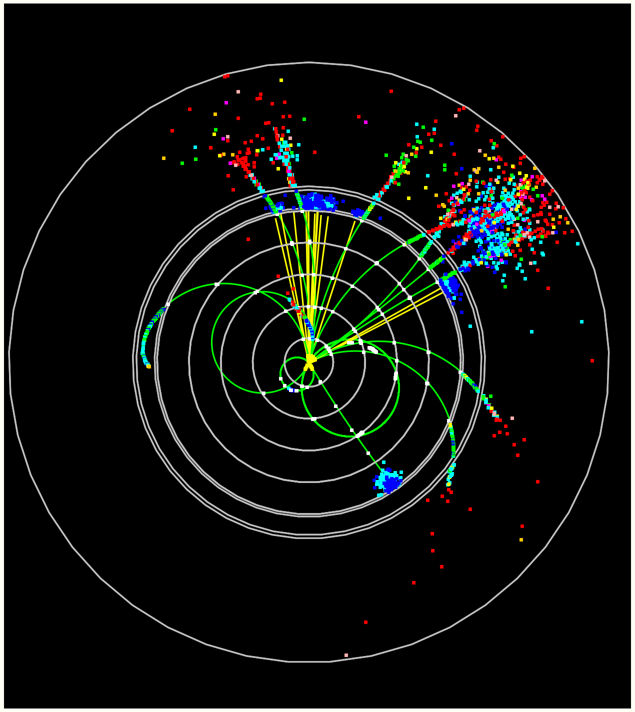
Constraints on SUSY parameters from present data

Howard Baer
Florida State University
ILC-Cosmology working group

- MSSM
- Models of SUSY breaking
- Constraints
- WMAP allowed regions
- Non-universality
- Beyond the MSSM



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 $\Rightarrow$ spontaneous electroweak symmetry breaking:

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

- ⋆ Yukawa interactions $\Rightarrow$ 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 $\eta \sim 10^{-10}$ (matter anti-matter asymmetry)
- cold dark matter
- dark energy

$\Rightarrow$ Note astro/cosmological origin of all discrepancies!

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 $\Rightarrow$ superfields

– fermions $\Rightarrow$ (left) chiral scalar superfields

– gauge fields $\Rightarrow$ 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 (178) 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

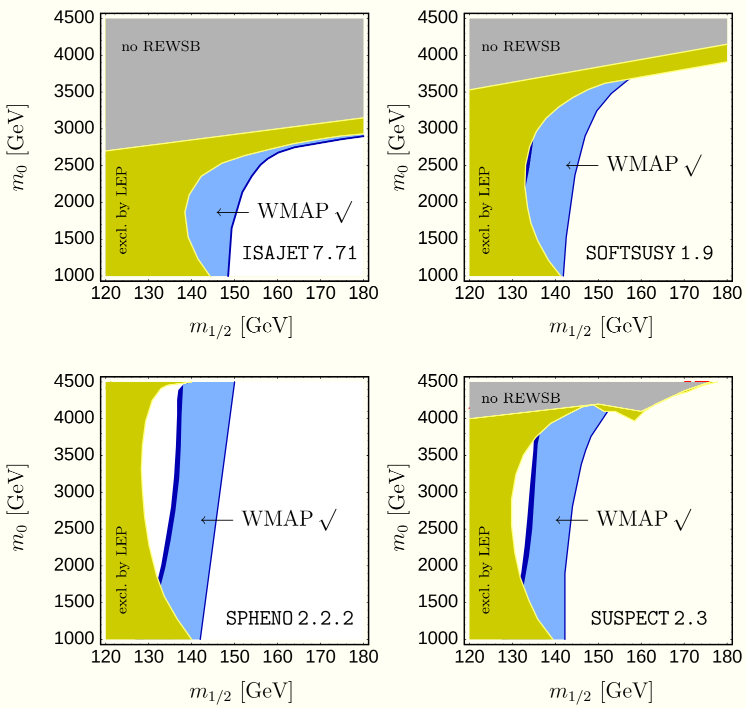
- non-universal scalar masses
- non-universal gaugino masses
- FC soft SUSY breaking terms
- large CP violating phases
- additional fields beyond MSSM below M_{GUT}?
- $\cdots$

Sparticle mass spectra

⋆ Mass spectra codes
- Isajet (HB, Paige, Protopopescu, Tata)
- 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 $\tan\beta \gtrsim 50$

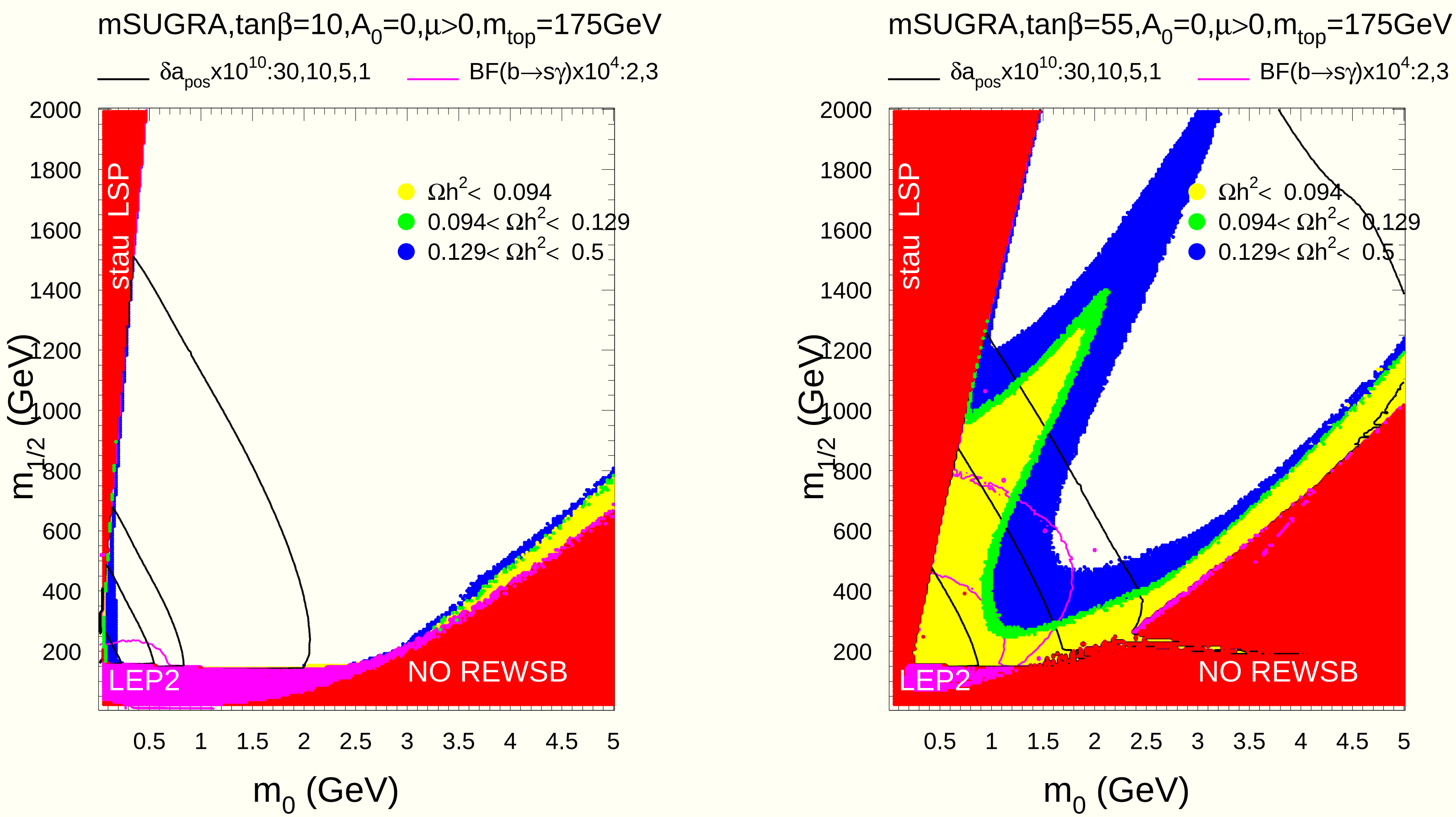
⋆ $\Omega_{CDM} h^2 = 0.113 \pm 0.009$ (WMAP)

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
  - Neutdriver (Jungman; not maintained)
  - DarkSUSY: (Gondolo, Edsjo, Ullio, Bergstrom, Schelke, Baltz)

- Micromegas (Belanger, Boudjema, Pukhov, Semenov)
- IsaRED: (HB, Balazs, Belyaev)
- SSARD: (Ellis, Falk and Olive)
- Drees/ Nojiri code
- Roszkowski code
- Arnowitt/ Nath code
- Lahanas/ Nanopoulos code
- Bottino/ Fornengo *et al.* code
- ...

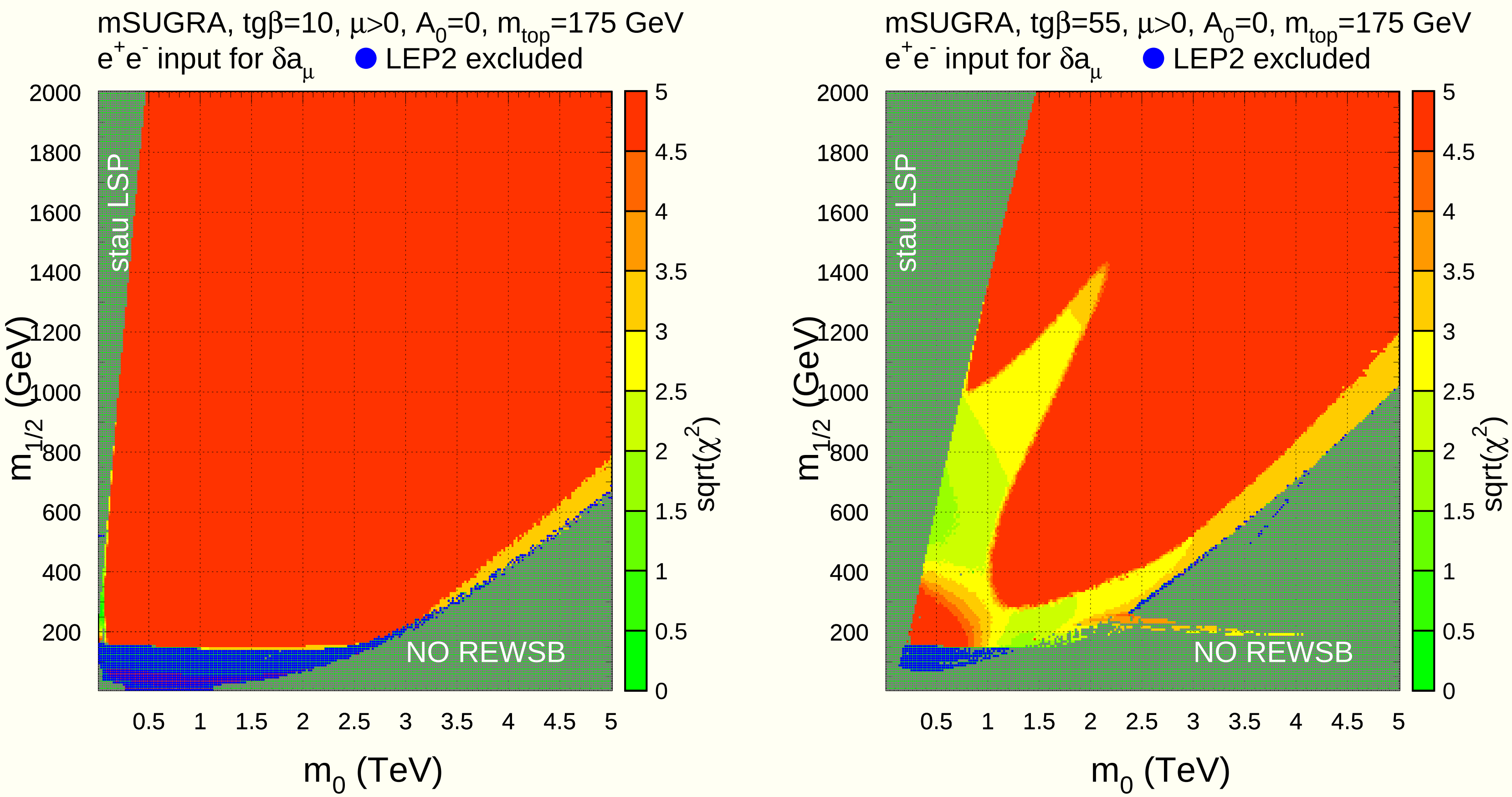
Effect of constraints on mSUGRA model



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 $m_{\tilde{t}_1} \simeq m_{\widetilde{Z}_1}$)

Constraints as χ^2 on mSUGRA model

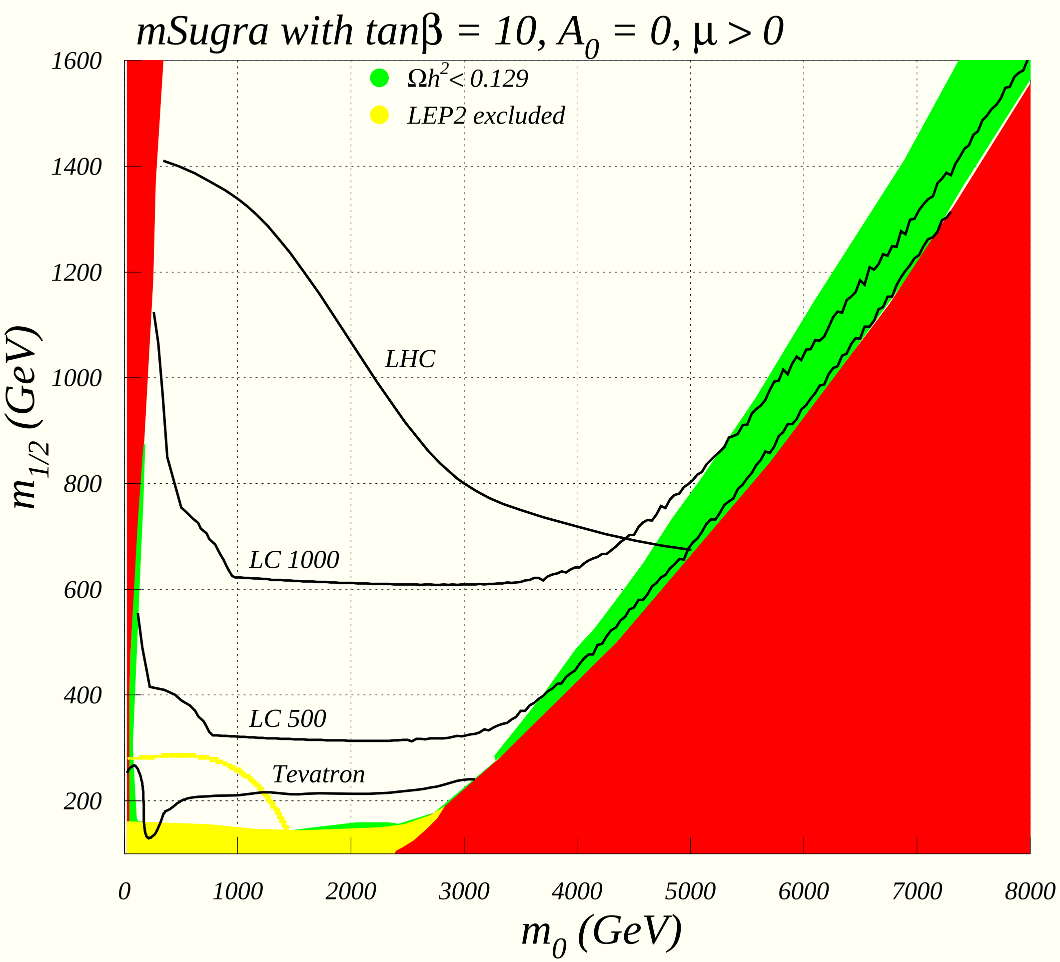


HB, Balazs; HB, Belyaev, Krupovnickas, Mustafayev

ILC-Cosmology group: 4 simulation points

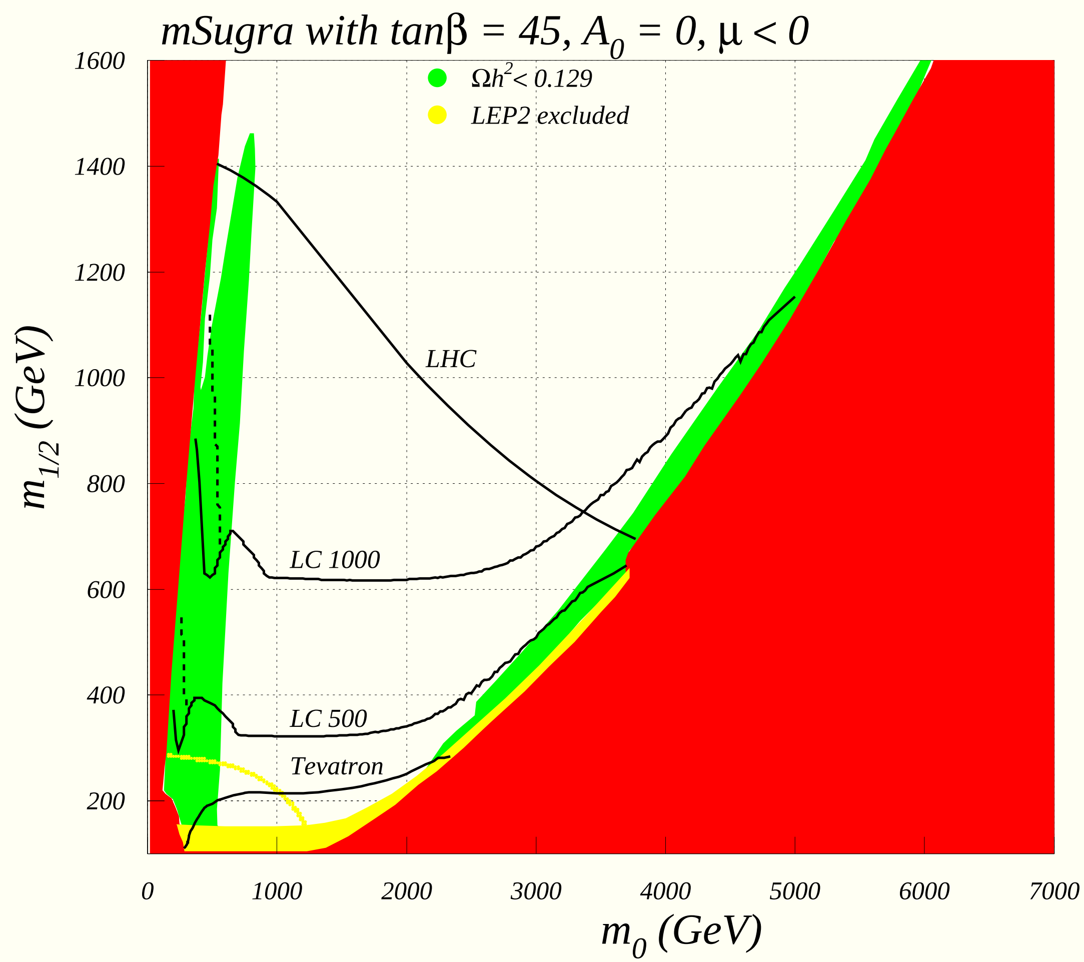
- ⋆ bulk region
  - $(m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sgn(\mu),\ m_t =$ $100\ \mathrm{GeV},\ 250\ \mathrm{GeV},\ -100\ \mathrm{GeV},\ 10,\ +1,\ 178)$
- ⋆ HB/FP region
  - $(m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sgn(\mu),\ m_t =$ $3280\ \mathrm{GeV},\ 300\ \mathrm{GeV},\ 0,\ 10,\ +1,\ 175\ )$
- ⋆ $\tilde{\tau}$ co-ann. region
  - $(m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sgn(\mu),\ m_t =$ $210\ \mathrm{GeV},\ 360\ \mathrm{GeV},\ 0,\ 40,\ +1,\ 178\ )$
- ⋆ A funnel
  - $(m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sgn(\mu),\ m_t =$ $380\ \mathrm{GeV},\ 420\ \mathrm{GeV},\ 0,\ 53,\ +1,\ 178\ )$
- ⋆ Results: see talks by Battaglia, Alexander, Peskin

Sparticle reach of all colliders and relic density



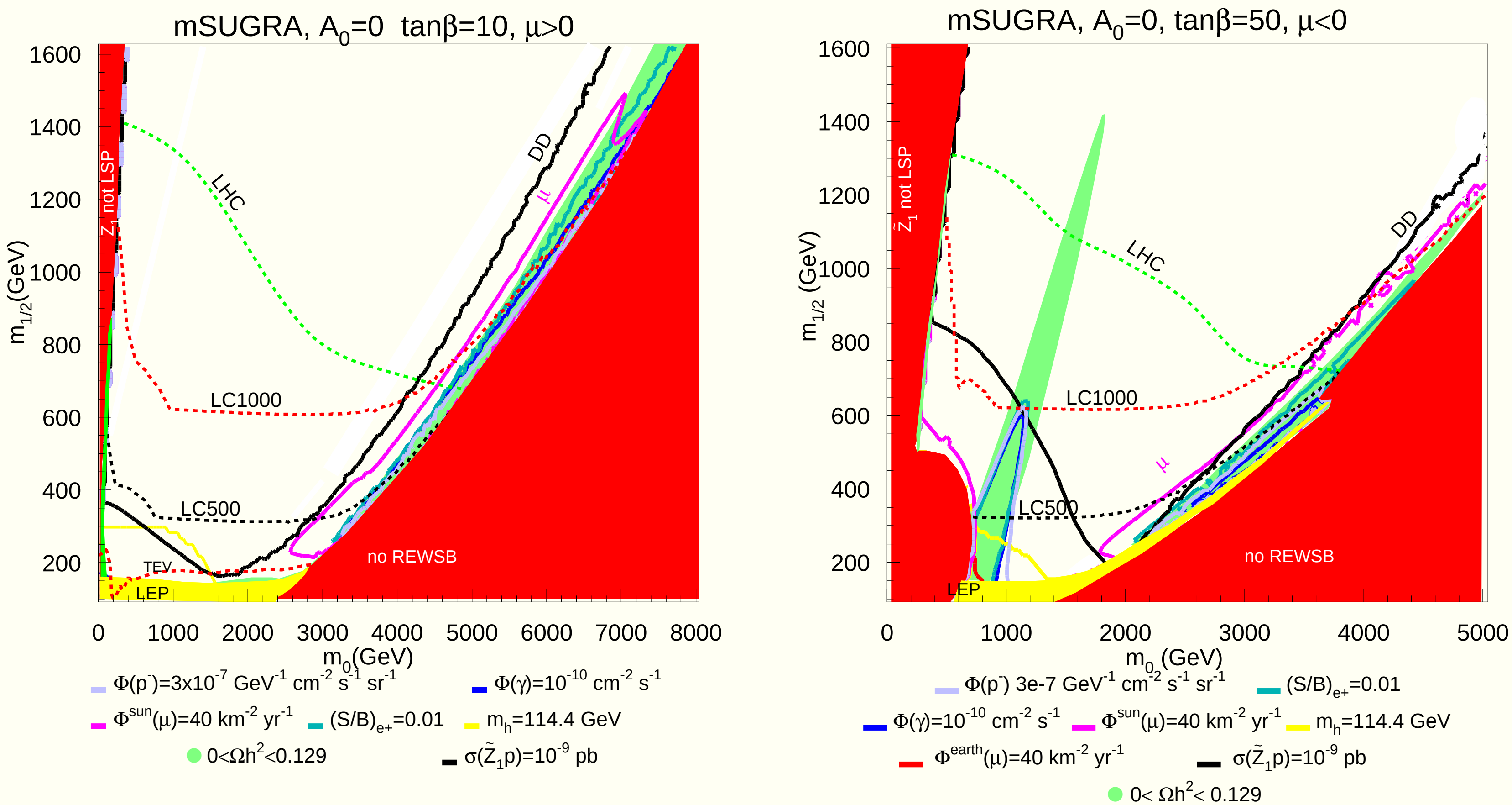
HB, Belyaev, Krupovnickas, Tata

Sparticle reach of all colliders and relic density



HB, Belyaev, Krupovnickas, Tata

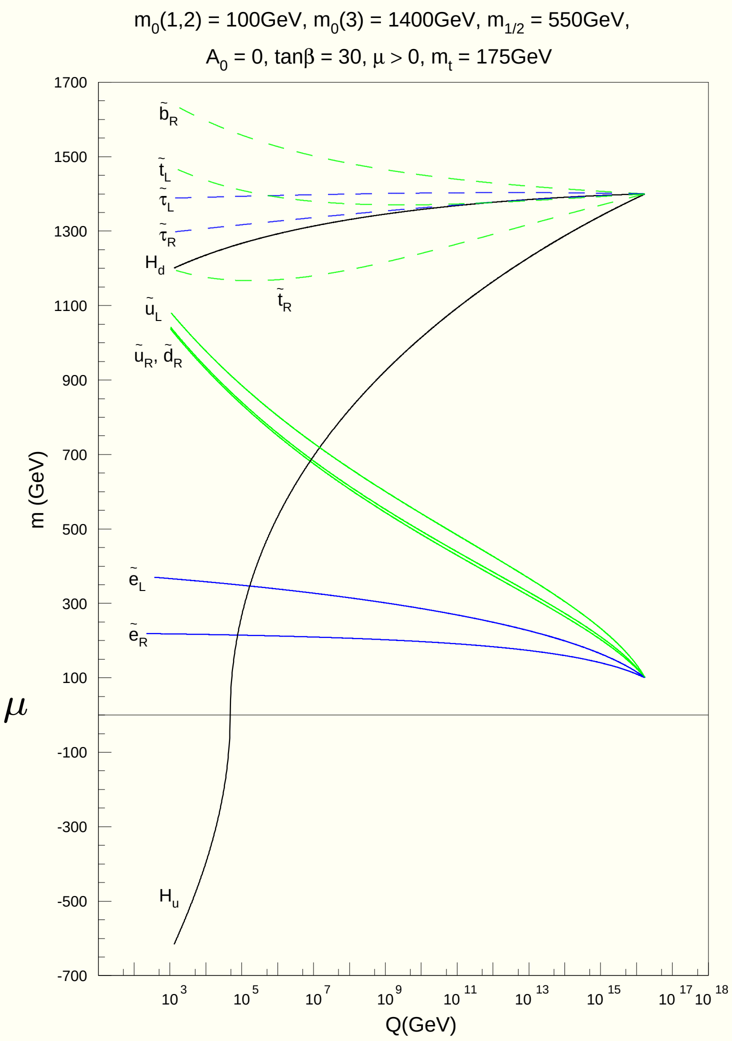
Direct and indirect detection of neutralino DM



HB, Belyaev, Krupovnickas, O'Farrill

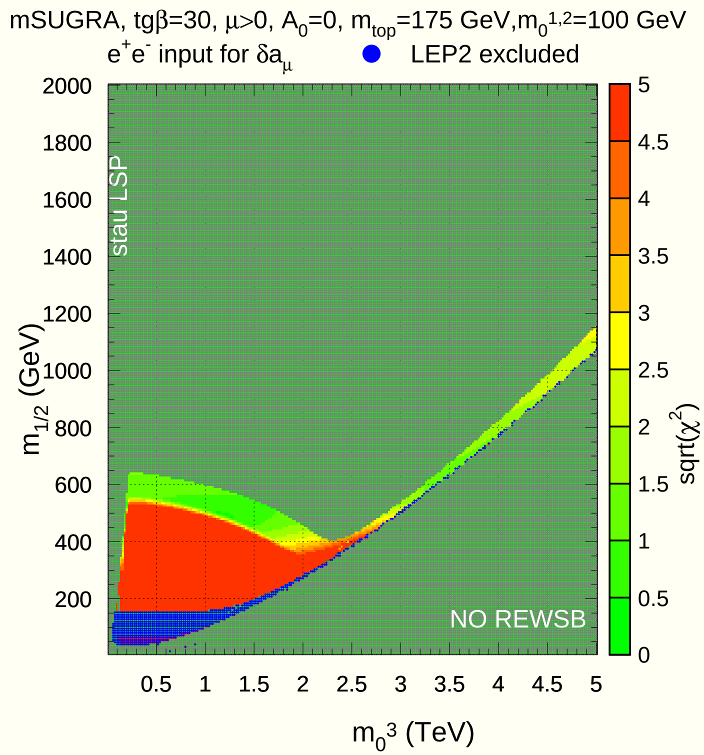
SUGRA models with non-universal scalars

- Normal scalar mass hierarchy (NMH):
  - HB, Belyaev, Krupovnickas, Mustafayev
- $BF(b \to s\gamma)$ 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 $(g-2)_\mu$



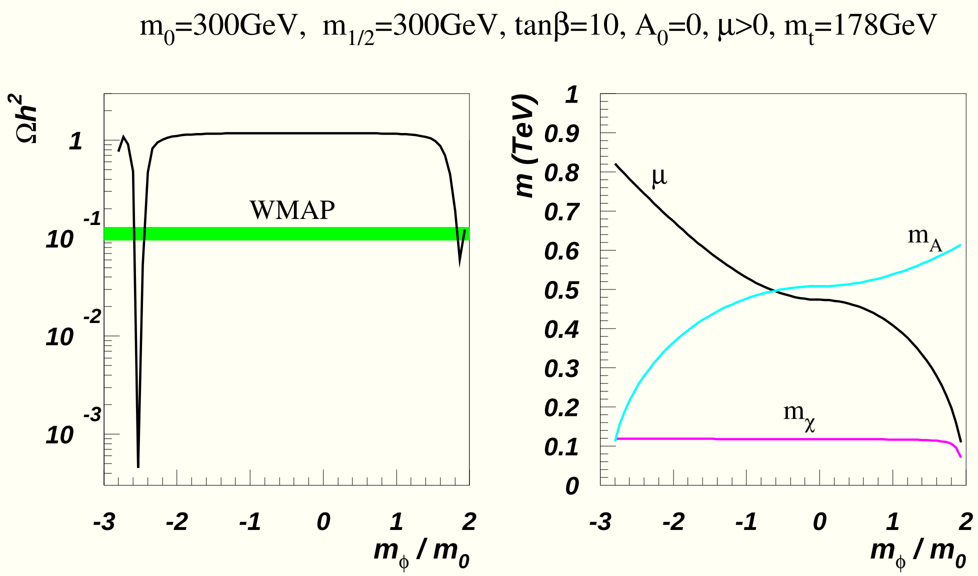
Normal scalar mass hierarchy: parameter space

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



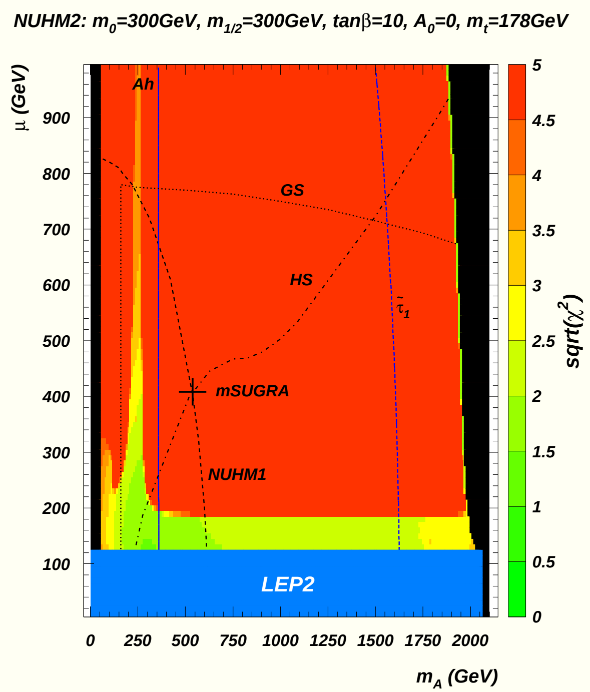
SUGRA models with non-universal Higgs mass (NUHM1)

- $m_{H_u}^2 = m_{H_d}^2 \equiv m_\phi^2 \neq m_0$: 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 $\tan\beta$



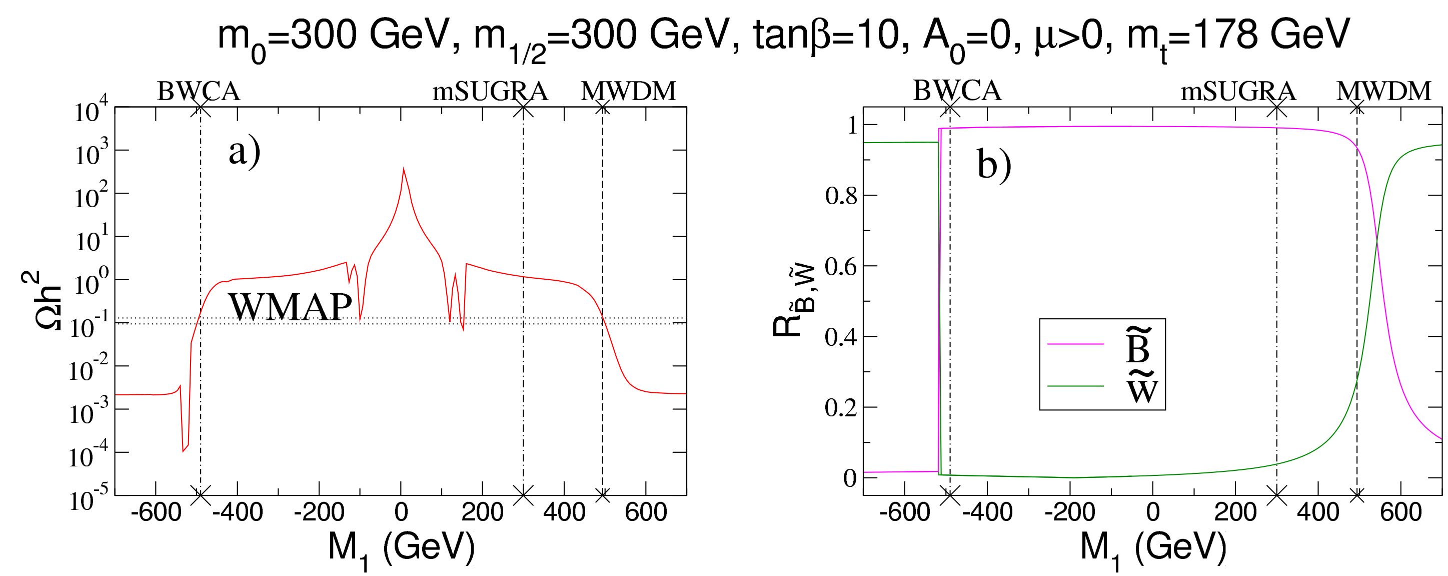
NUHM2 (2-parameter case)

- $m_{H_u}^2 \neq m_{H_d}^2 \neq m_0$: 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, $m_{\tilde{e}_L} < m_{\tilde{e}_R}$



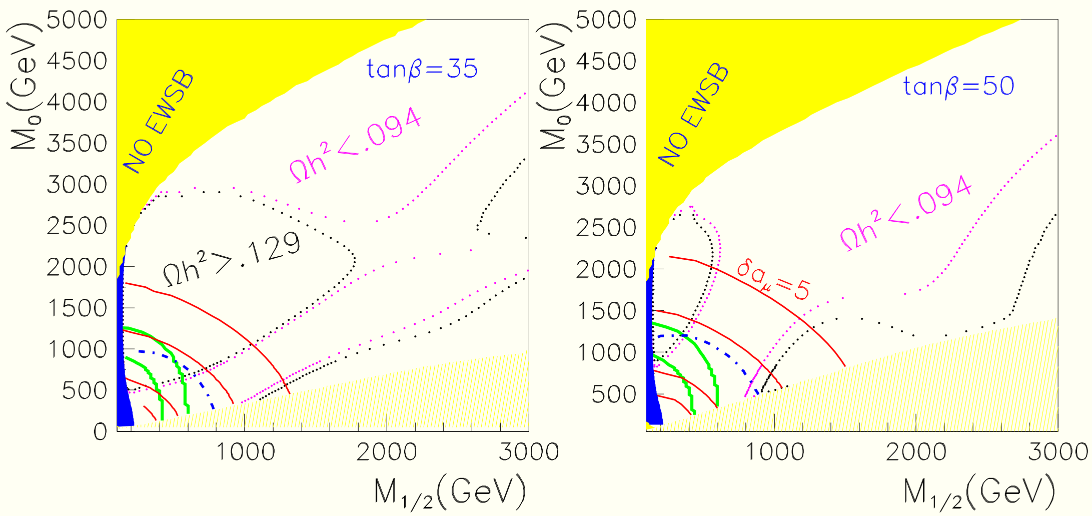
Gaugino mass non-universality

- $M_1 \neq M_2 \neq M_3$: HB, Krupovnickas, Mustafayev, Park, Profumo, Tata
- motivation: SUSYGUTs where gauge kinetic function transforms non-trivially
- $M_2 \sim M_1$ at M_{GUT}: mixed wino dark matter (MWDM)
- $M_2 \simeq -M_1$ at M_{GUT}: bino-wino co-annihilation (BWCA)



Gaugino mass non-universality: low M_3 case

- $M_3 = \frac{1}{2}M_2 = \frac{1}{2}M_1$
- lower $M_3 \Rightarrow$ small μ so higgsino-enhanced annihilation rates $\Rightarrow$ lower $\Omega_{\widetilde{Z}_1}h^2$

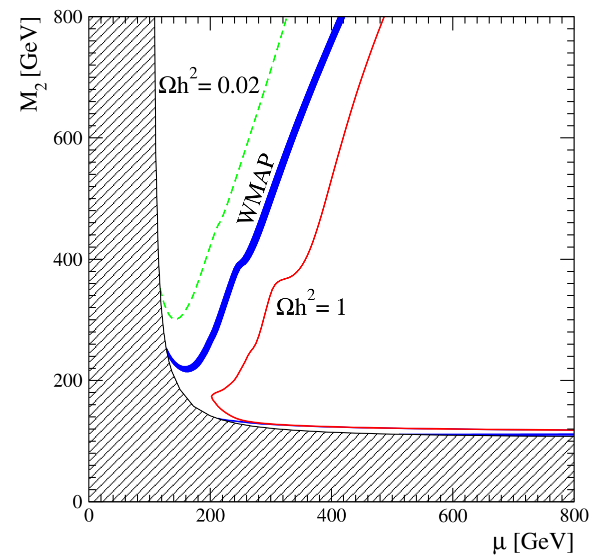


Belanger, Boudjema, Cottrant, Pukhov, Semenov

SUGRA models beyond MSSM: NMSSM

⋆ Add extra singlet SF $\hat{S}$

- motivation: introduce μ parameter via SUSY breaking
- 3 neutral scalar higgs, 2 pseudoscalars and 5 neutralinos



Belanger, Boudjema, Hugonie, Pukhov, Semenov; Ellwanger, Gunion, Hugonie

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 mass hierarchy
  - NUHM1, NUHM2 models
  - gaugino mass non-universality: MWDM, BWCA, low M_3
- ⋆ Beyond MSSM? e.g. NMSSM

If weak scale SUSY exists, ILC will be critical tool
and provide a window to GUT/Planck scale physics