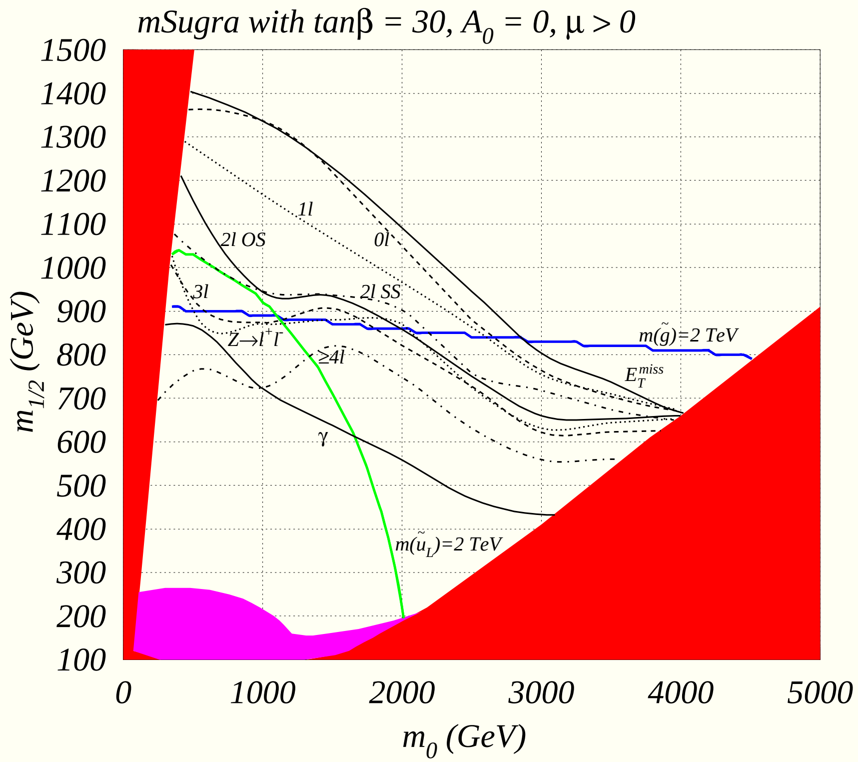
- ⋆ $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV
- ⋆ lengthy cascade decays are likely
  - $\not{E}_T +$ jets
  - $1\ell + \not{E}_T +$ jets
  - $OS\ 2\ell + \not{E}_T +$ jets
  - $SS2\ell + \not{E}_T +$ jets
  - $3\ell + \not{E}_T +$ jets
  - $4\ell + \not{E}_T +$ 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

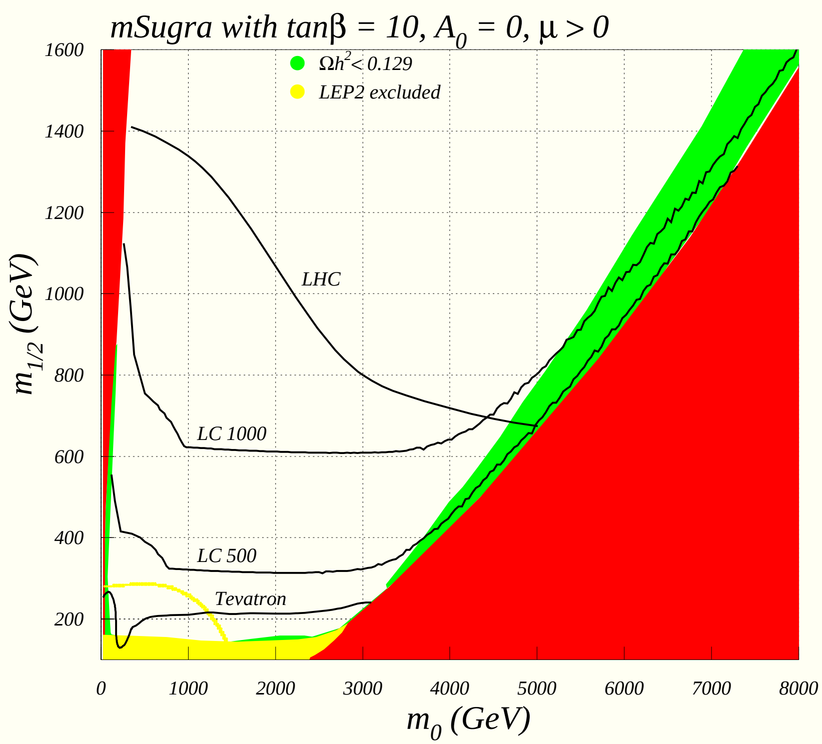
Sparticle reach of LHC for 100^{-1} fb

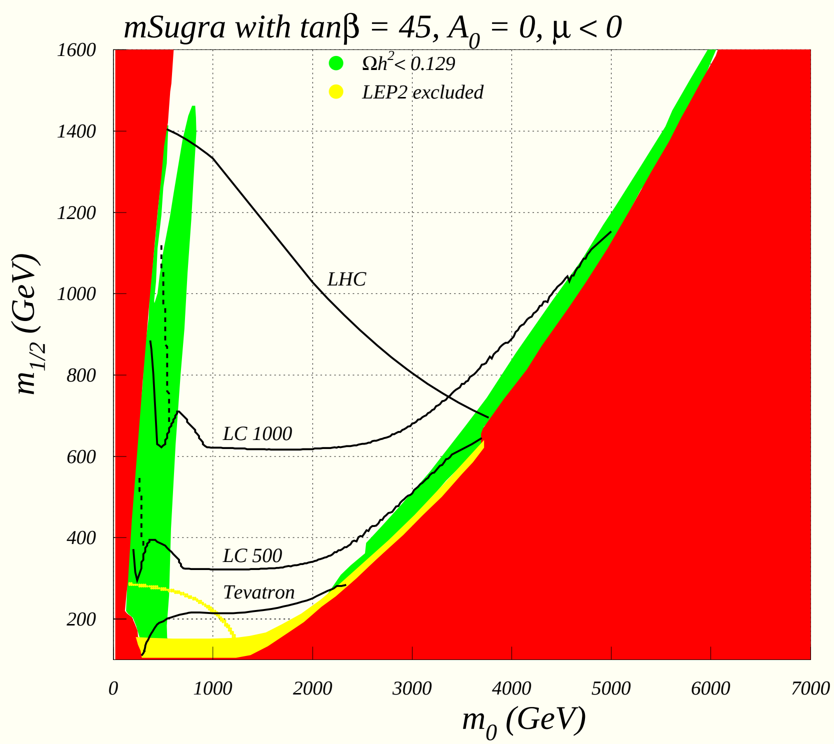




HB, Balazs, Belyaev, Krupovnickas, Tata: JHEP 0306, 054 (2003)

Sparticle reach of all colliders and relic density





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

Precision measurements at LHC

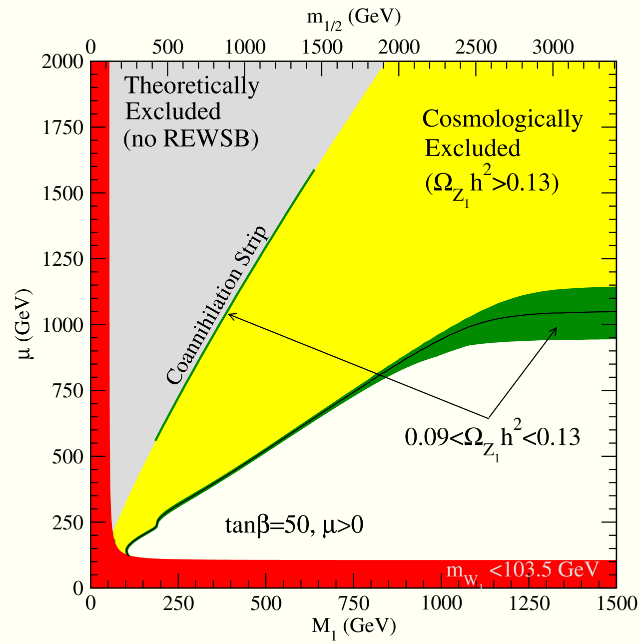
- $M_{eff} = \not{E}_T + E_T(j1) + \cdots + E_T(j4)$ sets overall $m_{\tilde{g}},\ m_{\tilde{q}}$ scale
- $m(\ell\bar{\ell}) < m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ mass edge
- $m(\ell\bar{\ell})$ distribution shape
- combine $m(\ell\bar{\ell})$ with jets to gain $m(\ell\bar{\ell}j)$ mass edge: 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

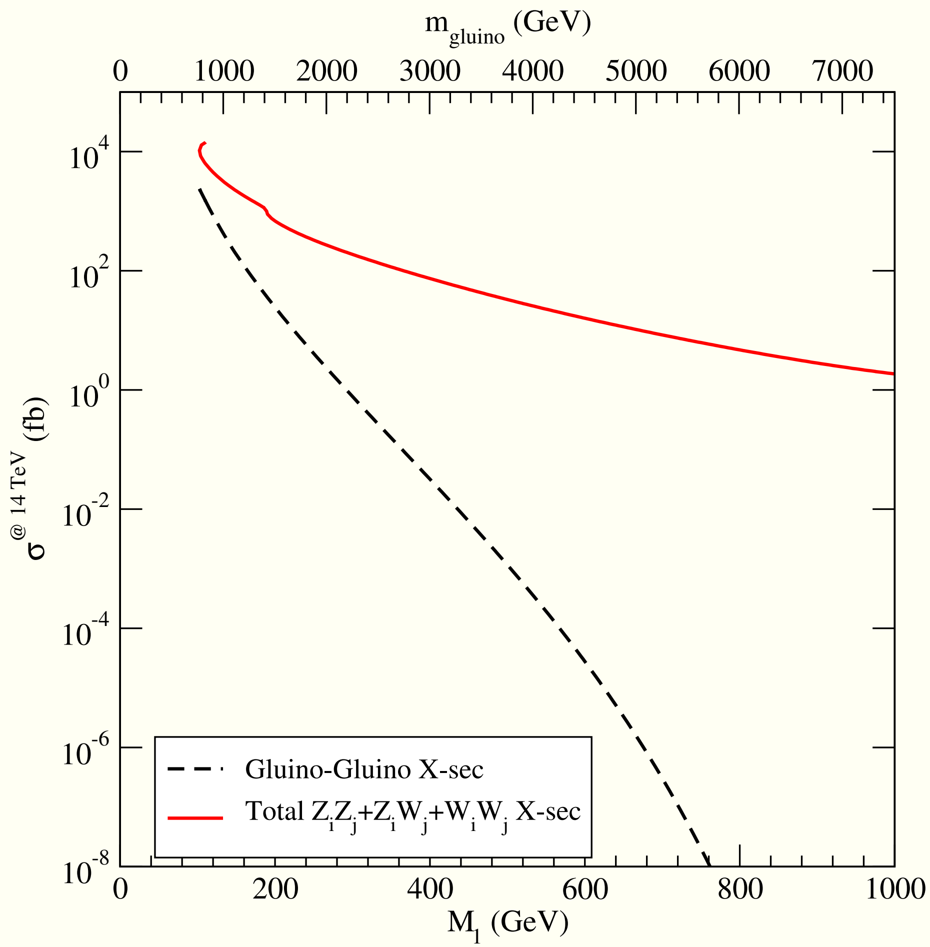
Focus on the Focus Point region

- ⋆ model independent approach:
  - M_1 vs. μ p-space
  - gaugino mass unification
  - scalars to 5 TeV
  - low $\tilde{m}$ limit of split SUSY
  - collider signals
  - direct/indirect DM detection



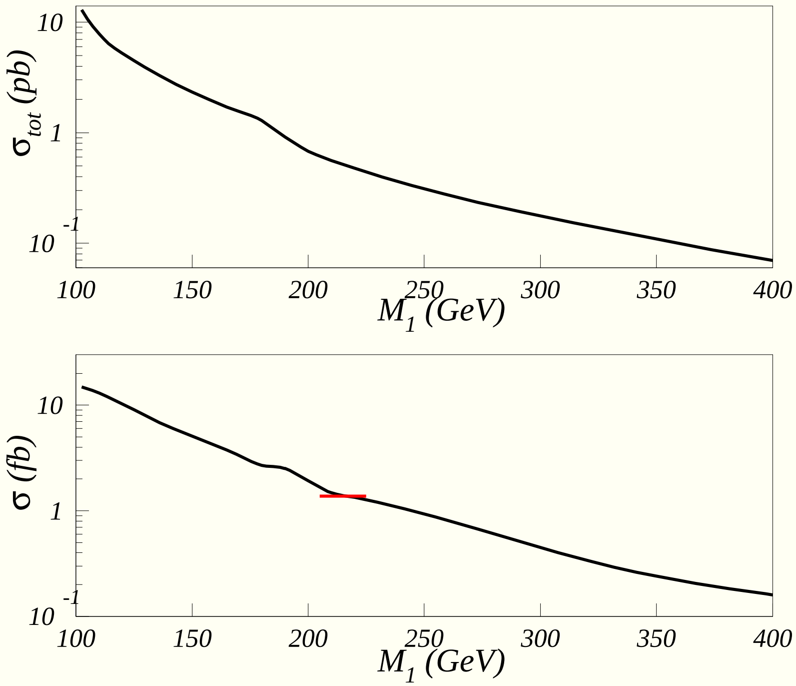
- ⋆ HB, Krupovnickas, Profumo, Ullio: JHEP 0510, 020 (2005)
- ⋆ also see Mercadante, Mizukoshi, Tata: b-jet tag increase of reach in HB/FP

Sparticle cross sections in WMAP allowed strip of FP region



The gluino pair production cross section, along the good-relic-abundance slice at $\tan\beta = 50$ and $\mu > 0$, compared to the total neutralino-chargino cross section.

Clean trilepton signal in WMAP allowed strip of FP region



(Upper) Total cross section for $pp \to$ SUSY particles at the CERN LHC along the $\Omega_{\widetilde{Z}_1} h^2 = 0.11$ line, as a function of M_1. (Lower): LHC clean trilepton cross section after cuts SC2 and corresponding 5σ discovery limits for 100 fb^{-1} integrated luminosity along the $\Omega_{\widetilde{Z}_1} h^2 = 0.11$ line as a function of M_1.

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:

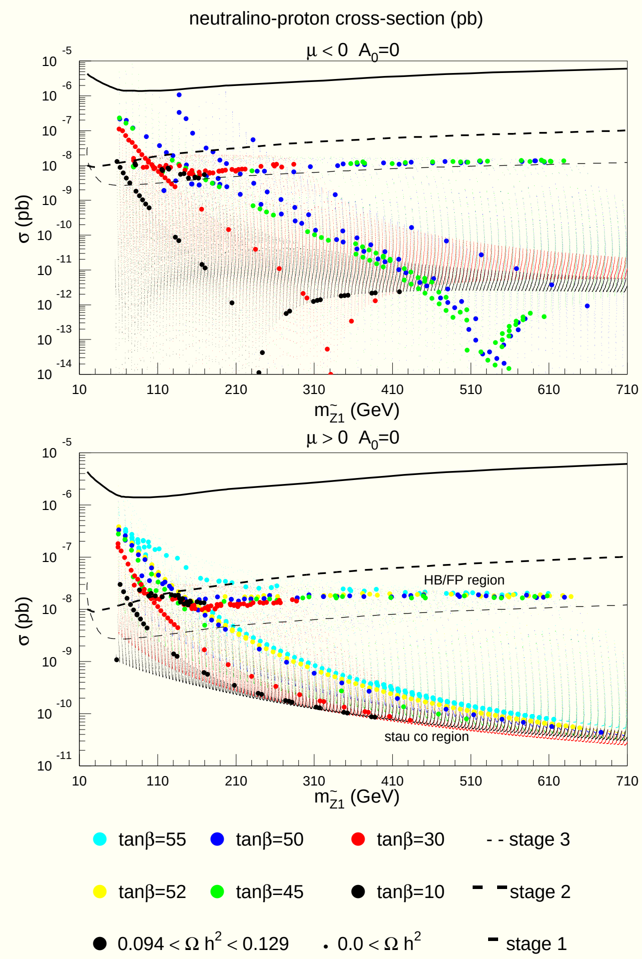
- CDMS1, Edelweiss, Zeplin1

★ Stage 2:

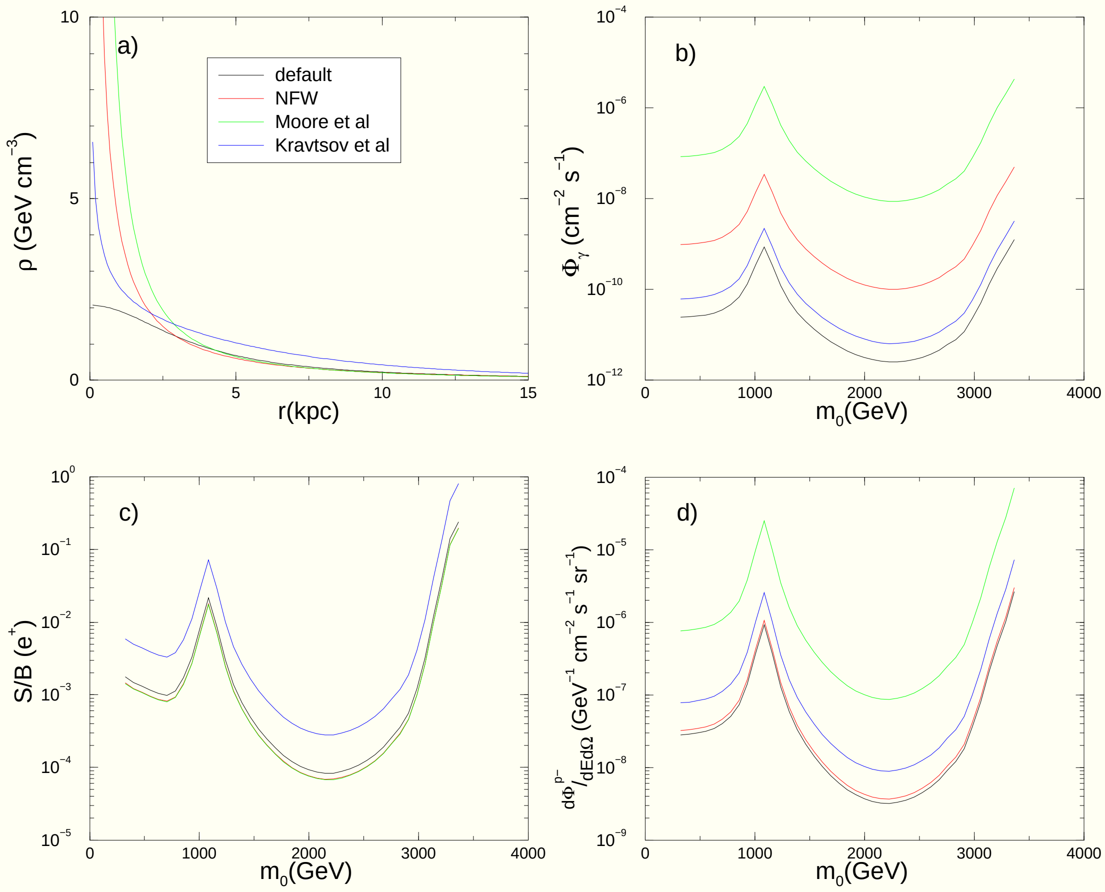
- CDMS2, CRESST2, Zeplin2, Edelweiss2

★ Stage 3:

- SuperCDMS, Zeplin4, Xenon, WARP

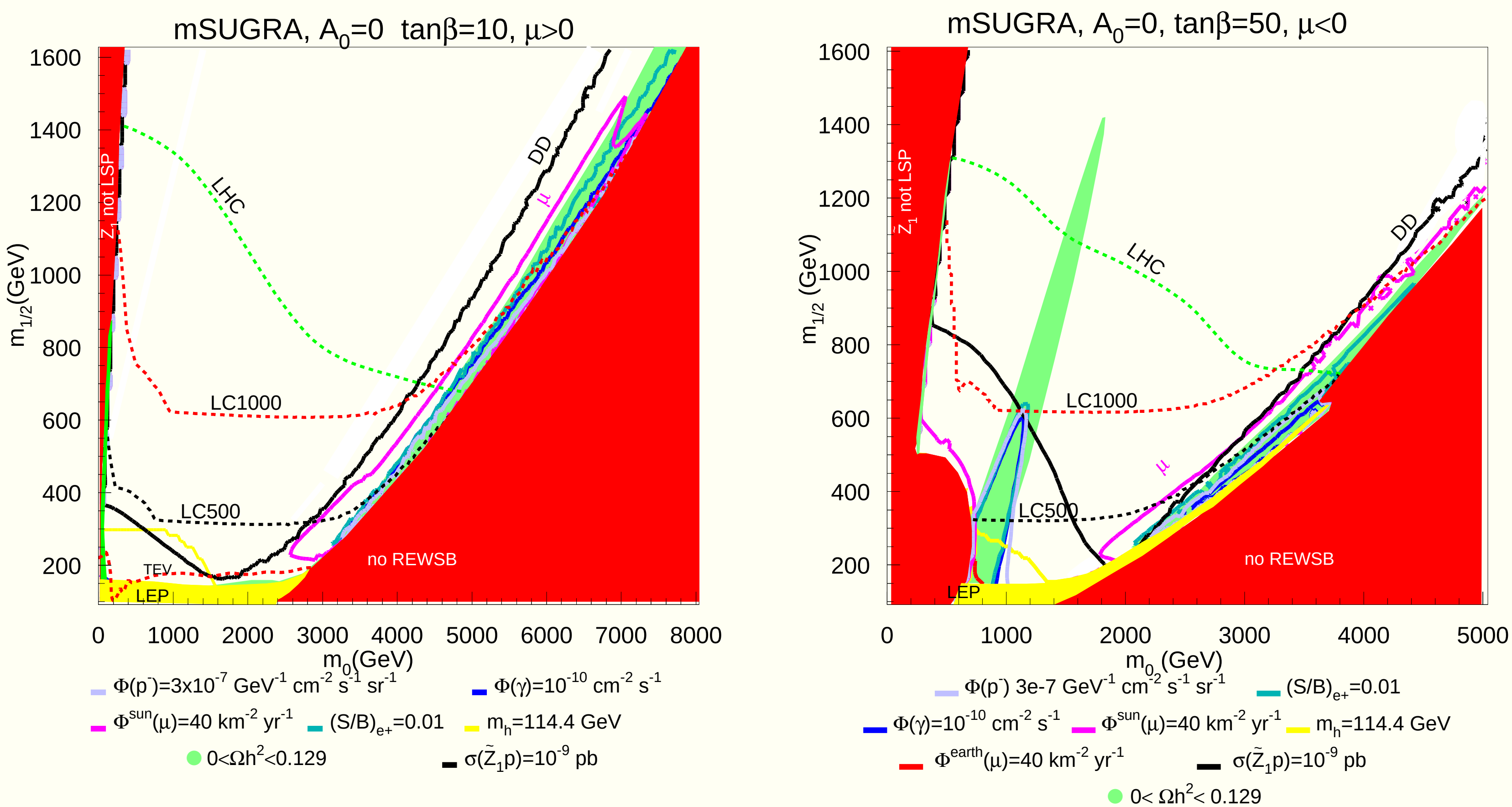


Rates for γs, e^+s, $\bar{p}$s



- HB, Belyaev, Krupovnickas and O' Farrill

Direct and indirect detection of neutralino DM



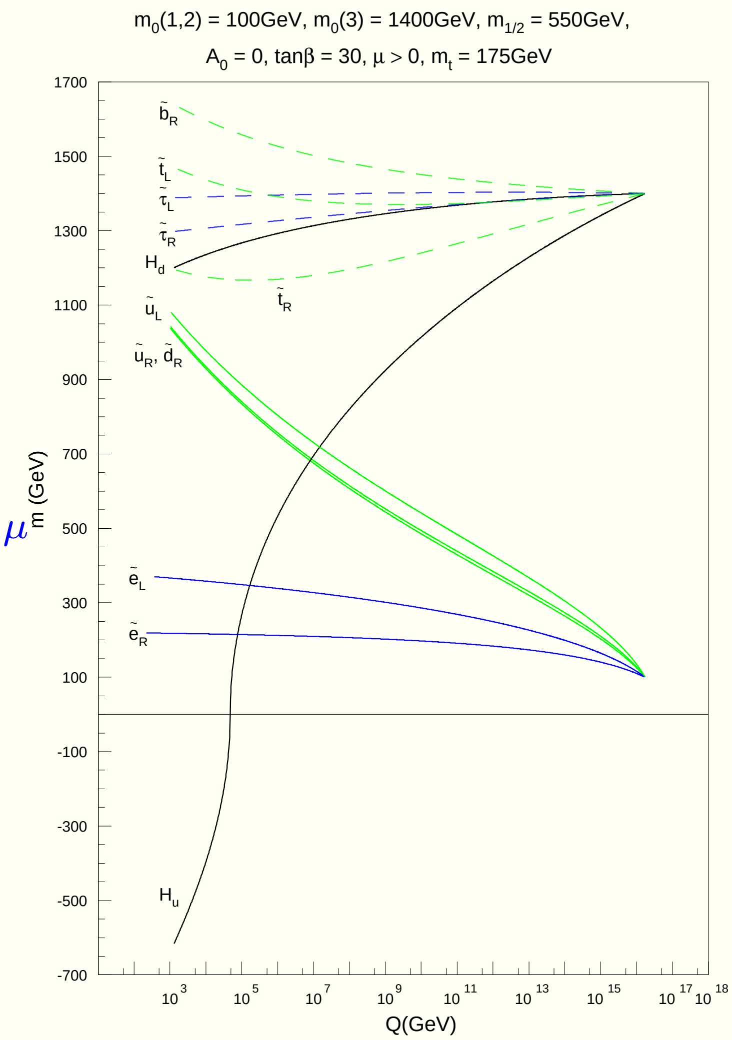
HB, Belyaev, Krupovnickas, O'Farrill: JCAP 0408, 005 (2004)

Impact of DM direct/indirect detection on LHC program

- Extend reach in $\sigma_{SI} \sim 10^{-9} - 10^{-10}$ pb
  - explore thoroughly region of MHDM, possibly MWDM
- after discovery, extract m_{wimp}?
  - $m_{\widetilde{Z}_1}$ sets absolute mass scale for SUSY particles-
  - combine with LHC mass edges to gain LHC absolute sparticle masses
  - learn if $\widetilde{Z}_1$ is absolutely stable: R-conservation
- IceCube turn-on can discover/verify especially MHDM
- knowledge of LHC spectra, σ_{SI}, σ_{SD} combined with possible gamma ray signals may allow map of dark matter distribution in the galaxy
- role of $\bar{p}$, e^+, $\bar{D}$ signals

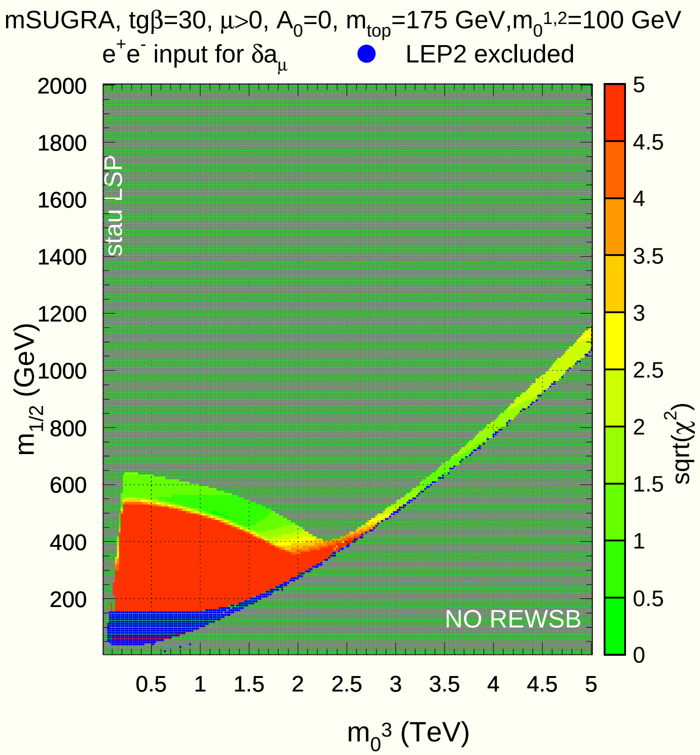
SUGRA models with non-universal scalars

- 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)



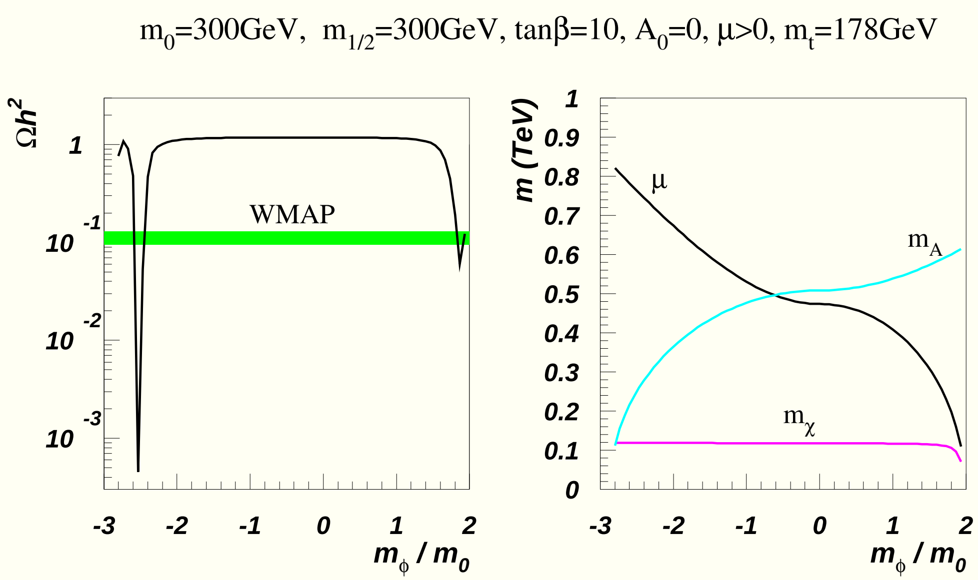
Normal scalar mass hierarchy: parameter space

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



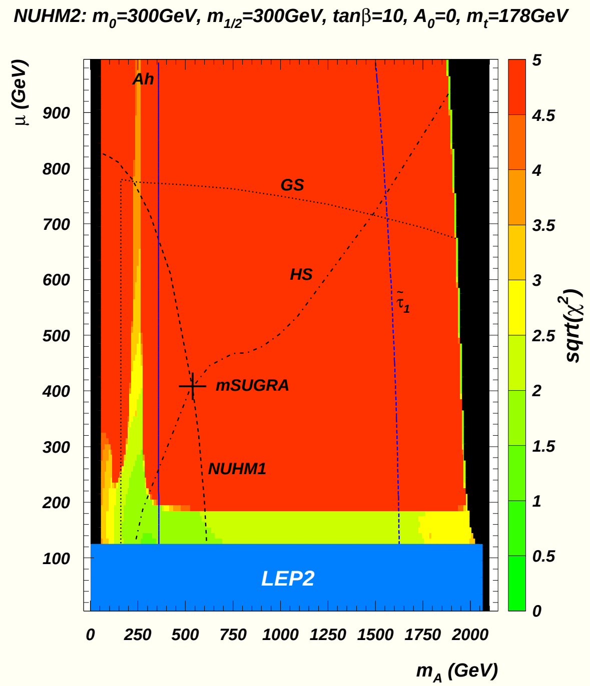
SUGRA models with non-universal Higgs mass (NUHM1)

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



NUHM2 (2-parameter case)

- $m_{H_u}^2 \neq m_{H_d}^2 \neq m_0$: 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 $m_{H_u}^2,\ m_{H_d}^2 \leftrightarrow \mu,\ m_A$ (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)

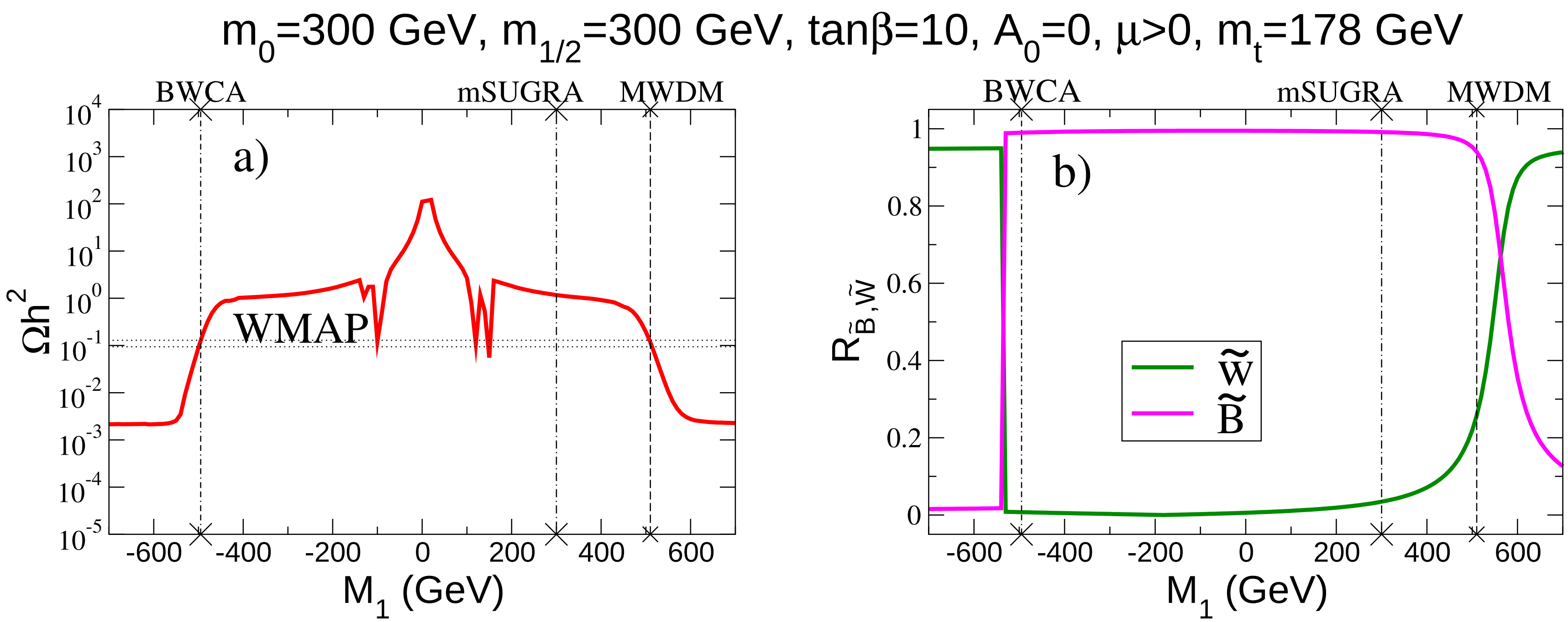
	M_{GUT}			M_Z		
F_h	M_3	M_2	M_1	M_3	M_2	M_1
1	1	1	1	~ 6	~ 2	~ 1
24	2	-3	-1	~ 12	~ -6	~ -1
75	1	3	-5	~ 6	~ 6	~ -5
200	1	2	10	~ 6	~ 4	~ 10

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

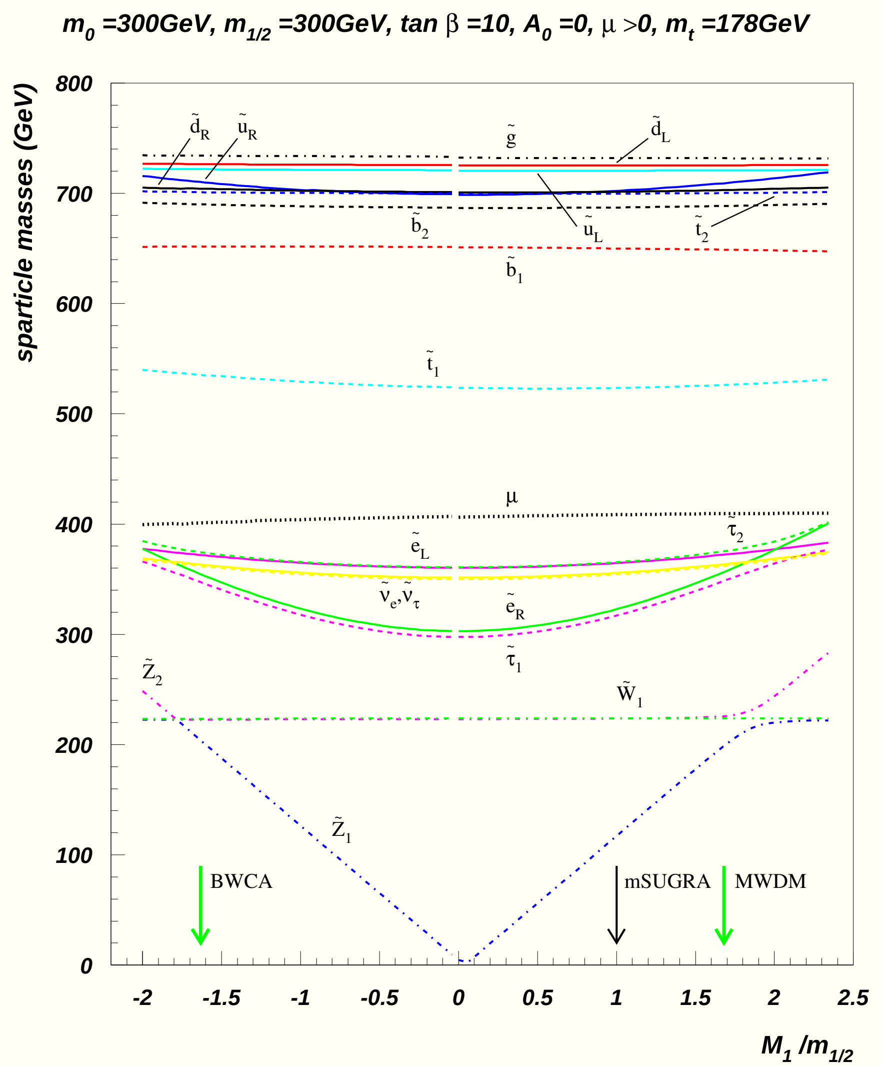
⋆ Extra-dimensional SUSY GUT models where SUSY breaking is communicated from the SUSY breaking brane to the visible brane via gaugino mediation (e.g. Dermisek-Mafi model)

- ⋆ $\cdots$
- ⋆ 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
- ⋆ Large/small M_3 case, see Belanger et al. NPB706, 411 (2005)
- ⋆ 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

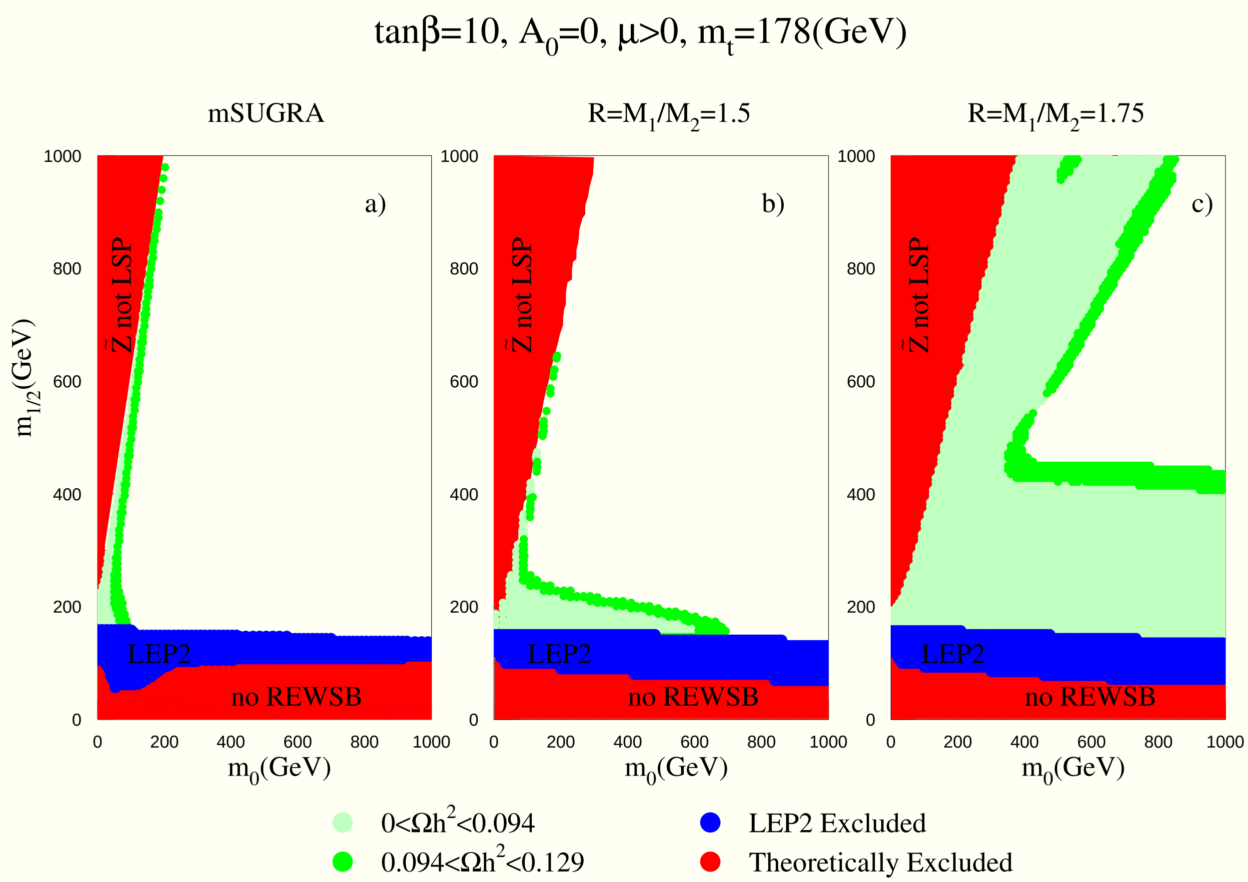
$\Omega_{\widetilde{Z}_1} h^2$ **vs.** M_1



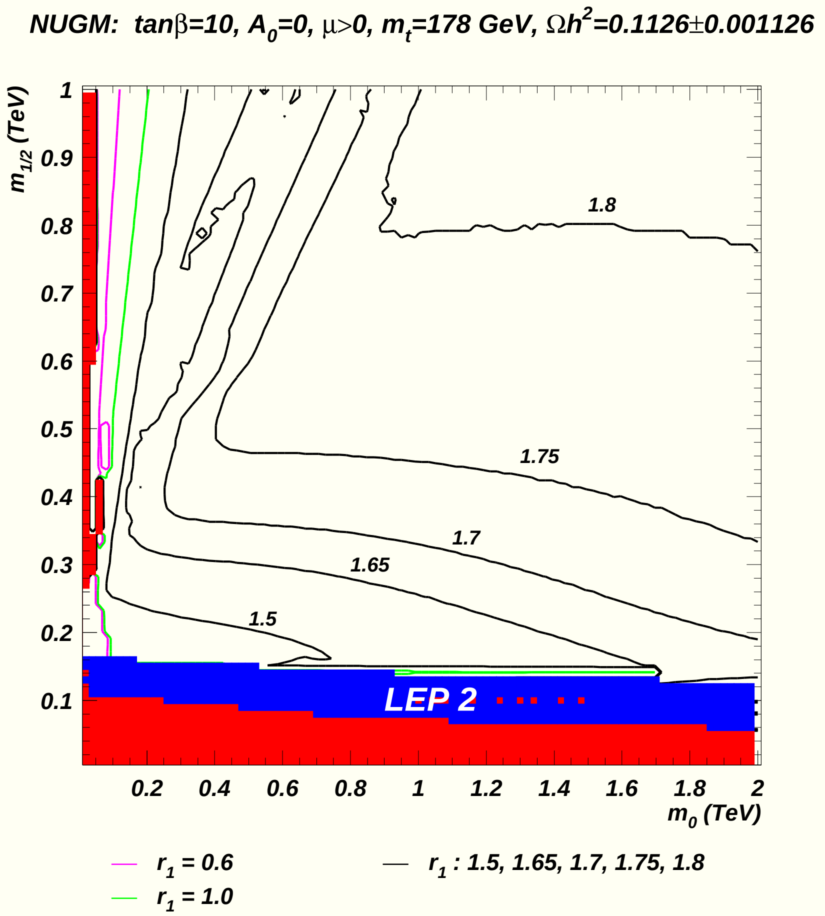
Sparticle mass spectra vs M_1



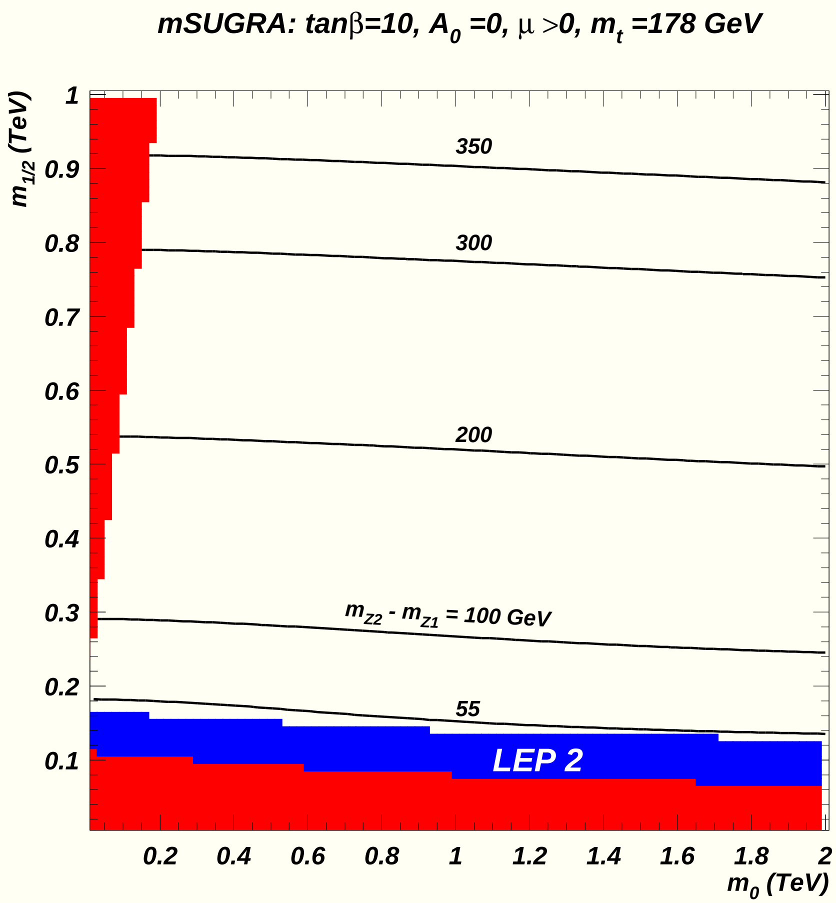
WMAP allowed regions for various M_1/M_2

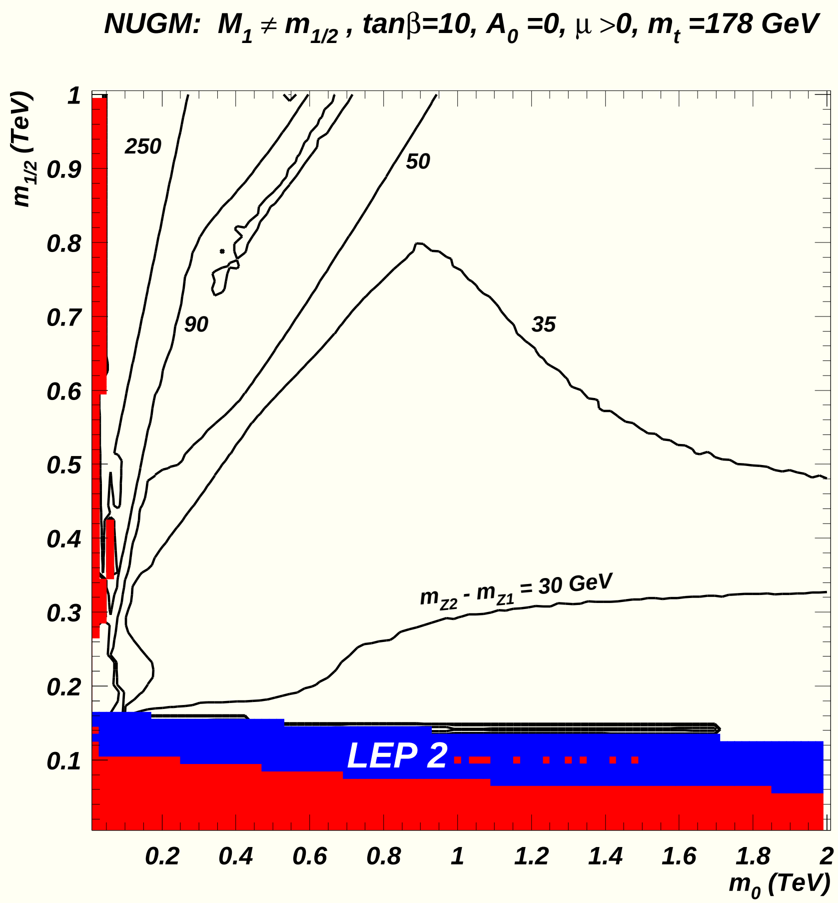


MWDM: *Any* point in m_0-$m_{1/2}$ plane can be WMAP allowed

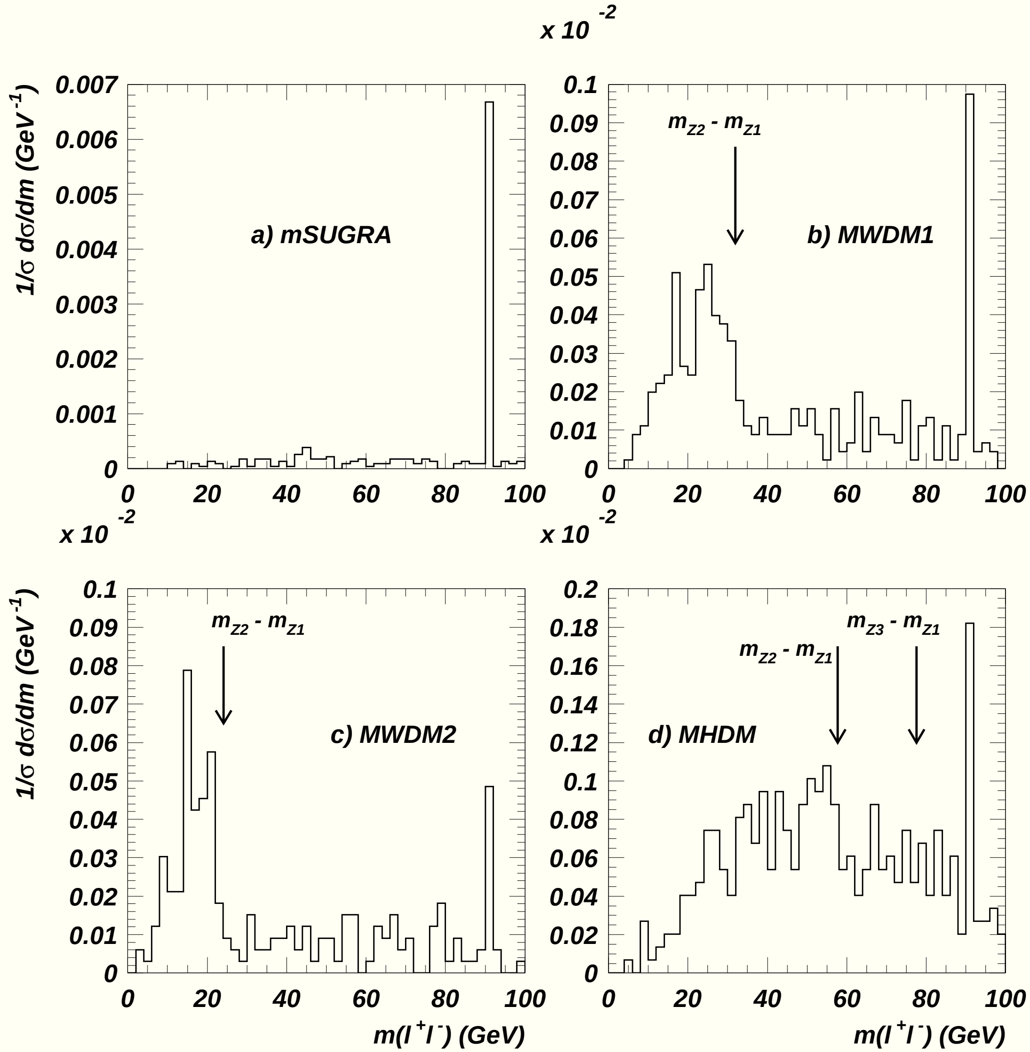


MWDM: small $\widetilde{Z}_2 - \widetilde{Z}_1$ mass gap



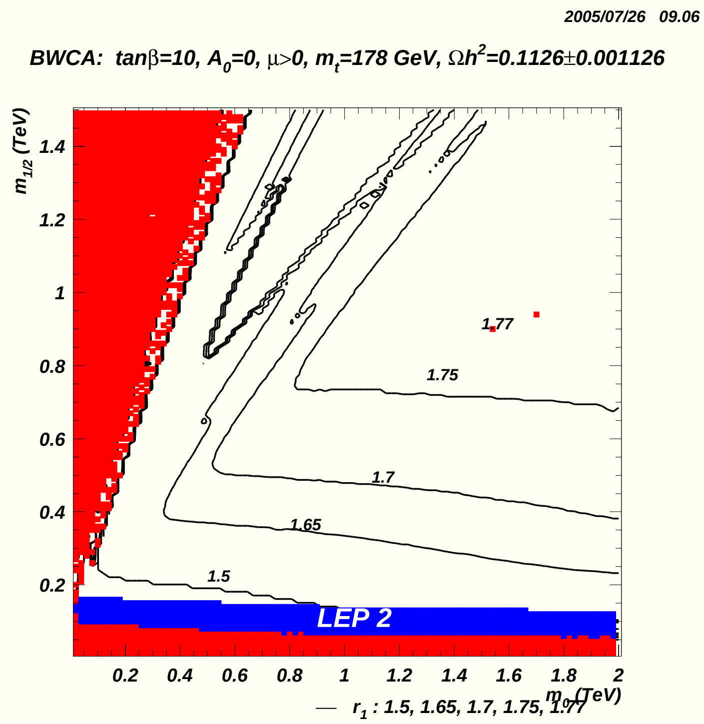


$m(\ell^+\ell^-)$: mass gap observable at LHC for MWDM

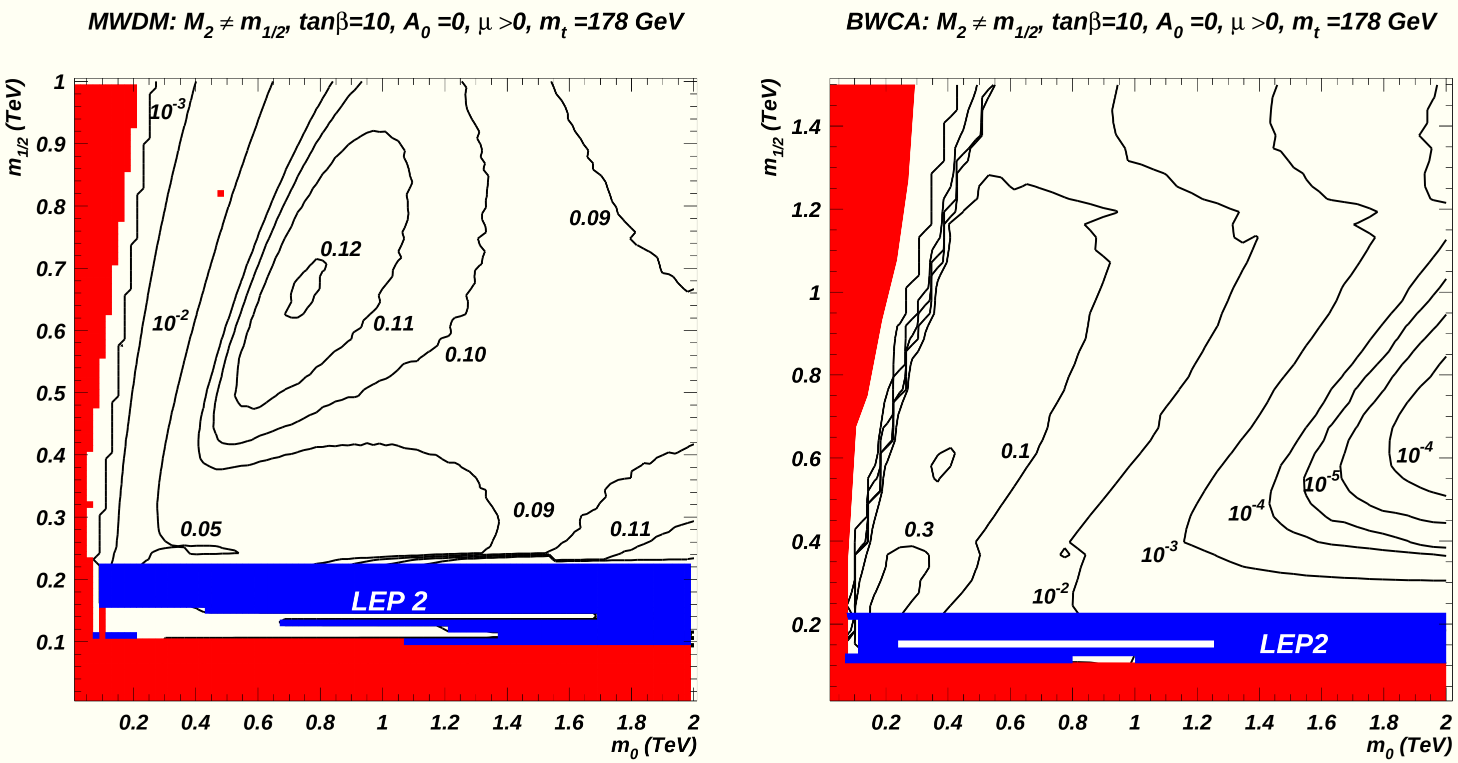


Bino-wino co-annihilation (BWCA) scenario

- 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 $Q = M_{weak}$

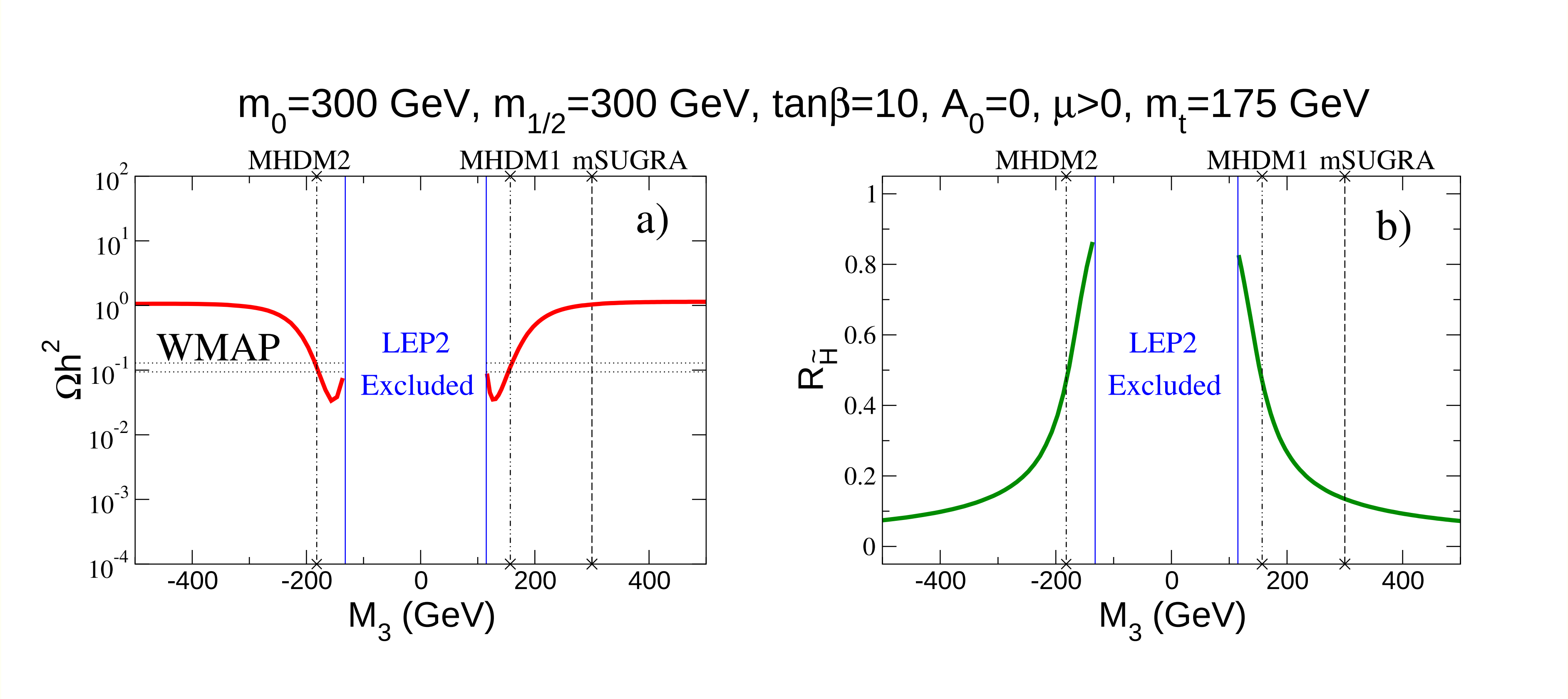


In BWCA at $m_0 \lesssim 500$ GeV, $BF(\widetilde{Z}_2 \to \widetilde{Z}_1\gamma)$ enhanced!



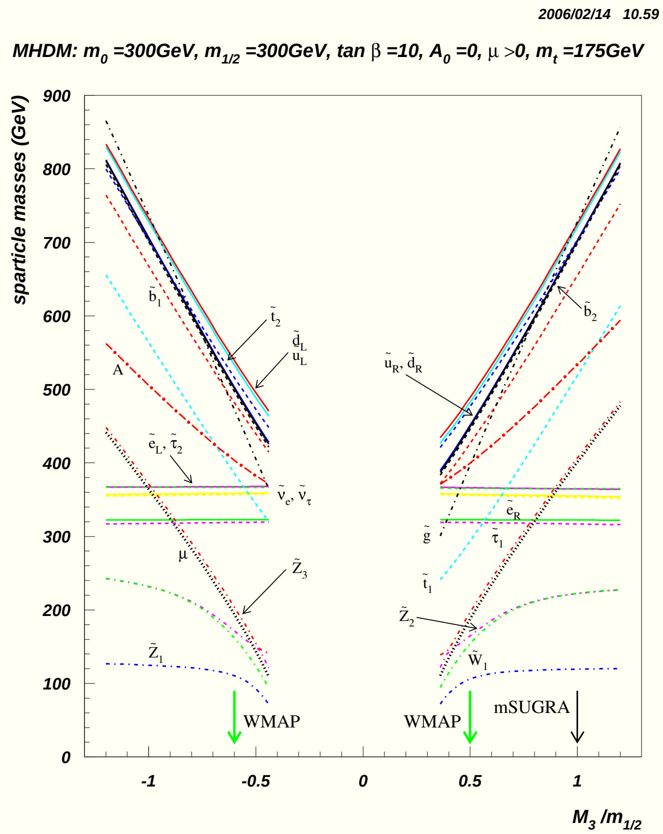
Haber+Wyler; Ambrosanio+Mele; Baer+Krupovnickas: JHEP 0209, 038 (2002)

Mixed higgsino DM from a low M_3 (LM3DM)



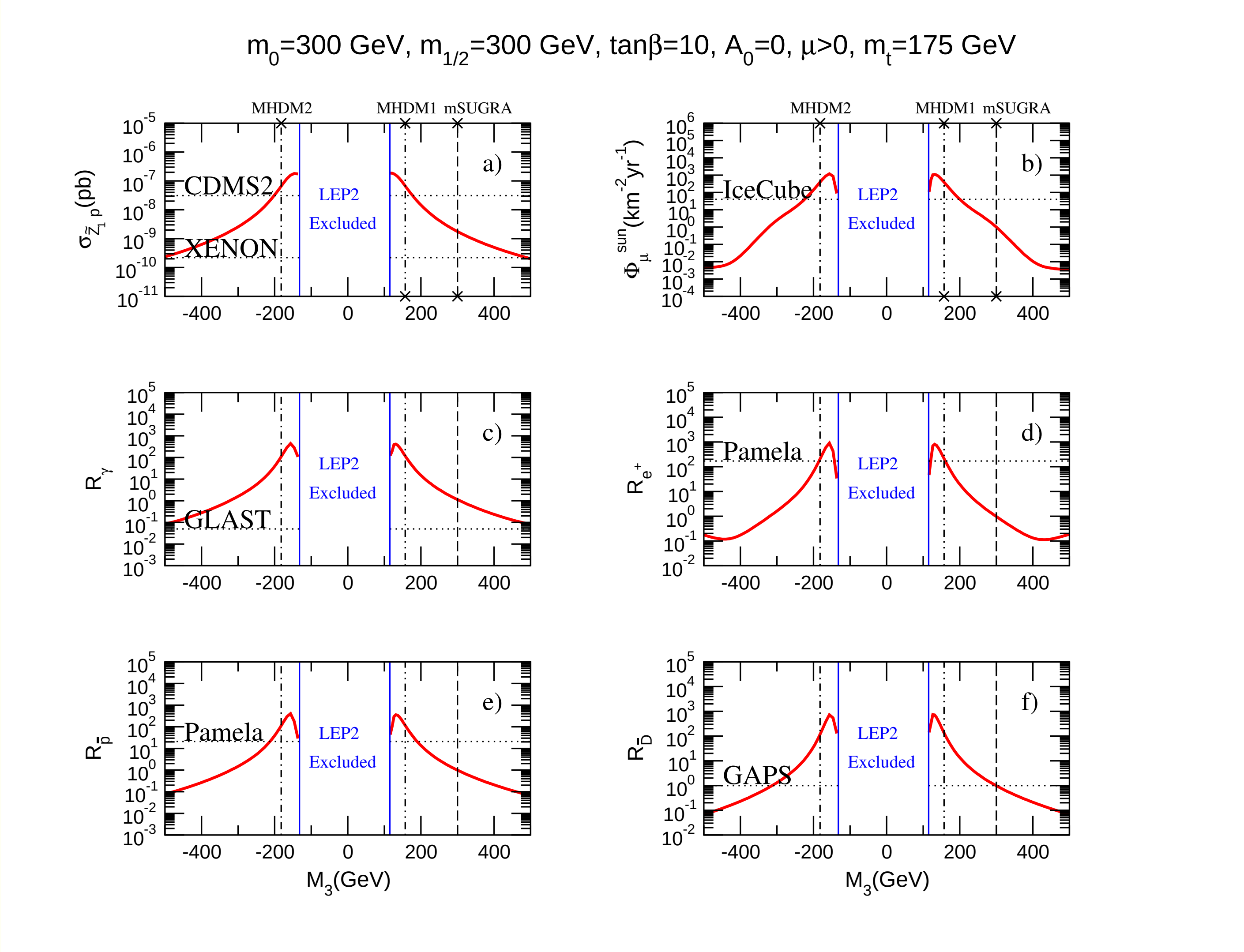
- low $M_3 \Rightarrow$ low $m_{\tilde{g}},\ m_{\tilde{q}},\ \mu$

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



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