Neutralino Dark Matter and the ILC

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Outline

- ⋆ WMAP constraint: $\Omega_{CDM}h^2 = 0.1126 \pm 0.0090$
- ⋆ SUSY spectrum evaluation
- ⋆ Evaluation of relic density
- ⋆ χ^2 plots of mSUGRA parameter space
  - reach of Tevatron, LHC, ILC
- ⋆ Direct and indirect DM detection
  - $\sigma(\widetilde{Z}_1 p)$
  - $\widetilde{Z}_1\widetilde{Z}_1 \to f\bar{f},\ WW, \cdots \to \nu_\mu \to \mu$
  - detection of γs, e^+s, $\bar{p}$s, anti-d's

Generation of sparticle mass spectrum

- ⋆ Generate sparticle mass spectrum
  - Isajet 7.72
  - SuSpect
  - SoftSUSY
  - Spheno
  - Latest comparison: see Belanger, Kraml and Pukhov, hep-ph/0502079.
- ⋆ Isajet features:
  - two-loop RGE running
  - RG-improved 1-loop eff. pot'l: opt. scale choice $\Rightarrow$ dom. two-loop terms
  - complete sparticle mass radiative corrections
- ⋆ Models: min+non-min SUGRA, AMSB, GMSBm, SUGRA+RHN

Neutralino relic density

- Must solve Boltzmann eq'n for neutralino number density in FRW universe
- Central part of calculation: evaluate thermally averaged neutralino-neutralino annihilation cross section times velocity
- Previously, HB, Brhlik used fully relativistic formulation by Gondolo/Gelmini to obtain proper relic density in vicinity of s-channel annihilation poles; h, Z, A and H
- Importance of co-annihilation stressed by Griest (chargino-neutralino), Ellis, Olive, Falk (neutralino-stau)
- Thus, we have recalculated relic density using Edsjo/Gondolo relativistic thermal averaging which has been generalized to include co-annihilations
- > 2000 annihilation/coannihilation subprocesses including > 8000 Feynman diagrams evaluated using CompHEP

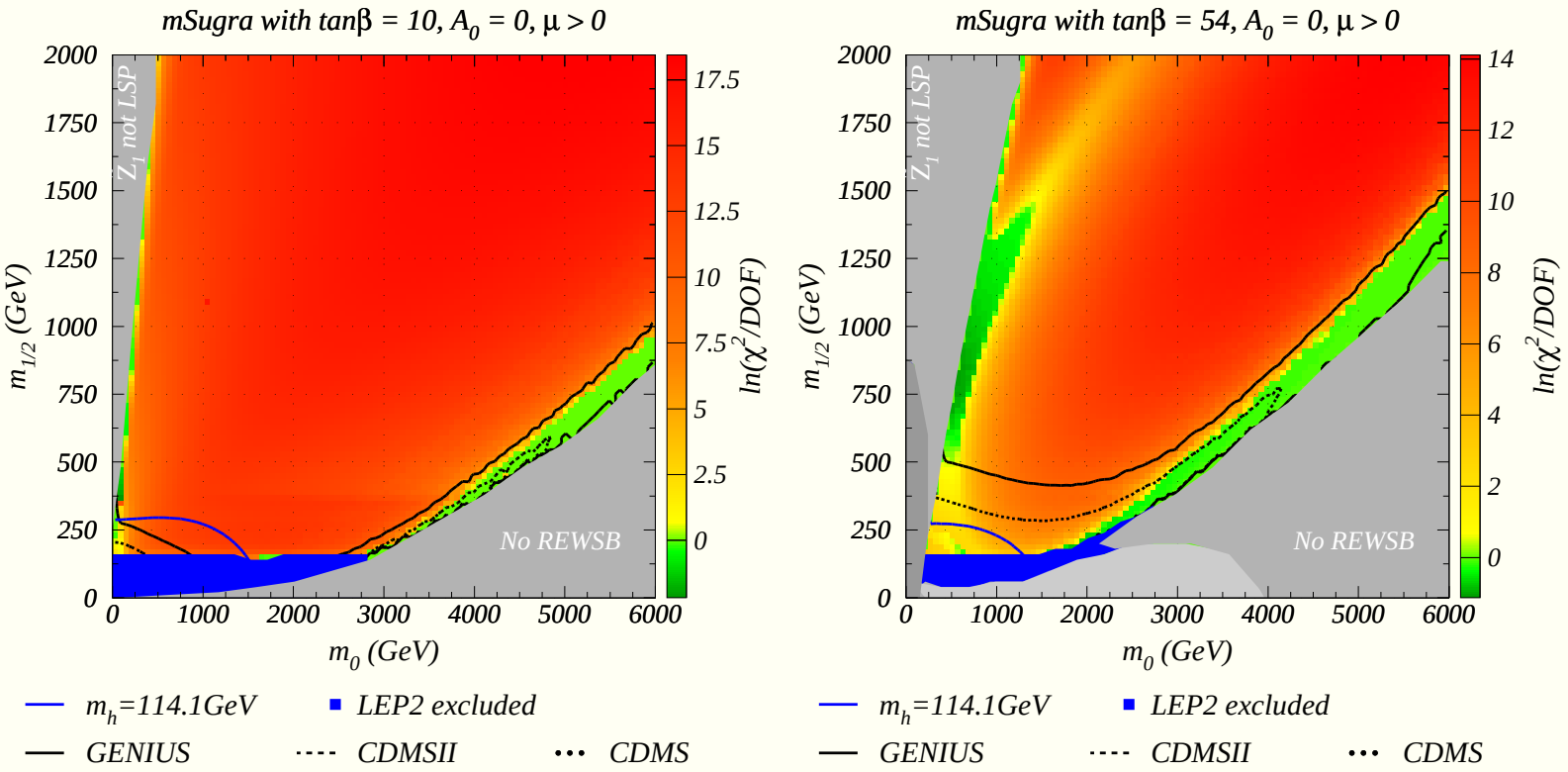
Relic density codes

- DarkSUSY (Gondolo et al.)
- Micromegas (Belanger et al.)
- IsaReD (Baer/Belyaev)
- Neutdriver (Jungman; not maintained)
- SSARD: (Ellis, Falk and Olive)
- Drees/Nojiri code
- Roszkowski code
- Arnowitt/Nath code
- Lahanas/nanopoulos code
- Bottino/Fornengo et al. code
- ...

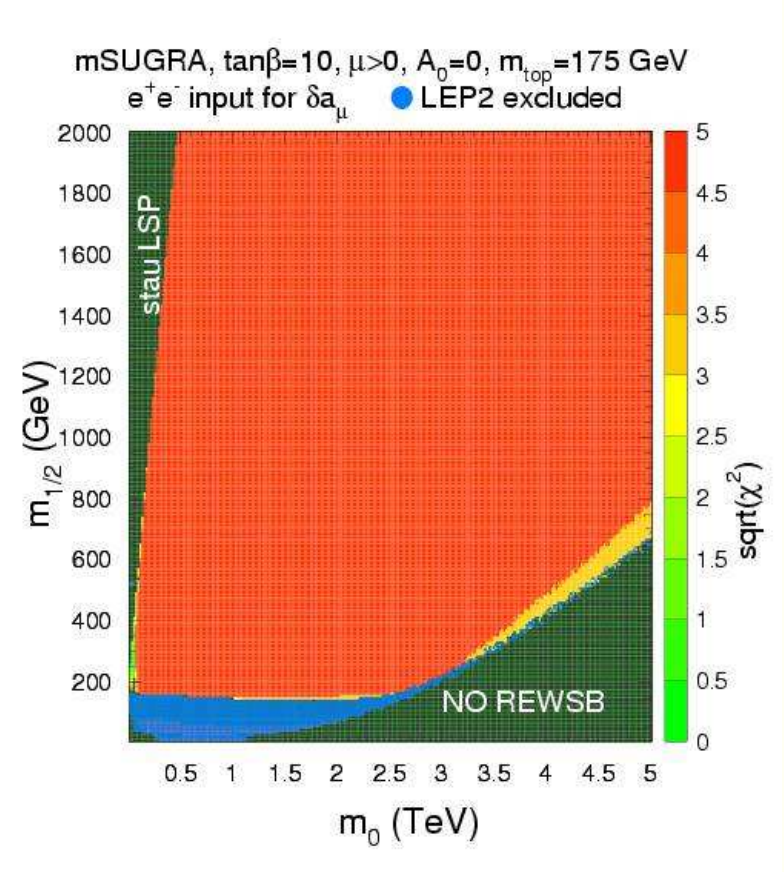
From Ωh^2, $BF(b \to s\gamma)$, Δa_μ, compute χ^2

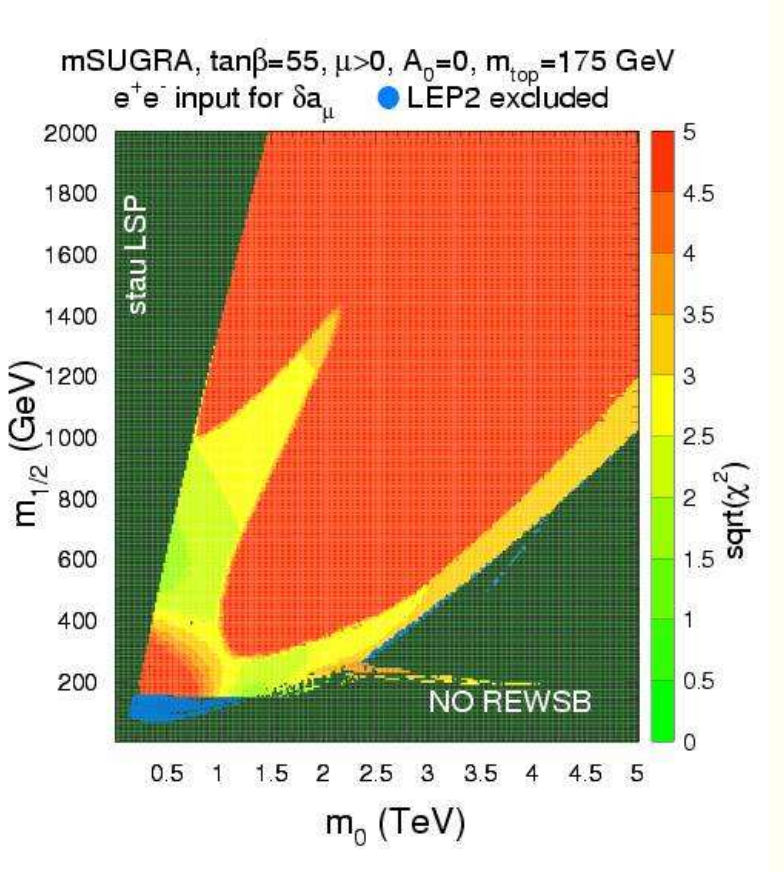
- calculate χ^2, plot in mSUGRA parameter space HB, Balazs
- allowed regions
  - stau co-annihilation (Ellis, Falk, Olive; Arnowitt, Dutta, Santoso)
  - HB/FP (Chan, Chattopadyay, Nath; Feng, Matchev, Moroi; HB, Brhlik)
  - A-annihilation funnel (Drees, Nojiri; HB, Brhlik)
  - "bulk" region at low m_0, $m_{1/2}$ disfavored (LEP2, $b \to s\gamma$, $(g-2)_\mu$)
  - light Higgs h corridor at low $m_{1/2}$ (Arnowitt, Nath)
  - other co-annihilations *e.g.* $\widetilde{Z}_1\tilde{t}_1$, etc.
- See also Ellis, Olive, Santoso and Spanos; Lahanas, Mavromatos, Nanopoulos; Chattopadhyay, Corsetti, Nath; Roskowski, Ruiz de Austri, Nihei; Bottino, Donato, Fornengo, Scopel; Drees, Djouadi, Kneur; Bednyakov, Klapdor-Kelingrothaus and Kovalenko; Accomando, Arnowitt, Dutta, Santoso; Edsjo, Gondolo, Schelke, Ulio; Gomez, Vergados; Corsetti, Nath; $\cdots$

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



Results of χ^2 fit using e^+e^- data for a_μ :





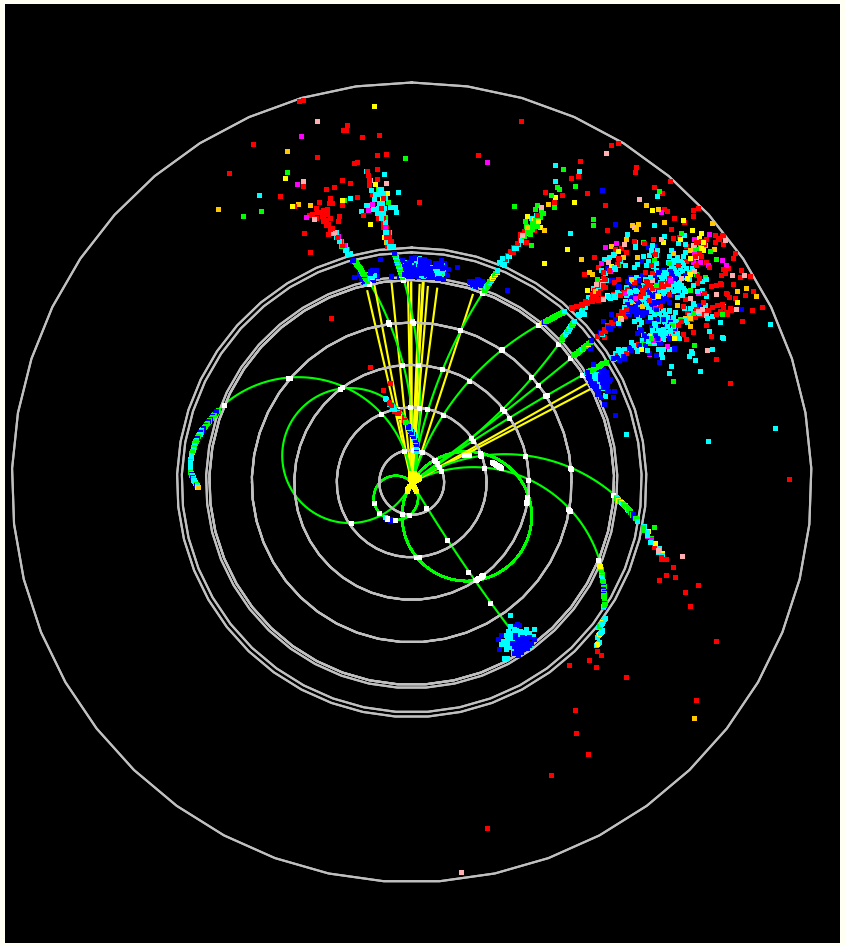
Search for SUSY at colliders

- ⋆ Fermilab Tevatron: $p\bar{p}$ collider; $\sqrt{s} = 2$ TeV; $2 - 10$ fb^{-1}; currently running
  - HB, Krupovnickas and Tata; JHEP**07**, 020 (2003).
- ⋆ CERN LHC: pp collider; $\sqrt{s} = 14$ TeV; 100-300 fb^{-1}; start-up, 2007?
  - HB, C. Balazs, A. Belyaev, Krupovnickas and Tata; JHEP**06**, 054 (2003).
- ⋆ linear e^+e^- collider: $\sqrt{s} = 0.5 - 1$ TeV; 100-300 fb^{-1};pending, 2015-2020?
  - HB, A. Belyaev, Krupovnickas and Tata; JHEP**02**, 007 (2004).

Isajet v7.72 for sparticle event generation

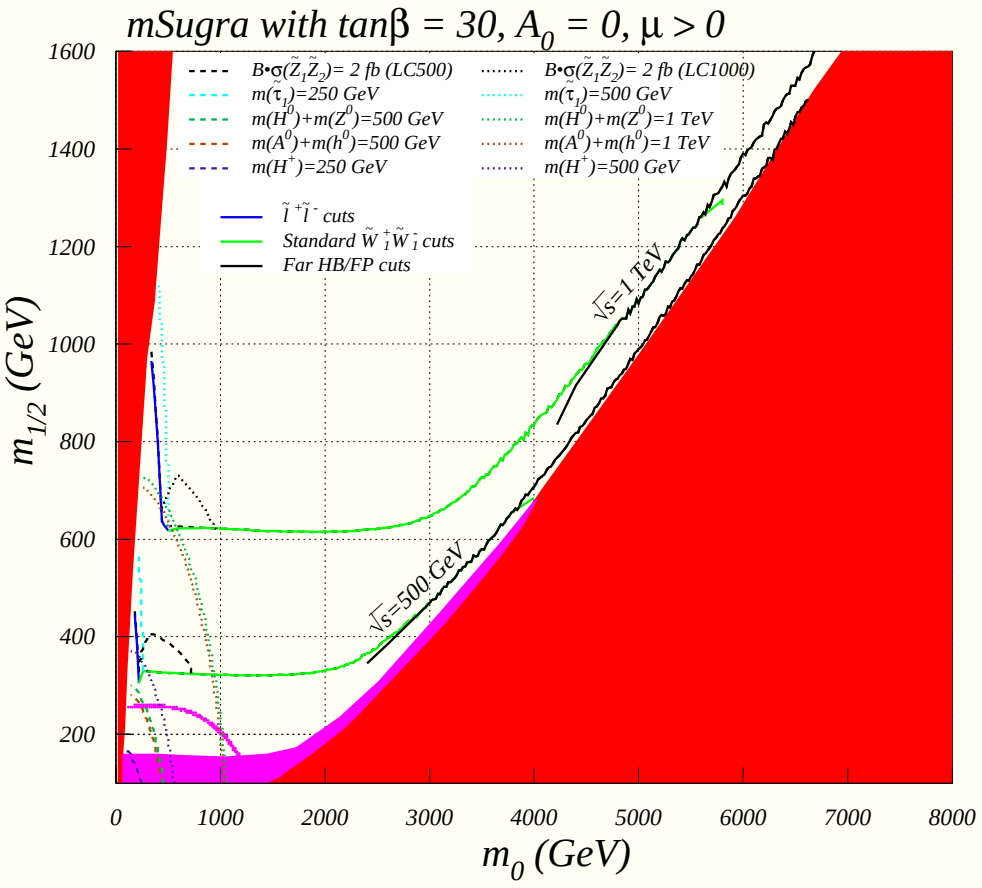
- ⋆ Isajet (1979), by F. Paige and S. Protopopescu
- ⋆ Isajet 7.0 (1993) -7.69: FP, SP, HB and X. Tata
  - Isasugra subprogram: SUGRA models (and others)⇒ sparticle masses, mixings, decay rates
- ⋆ SUSY and SM event generation for hadron colliders
- ⋆ e^+e^- colliders
  - polarized beams
  - bremsstrahlung/ beamstrahlung (Peskin solution)
  - added $\gamma\gamma \to f\bar{f}$ processes
  - 3-body decay MEs
  - decays to (polarized) τs; τ-decay MEs

Chargino pair production at e^+e^- linear collider



- Thx to N. Graf

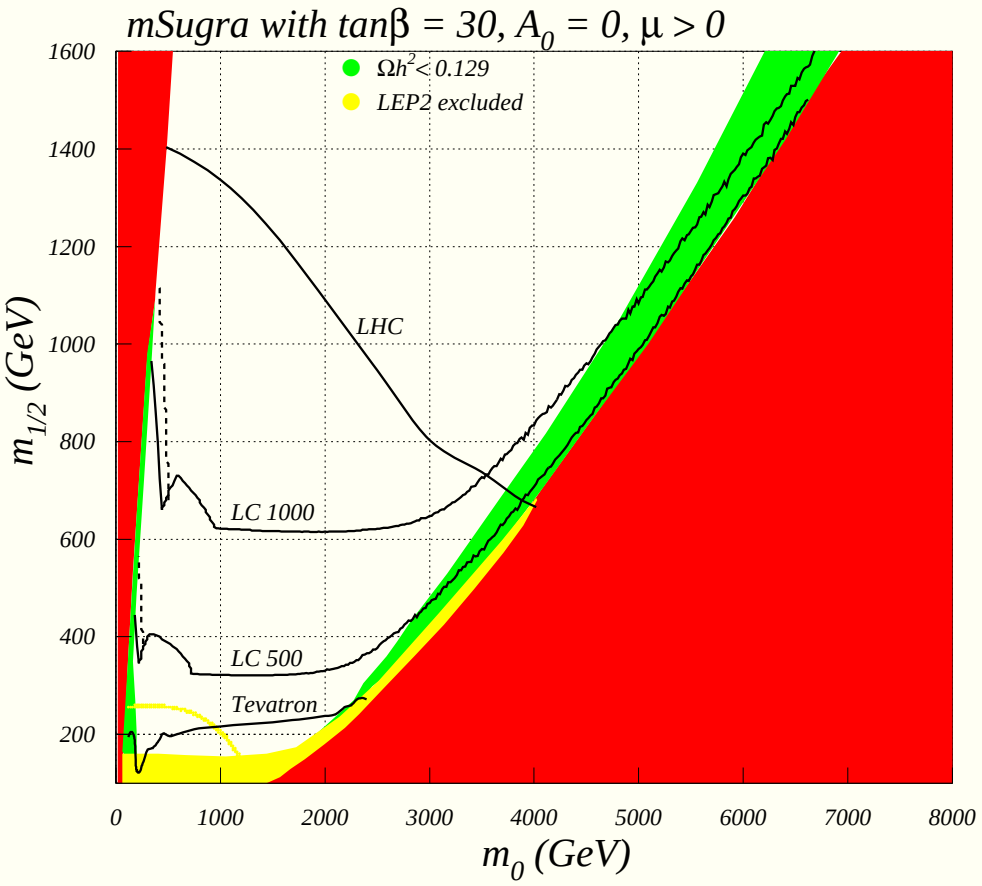
Evaluate reach of LC



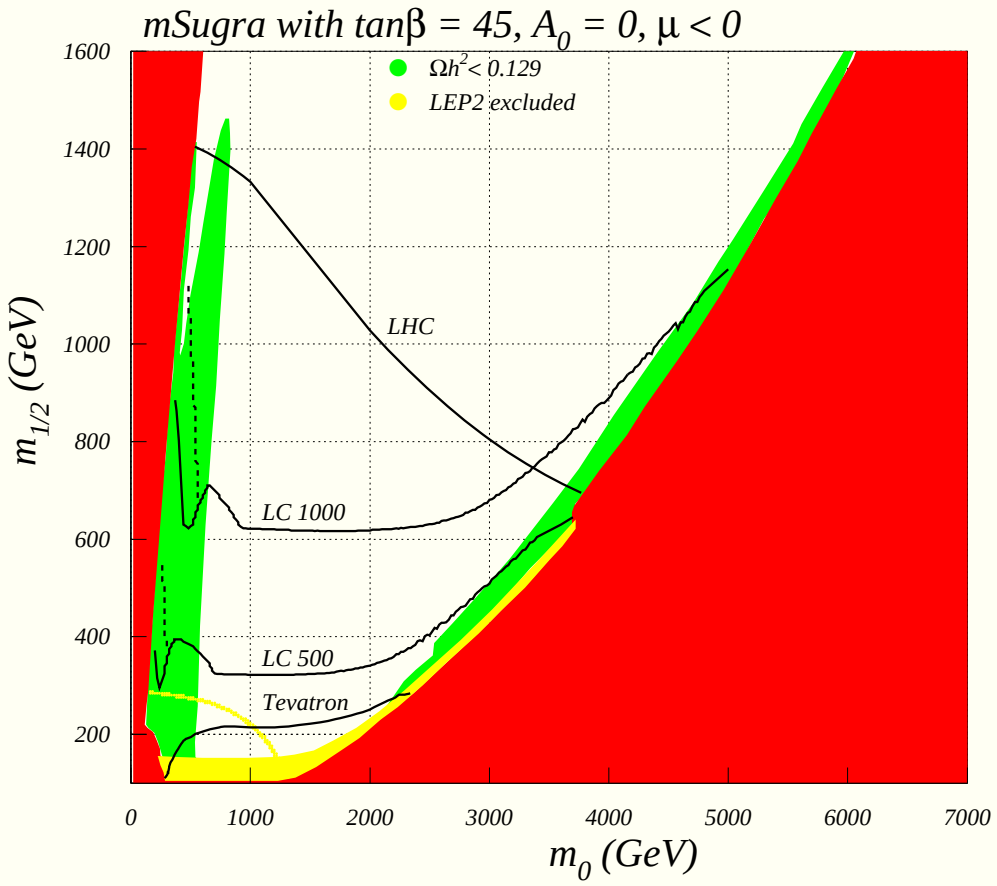
Special cuts for $\widetilde{W}_1^+\widetilde{W}_1^-$ in HB/FP region

- small $m_{\widetilde{W}_1} - m_{\widetilde{Z}_1}$ mass gap
- require 1ℓ plus $2-jets$
- 20 GeV $< E_{vis} <$ 100 GeV
- $\cos\phi(jj) > -0.6$
- $m(lj_{near}) > 5$ GeV
- rejects $\gamma\gamma \to b\bar{b}$, etc.

Sparticle reach of all colliders with relic density



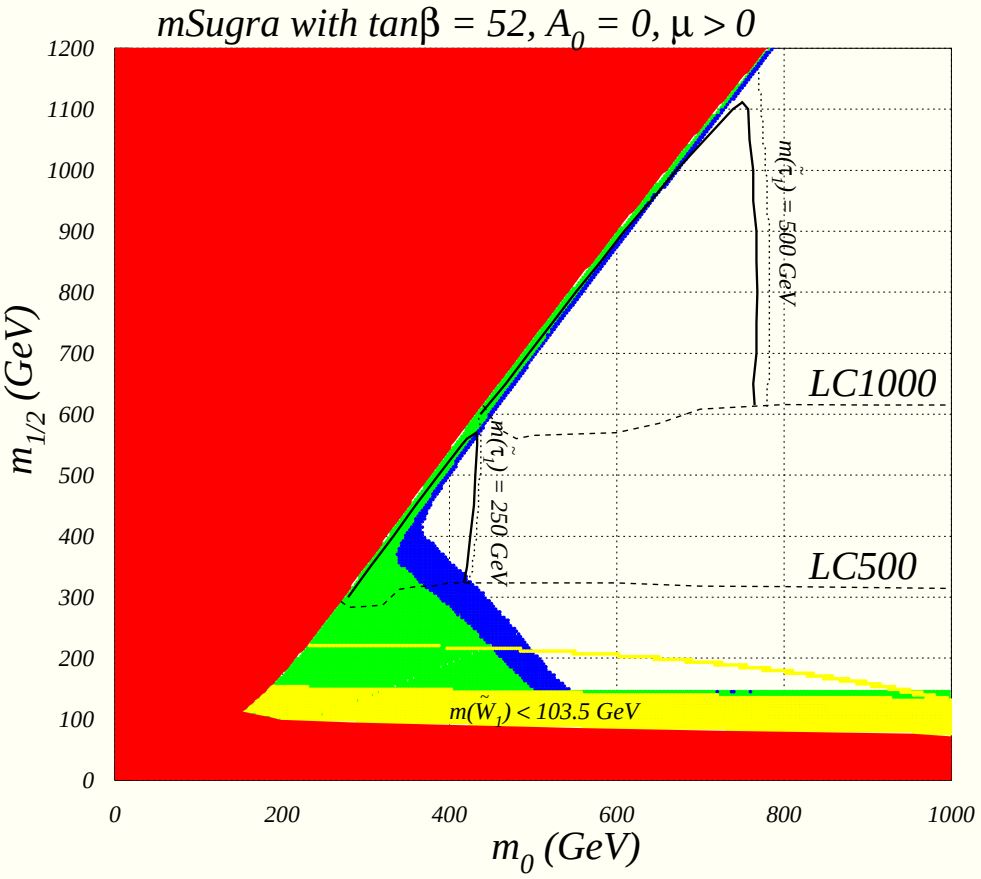
Sparticle reach of all colliders and relic density



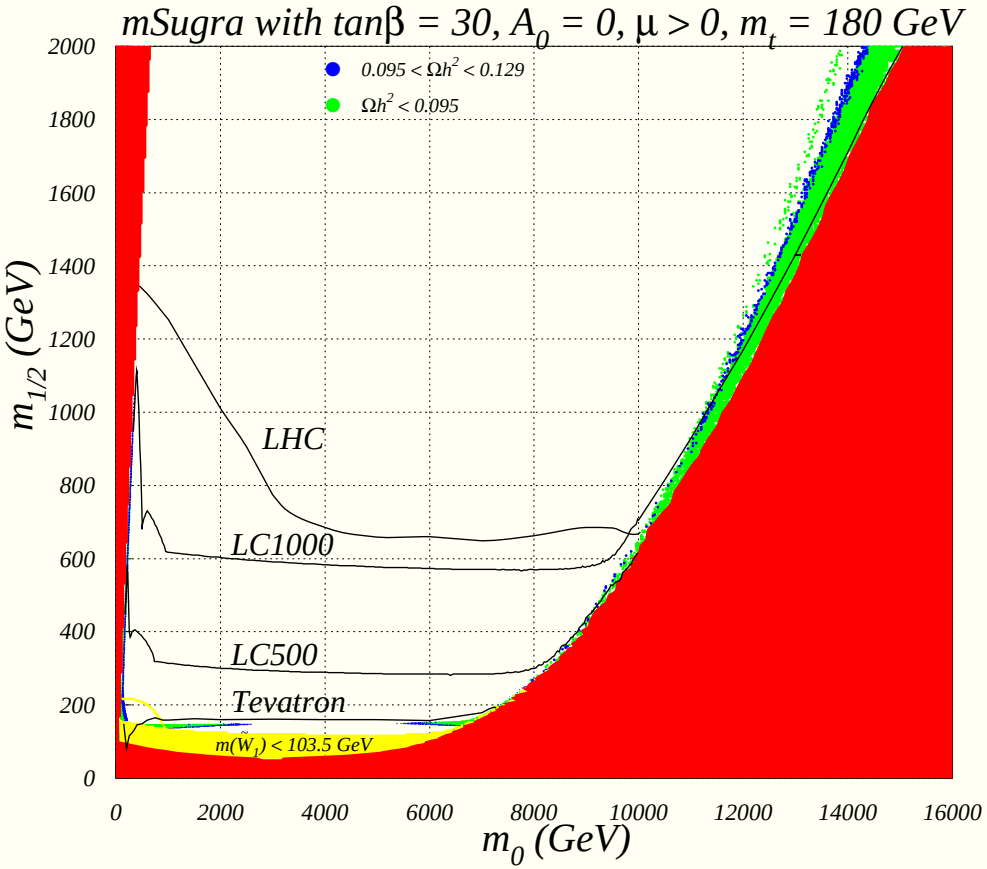
Special cuts in stau co-ann. region

- small $m_{\tilde{\tau}_1} - m_{\widetilde{Z}_1}$ mass gap
- require 2 τ jets (1 or 3 prongs)
- no isol. leptons
- $E_{vis} > 10$ GeV
- $\not{E}_T > 0,\ 5,\ 10, \cdots,\ 200$ GeV
- $E_{vis.} < 15,\ 20,\ \cdots,\ 500$ GeV

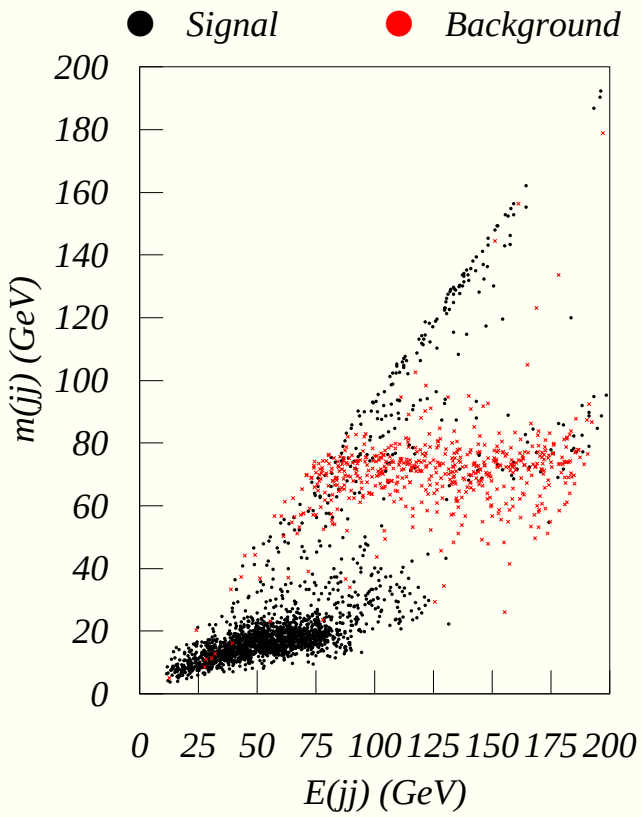
Special reach in stau co-ann. region



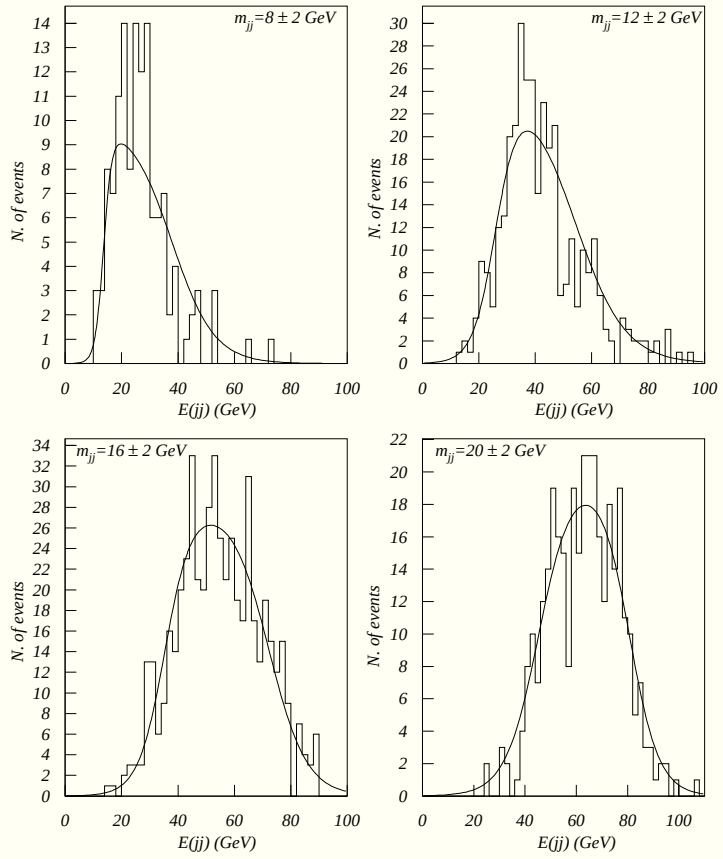
Sparticle reach if $m_t = 180$ GeV



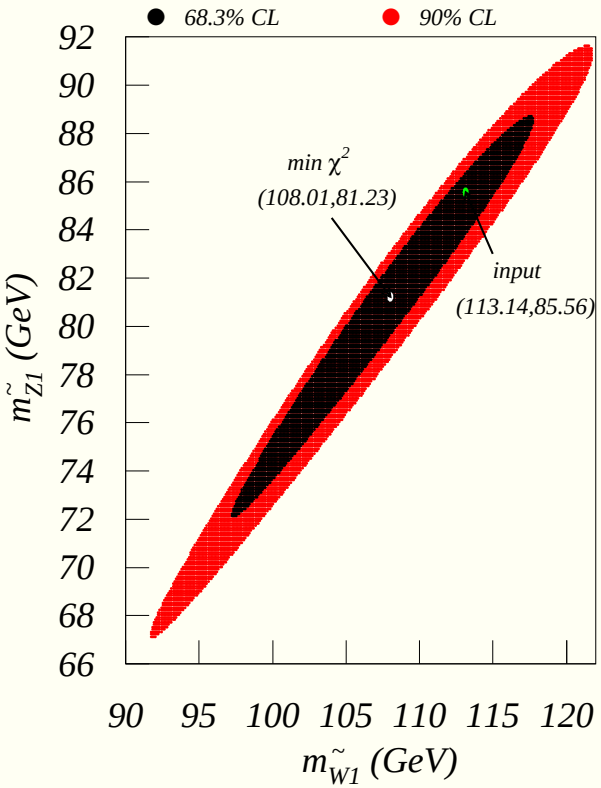
Extract $\widetilde{W}_1^+\widetilde{W}_1^-$ signal in HB/FP region



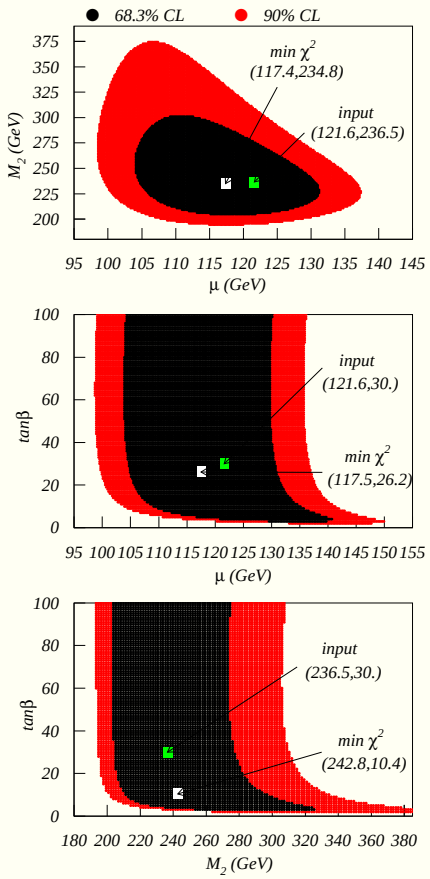
Quasi-2 body chargino decays by taking $m(jj)$ bins



Extract $m_{\widetilde{W}_1}$ $vs.$ $m_{\widetilde{Z}_1}$



Extract M_2 vs. μ



Direct and indirect detection of SUSY DM

★ Direct search via neutralino-nucleon scattering

- Stage 3: Genius, Zeplin4, Xenon, WARP; $\sigma_{SI}(\widetilde{Z}_1 p) \sim 10^{-9} pb$

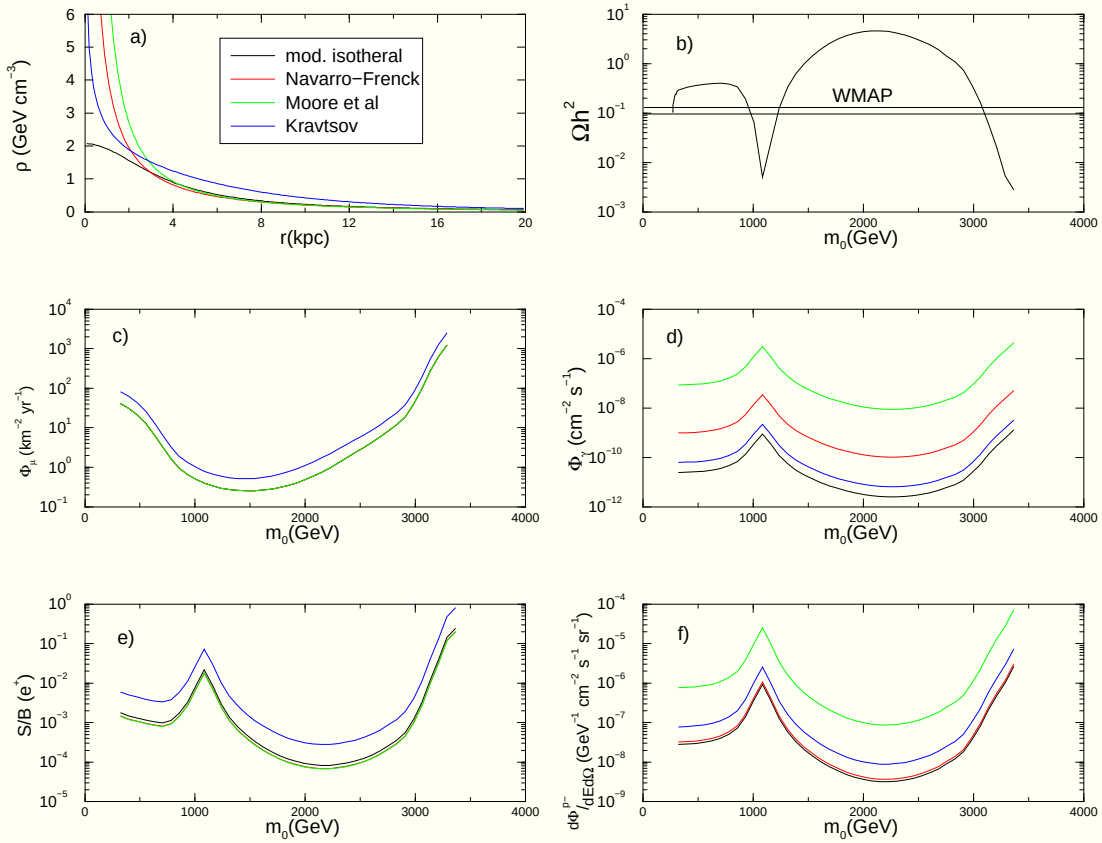
★ Indirect search for SUSY DM:

- $\tilde{Z}_1\tilde{Z}_1 \to b\bar{b}, etc.$ 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

★ To estimate indirect rates, we use DarkSUSY (Gondolo *et al.*) Isajet interface

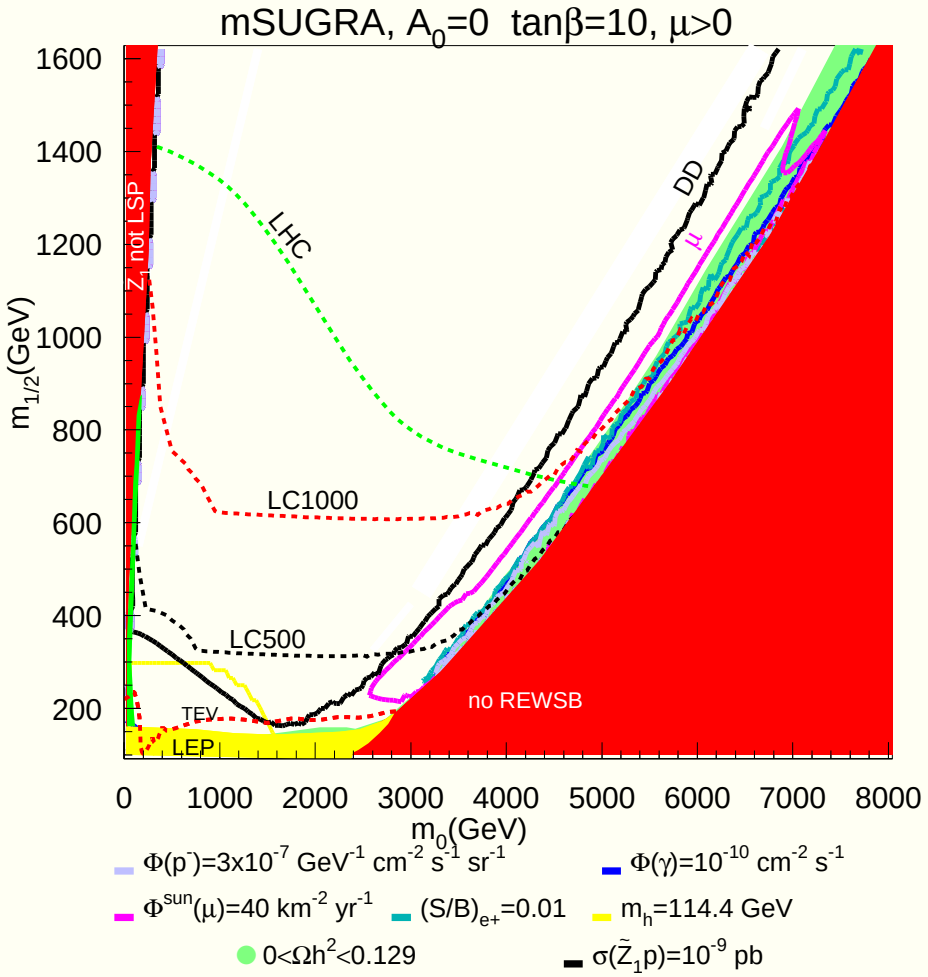
- See also Feng, Matchev and Wilczek

Rates for μs, γs, e^+s, $\bar{p}$s

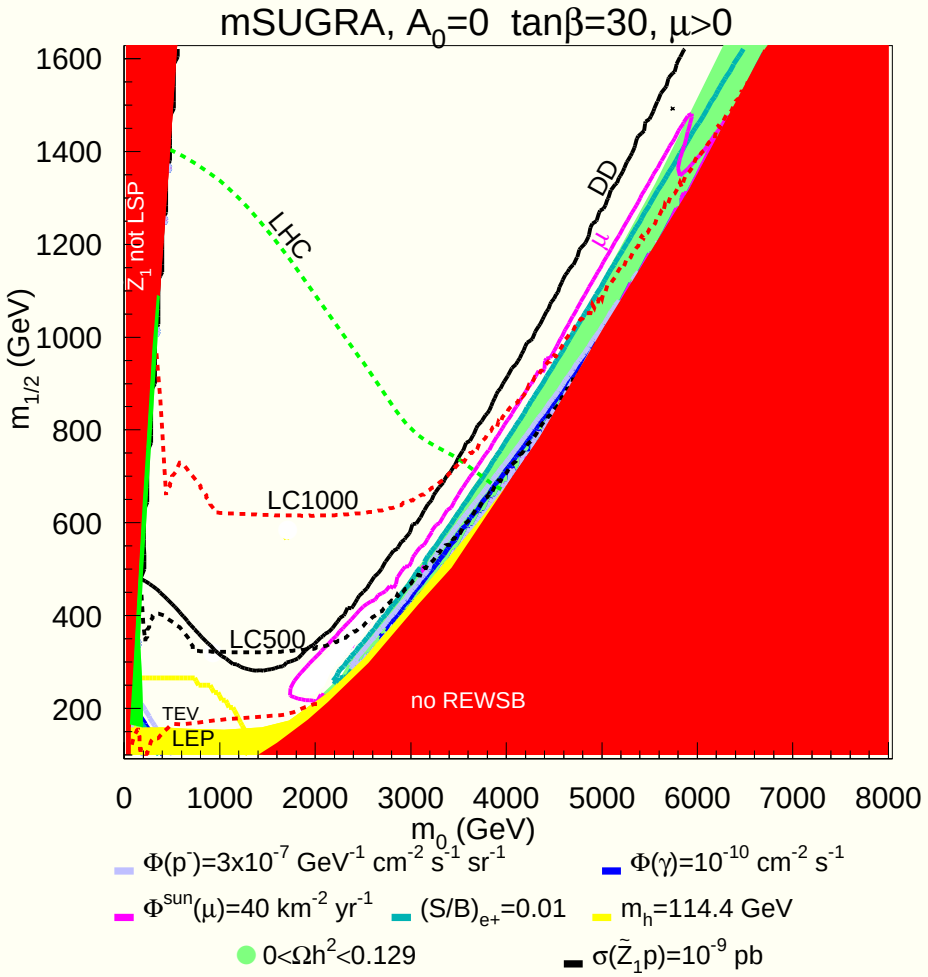


- HB, Belyaev, Krupovnickas and O' Farrill

Sparticle reach for direct and indirect detection of DM



Sparticle reach for direct and indirect detection of DM



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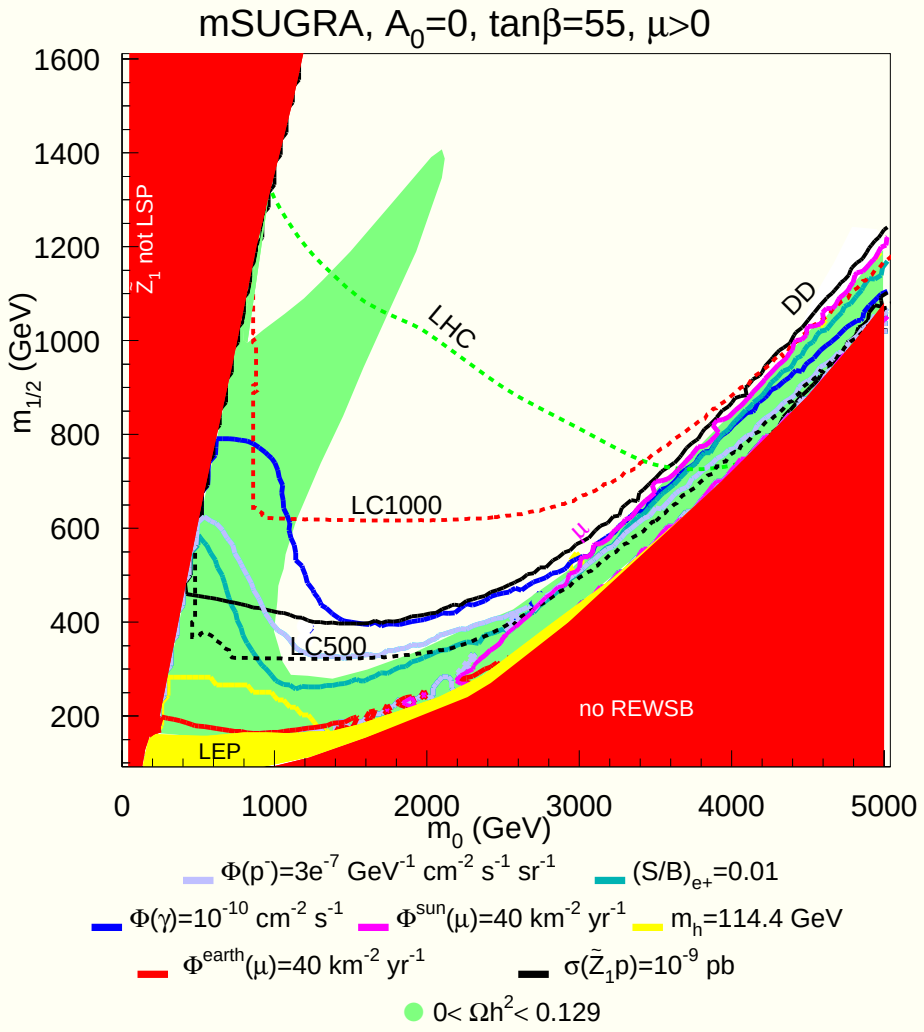
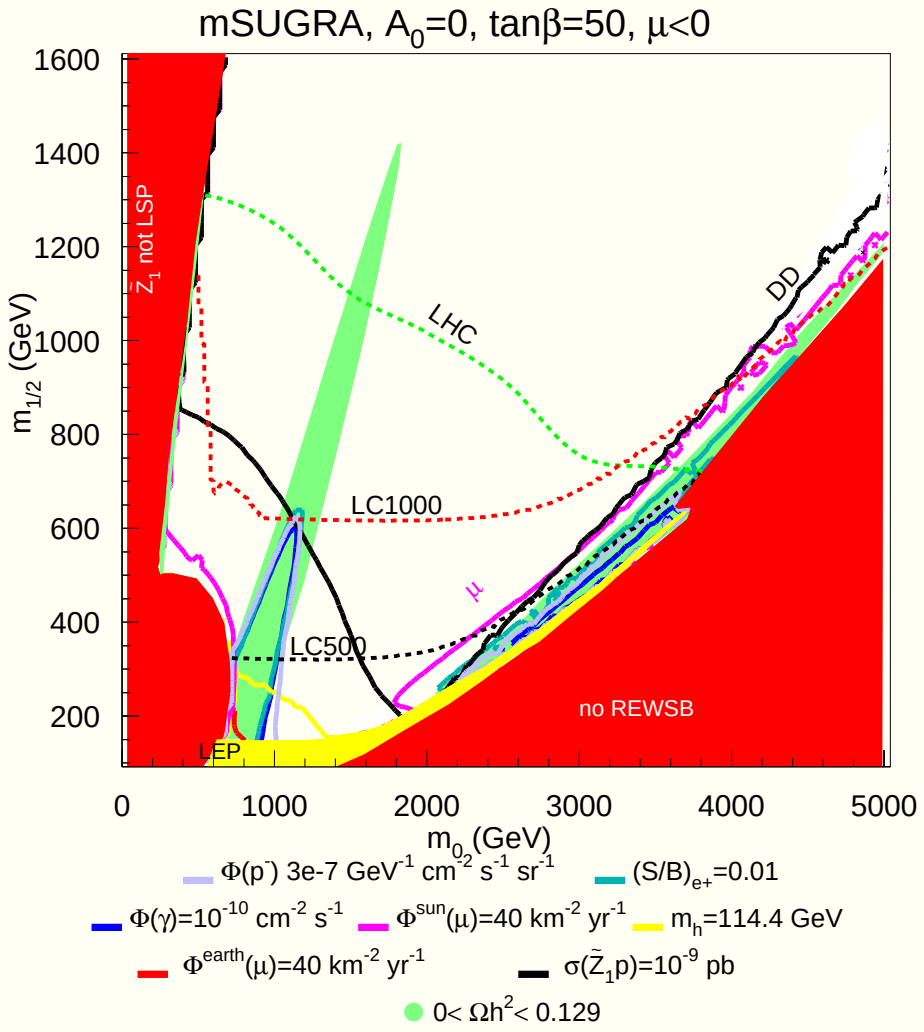


Sparticle reach for direct and indirect detection of DM



Conclusions

- ⋆ WMAP greatly restricts parameter space of SUGRA models
  - bulk region
  - stau co-annihilation
  - HB/FP region: mixed higgsino/bino LSP
  - A annihilation funnel
- ⋆ Tevatron enhanced reach in HB/FP region
- ⋆ LHC reach to $m_{\tilde{g}} \sim 3$ TeV (1.8 TeV) for $m_{\tilde{q}} \sim m_{\tilde{g}}$ ($m_{\tilde{q}} \gg m_{\tilde{g}}$)
- ⋆ LC reach outlined; surpasses LHC reach in HB/FP region!
- ⋆ Stage 3 direct DM detectors can explore *all* HB/FP region
- ⋆ IceCube ν telescope can rule in/out HB/FP region!
- ⋆ γs, e^+s and $\bar{p}$s seeable in HB/FP and also in A-annihilation funnel