Supersymmetry, Dark Matter and the LHC

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⋆ Although Fayet had been exploring SUSY phenomenology before all of us, the subject really took off in the early 1980's when it was realized that supersymmetry stabilized the scalar sector in the presence of radiative corrections. This was then the only rationale for TeV scale new physics.....interesting to supercolliders such as the LHC.

TODAY THE SITUATION IS DIFFERENT.

We know that the SM is incomplete!

- Neutrino masses (suggestive of $SO(10)$ grand unification?)
- Dark Matter
- Stability of the EWSB scalar sector

⋆ LEP measurement of the gauge couplings is compatible with a SUSY GUT with two Higgs doublets if the sparticle scale is 100 GeV - 10 TeV.

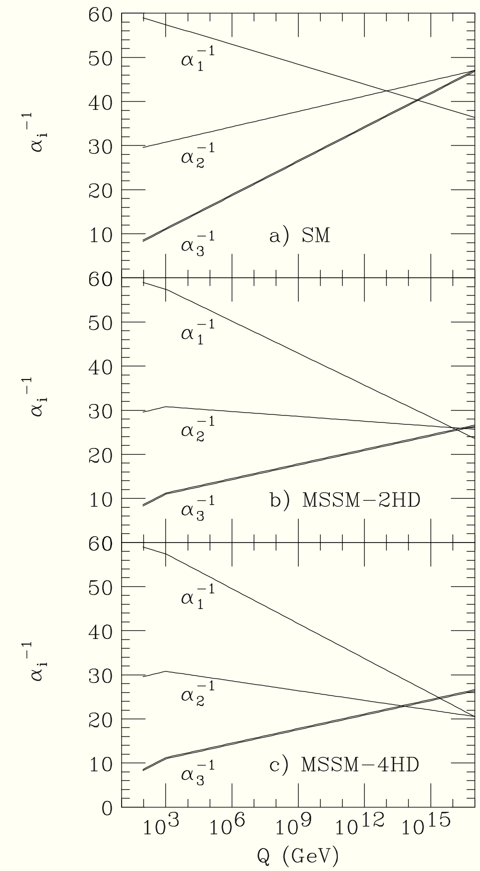
⋆ In SUSY models with a conserved R-parity, the lightest supersymmetric particle is stable, and if electrically neutral and only weakly interacting is consistent with the observed density of cold dark matter if the sparticle mass scale is around a TeV....Thermal DM, Standard Big Bang cosmology.

⋆ The weak scale is relatively stable to radiative corrections if sparticle masses are in the TeV range.

A REMARKABLE TRIPLE COINCIDENCE OF SCALES!!!

The LHC is the natural machine for the explortion of weak scale SUSY. The LEP collider and the Tevatron could have fortituously discovered sparticle signals, but......

GAUGE COUPLING (NON)-UNIFICATION



The MSSM particle content is special.

GENERIC SUSY CREATES NEW PROBLEMS

1) Renormalizable baryon and lepton number violating operators

Fixed by imposing conserved R-parity. But 178 arbitrary parameters $\Longrightarrow$

INTRACTABLE PHENOMENOLOGY.

2) Unacceptable flavour violation in hadron and lepton sectors

Problem generic to ANY theory with many scalars

VITAL CLUES ABOUT HOW MSSM SPARTICLES "FEEL" SUSY BREAKING.

NEED TO RESORT TO MODELS

- ⋆ Alignment of quark and squark matrices
- ⋆ Sfermions with same Q. nos. degenerate
- ⋆ Sparticles very heavy

CAUTION

Be careful with exclusion of SUSY models from flavour physics because small changes in the model may cause large changes in low energy flavour-violating observables.

From 178 parameters to tractable physics

MODELS ARE CHARACTERIZED BY THE MECHANISM FOR THE MEDIATION OF SUSY BREAKING TO THE MSSM SECTOR

- ⋆ Gravity mediation (neutralino LSP easily accommodated)
- ⋆ Gauge mediation (a very light gravitino likely the LSP)
- ⋆ Anomaly-mediation (wino LSP)
- ⋆ Gaugino-mediation (bino LSP)
- ⋆ Combinations of these (novel phenomena such as mirage unification)

Based on untested assumptions about high scale physics.
However, these assumptions will be testable once sparticles are discovered and their properties determined.
Since gravity-mediation readily leads to thermal WIMP DM, we will use the mSUGRA model as a paradigm and examine the effects of relaxing the assumed universality of parameters.

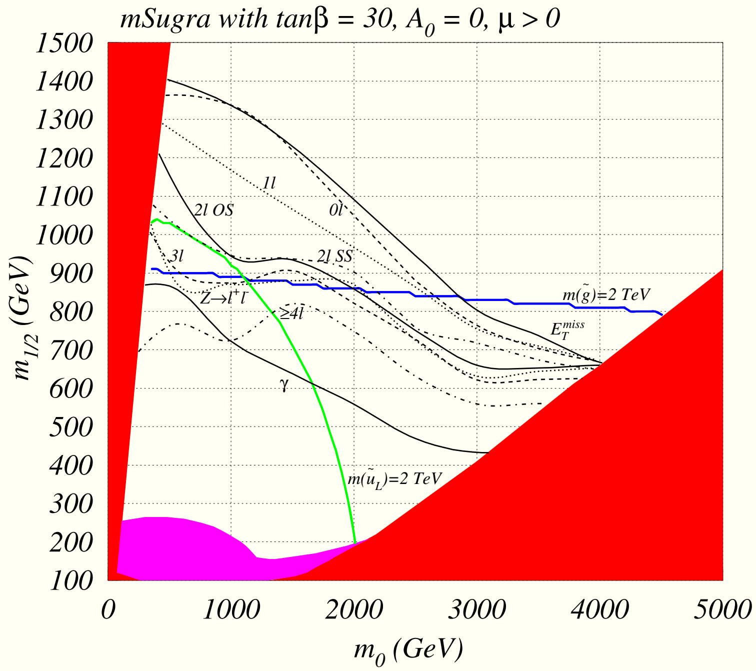
LHC Signals

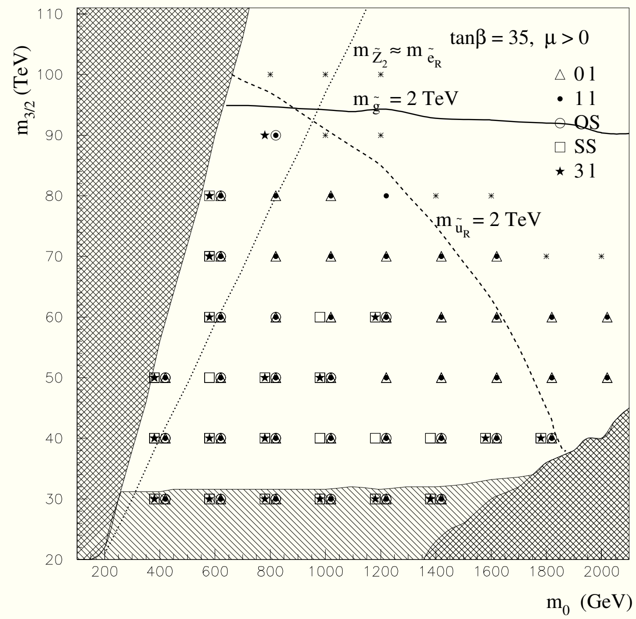
Strongly-interacting gluinos and squarks most copiously produced.

If squarks are degenerate and Yukawa couplings can be neglected, the $SU(2) \times U(1)$ gauge symmetry dictates that decays to winos dominate decays to binos. Thus these particles are likely to cascade decay into lighter inos, until the decay cascade ends in the stable LSP

$$n\text{-leptons} + m\text{-jets} + k\text{-photons} + \not{E}_T$$

LHC Signals





JHEP 0306 (054)

Baer, Mizukoshi, XT

mSUGRA (100 fb^{-1})

mAMSB (10 fb^{-1})

Cascade decays $\Longrightarrow$ Multiple Signals

Note photon signal also

Observe that:

- ⋆ If $m_{\tilde{g}} \leq 1 - 1.5$ TeV (depending on $m_{\tilde{q}}$), there should be observable signals in several channels in many SUSY models.
- ⋆ The LHC reach, measured in terms of $m_{\tilde{g}}$ and $m_{\tilde{q}}$ is roughly the same for a wide variety of models. This is because the signals dominantly come from gluino/squark production with a large mass gap.
- ⋆ The relative rates for the various signals is model-dependent, and so can provide some information about the underlying framework. Of course, there is more direct information in the spectrum (if this can be determined).

Cautions and Caveats

- ⋆ SUSY spectrum may be "compressed" $i.e.$ Smaller than expected mass gaps. Efficiency affected.
- ⋆ R-parity may not be conserved, so LSP may decay. Softer $\not{E}_T$ spectrum, so hard $\not{E}_T$ cuts only at analysis level.
- ⋆ We have assumed prompt sparticle decays. Possibility of long-lived charged or coloured sparticles. Since coloured sparticles hadronize, the lightest R-hadron may be neutral but strongly interacting. It can have soft charge-exchange processes in traversing a detector, leading to unusual "dashed tracks".
- ⋆ Long-lived charged sparticles may leave stubby tracks with kinks, $e.g.$ $\widetilde{W}_1^+ \to \widetilde{Z}_1 \pi^+$ with $\tau(\widetilde{W}_1) \sim 10^{-9} s$.
- ⋆ Long-lived neutral particles may have very large decay gaps, $e.g.$ a neutralino NLSP of GMSB models, or neutralino LSP of R-parity violating models.

Agenda for 2010-2015

⋆ Establish a clear New Physics signal.

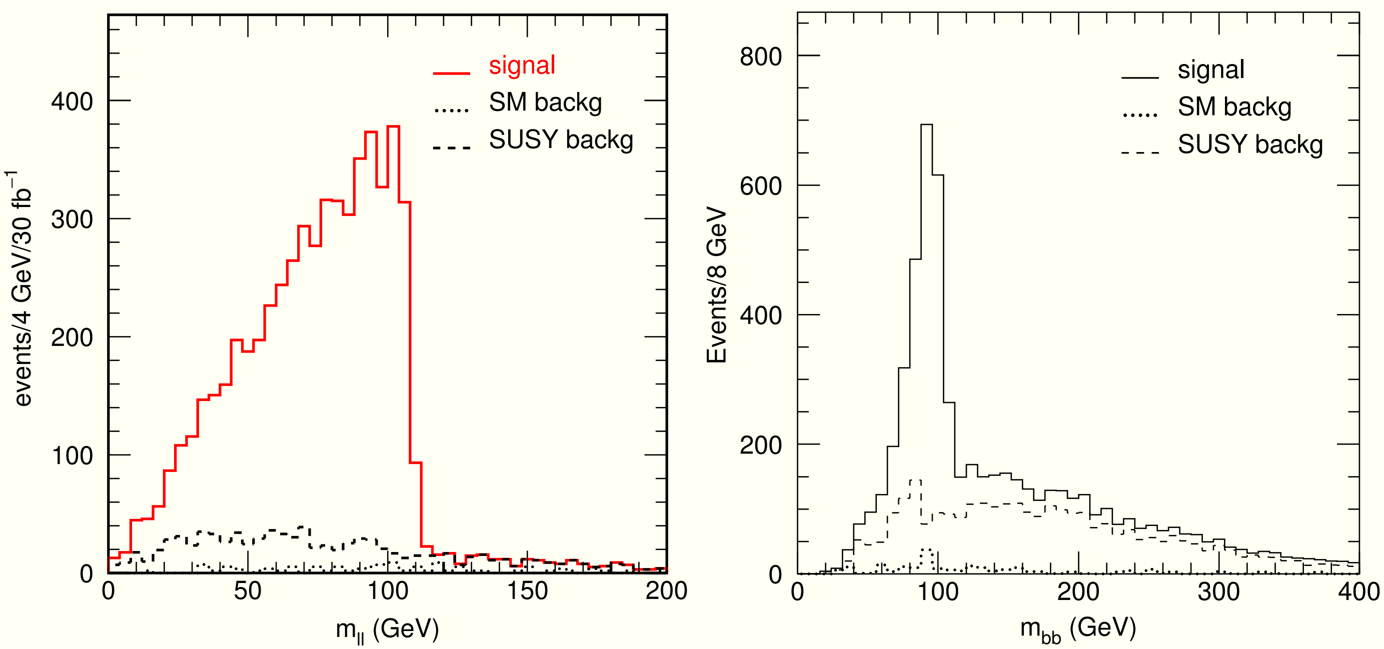
⋆ Make the case it is SUSY. The case will be circumstantial.

- Rates vs. mass. Strong vs. EW $\Longrightarrow$ Q. Nos.
- Same sign dileptons+jet+$\not{E}_T$ signal $\Longrightarrow$ strongly interacting Majorana particles. ($N(\ell^+\ell^+)$ vs. $N(\ell^-\ell^-)$)
- Cascade decays evidence of charginos and neutralinos?
- Clean trileptons as evidence of charginos and neutralinos
- Higgs bosons (Baer, Bisset, XT, Woodside) and stops in gluino cascade decays (Hisano, Kawagoe, Nojiri)
- Spin measurements (Cambridge, São Paulo,....)

BUILD A CONSISTENT PICTURE.

This is not the time to discuss mass measurement techniques in detail, but LHC may be able to determine some mass differences and even mass bumps.

ATLAS TDR Hichliffe,Paige,Shapiro,Soderqvist,Yao,Bachacou



$m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ or $\sqrt{m^2_{\widetilde{Z}_2} - m^2_{\tilde{\ell}}}\sqrt{1 - \frac{m^2_{\widetilde{Z}_1}}{m^2_{\tilde{\ell}}}}$ h in SUSY events

Determination of other mass edges allow reconstruction of event chains in the favourable sitation of a sequence two body decays, modulo ambiguities of interpretation.

Mass edges typically give Δm. Gunion, McElrath and collaborators say they can measure m at the LHC again for sequences of two-body decay chains.

Pay attention to the so-called m_{T2} (and related $m_{\rm TGen}$) variable idea.... Cambridge, Korea. End points and kinks in appropriate distributions claimed to give masses of parent and the escaping LSP.
Also suggested as a model-discriminator (Hubisz and friends).

In principle, if we have a sufficient number of measurements, we can readily falsify models with a few parameters, or determine them!

Although I am not aware of a real bottom up program of measurements at the LHC that lead us to an underlying model, I think with real data we will be able to do a lot.

Dark Matter

Wouldn't it be wonderful if thermal relics from the standard Big Bang constitute the bulk of the cold DM density measured today?

$$\Omega_{\rm CDM} h^2 = 0.111^{+0.011}_{-0.015}\ (2\sigma)$$

Since the DM could be multi-component, the relic density from any single component has to be smaller, in particular $\Omega_X h^2 < 0.122$.

This requires that XX annihilation be efficient enough.
$\Longrightarrow \langle v\sigma \rangle \propto \frac{g_X^4}{M_X^2}$ has to be in the right range.

Weak scale couplings together with weak scale masses work! (WIMP MIRACLE)
(see, however, Feng and Kumar.)

Generic SUSY models are bang-on if sparticles are light and the LSP is a bino-like neutralino with $m_{\rm SUSY} \sim \mathcal{O}(100)$ GeV ("bulk" region).

The mSUGRA bulk region is being constrained within mSUGRA by direct searches and constraints on rare processes, which force the SUSY scale to go up, and hence, $v\sigma(annihilation) \propto \frac{1}{m_{\rm SUSY^2}}$ to come down.

$\Longrightarrow$ neutralio relic density is too large.

Seek mechanisms to jack up the LSP annihilation rate.

Jacking up the annihilation cross section

★ Co-annihilation with a charged or coloured sparticle in thermal equilibrium with $\widetilde{Z}_1$ (usually $\tilde{\tau}_1$ or $\tilde{t}_1$)

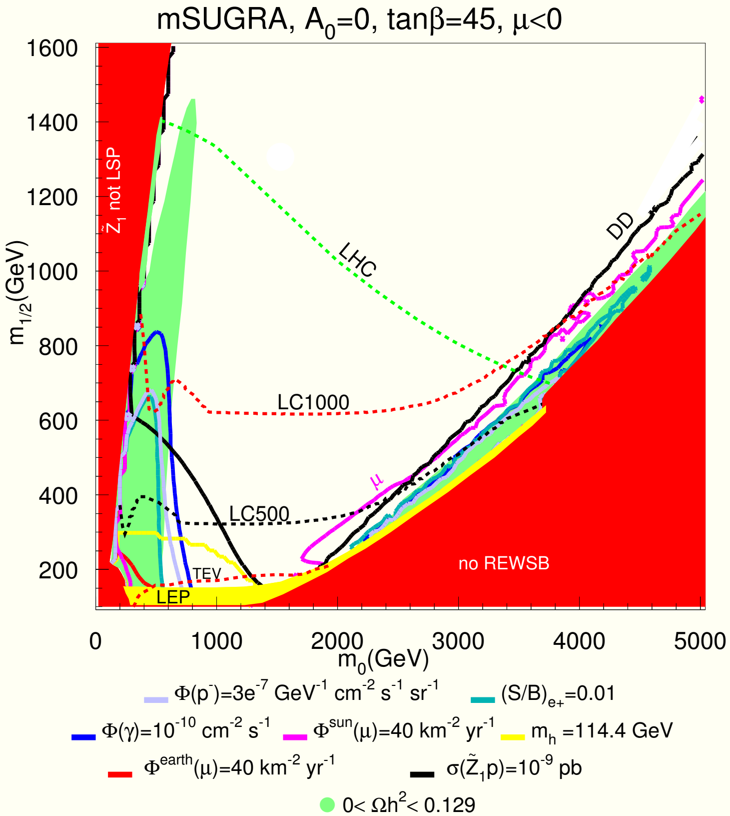
If $M_1 \simeq -M_2$, $m_{\widetilde{Z}_1} \simeq m_{\widetilde{W}_1} \simeq m_{\widetilde{Z}_2}$ but mixing is tiny, and a bino-like neutralino can co-annihilate with a chargino-wino (BWCA). But not in models with gaugino mass unification.

★ Resonance enhancement if $2m_{\widetilde{Z}_1} \simeq m_\phi$, where $\phi = A, H$ or even h or Z. Not as fine-tuned as it seems because resonances can be wide, and because LSP has thermal motion. (Higgs funnel)

★ Increase higgsino content of LSP since higgsinos couple to W/Z bosons (small μ hyperbolic branch/focus point region)

★ "Pseudo-bulk" region in models with non-universality. (one specie of light sfermions)

Relic-density-allowed regions in the mSUGRA model(Green)



b-tagging increases HB/FP reach where LSP has higgsino admixture. Notice DM detection reach in this MHDM region .

★ Increase wino content of LSP because winos have big couplings to Z and W (need non-universal gaugino masses at GUT scale.)

Implications for colliders

- ⋆ Co-annihilation clearly implies a relatively light charged/coloured sparticle.
- ⋆ Within mSUGRA, the Higgs funnel is possible only for rather large values of $\tan\beta$ $\Rightarrow$ large bottom Yukawas$\Rightarrow$ altered sparticle cascade decay patterns.
- ⋆ Within mSUGRA, small $|\mu|$ HB/FP region occurs for $m_0 \gg m_{1/2}$ $\Rightarrow$ scalars are essentially decoupled from even the LHC (sensitivity to m_t).
- ⋆ Within mSUGRA, the wino content of LSP is never large, and we never get bino-wino co-annihilation.

ARE THESE CONCLUSIONS ROBUST TO CHANGES OF THE MODEL?
RELAXING UNIVERSALITY OF SUSY BREAKING PARAMETERS, OBVIATES LAST THREE CONCLUSIONS.

Non-Universal SUSY Breaking Parameters

To examine the robustness of conclusions, give up universality of the SSB parameters, but in a controlled way to leave phenomenology tractable Study various one-parameter extensions of mSUGRA

- ⋆ Non-universal Higgs mass parameters

$$m_\phi^2 \equiv m_{H_u}^2 = m_{H_d}^2 \neq m_0^2$$

- ⋆ Non-universal gaugino mass parameters

$M_1(\text{weak}) \simeq M_2(\text{weak}) \Longrightarrow$ Mixed wino DM (MWDM);

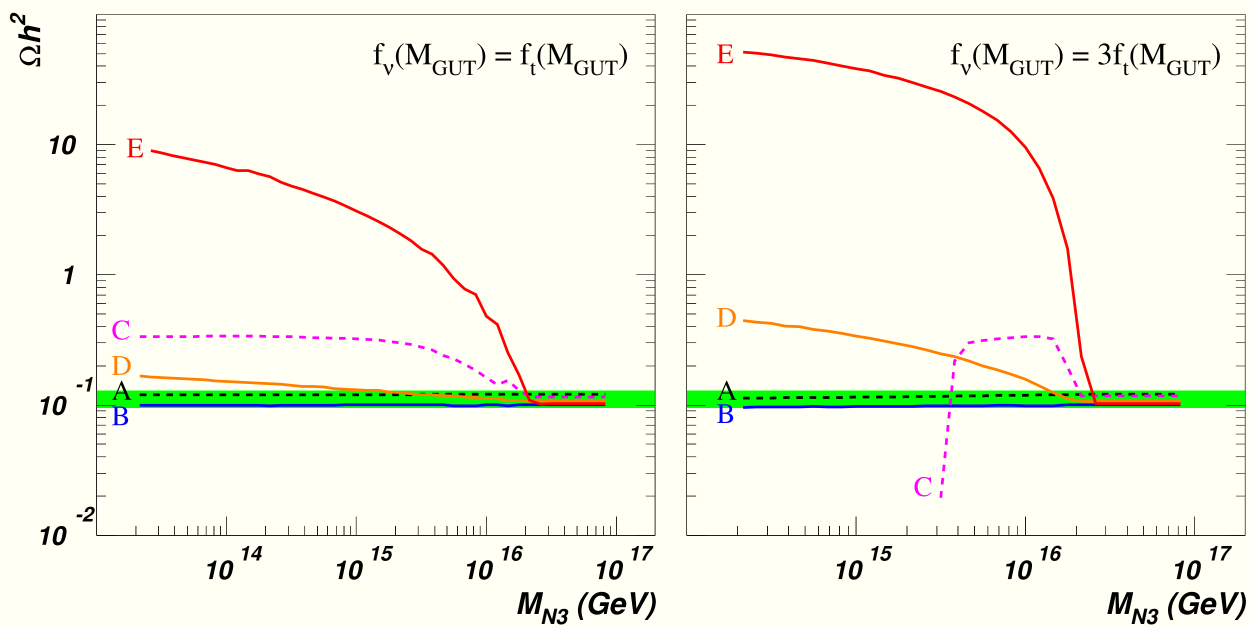
$M_1(\text{weak}) \simeq -M_2(\text{weak}) \Longrightarrow$ bino-wino co-annihilation (BWCA);

Low $|M_3|$ or large $M_2 \Longrightarrow$ Low $|\mu|$, so mixed higgsino DM (MHDM).

BY ADJUSTING THE ONE ADDITIONAL PARAMETER, ALL POINTS IN THE $m_0 - m_{1/2}$ MSUGRA PLANE BECOME RELIC-DENSITY-ALLOWED! INTERPRETE RELIC-DENSITY MEASUREMENT WITH CAUTION.

NEUTRINO YUKAWA COUPLINGS AFFECT NEUTRALINO RELIC DENSITY

Barger, Marfatia and Mustafayev have noted that in $SO(10)$ GUTS, the neutrino Yukawa coupling also has a significant impact on the relic density so move around the relic-density allowed region in the $m_0 - m_{1/2}$ plane, via the effect of $\mathbf{f}_\nu$ in the RG evolution of MSSM parameters. [Remember $\mathbf{f}_\nu$ is related to $\mathbf{f}_u$.]



A=bulk, B=$\tilde{\tau}$-co-annih., C=$\tilde{t}$-co-annih., D=Higgs funnel, E=HB/FP

Co-annihilation with $\tilde{\nu}_\tau$ in case C in the right frame.

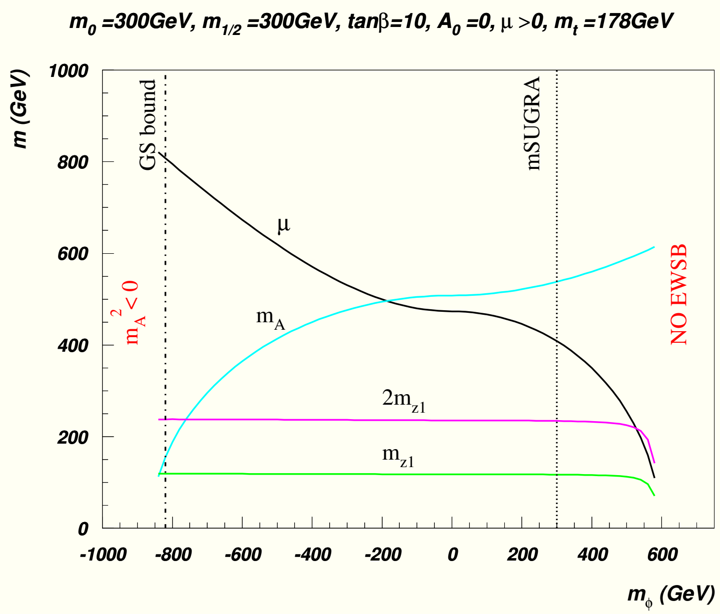
Non-Universal Higgs masses

Relax scalar mass universality. FCNC $\Longrightarrow$ Keep matter scalars universal.

$$m_\phi^2 \equiv m_{H_u}^2 = m_{H_d}^2 \neq m_0^2.$$

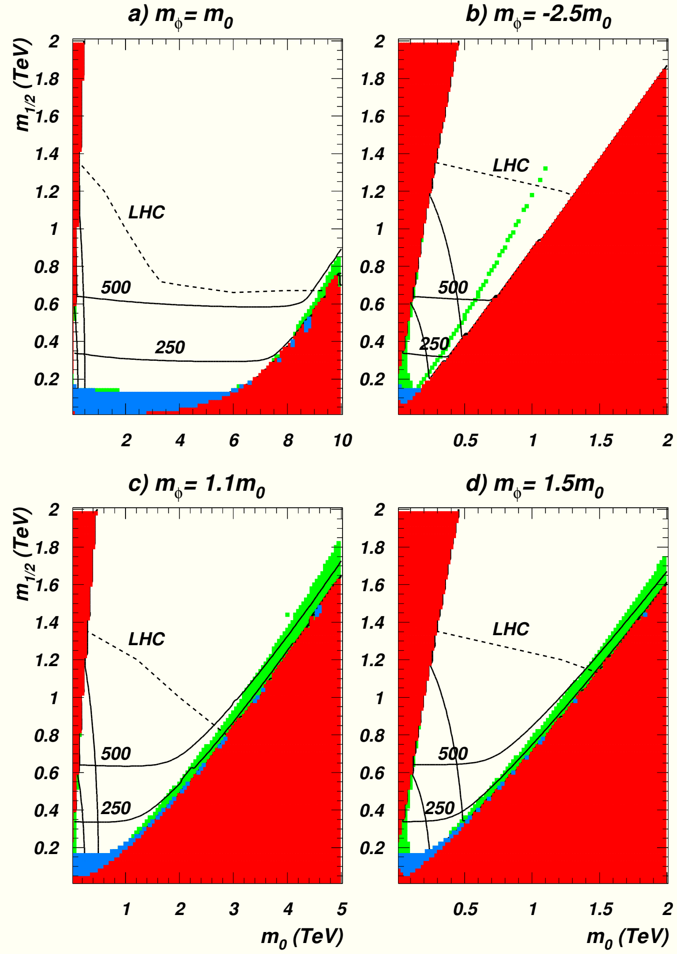
NUHM model specified by,

$$m_0, m_\phi, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu)$$



Small μ for large $m_\phi > m_0$ Higgs funnel anihilation for $m_\phi < 0$

COLLIDER PROSPECTS in NUHM: $\tan\beta = 10$



Baer, Mustafayev, Profumo, Belyaev, XT

Higgs funnel at low $\tan\beta$; MHDM with not-so-decoupled scalars

Non-Universal Gaugino Masses

GUT scale Universality $\Rightarrow M_3(\text{weak}) \sim 3.5 M_2(\text{weak}) \sim 7 M_1(\text{weak}) \Rightarrow$ Bino-like LSP in many models.

If $M_1(\text{weak}) = M_2(\text{weak})$, we have a photino LSP....rapidly annihilate to WW pairs. For $M_1(\text{weak}) \simeq M_2(\text{weak})$, we will have mixed wino dark matter (MWDM).

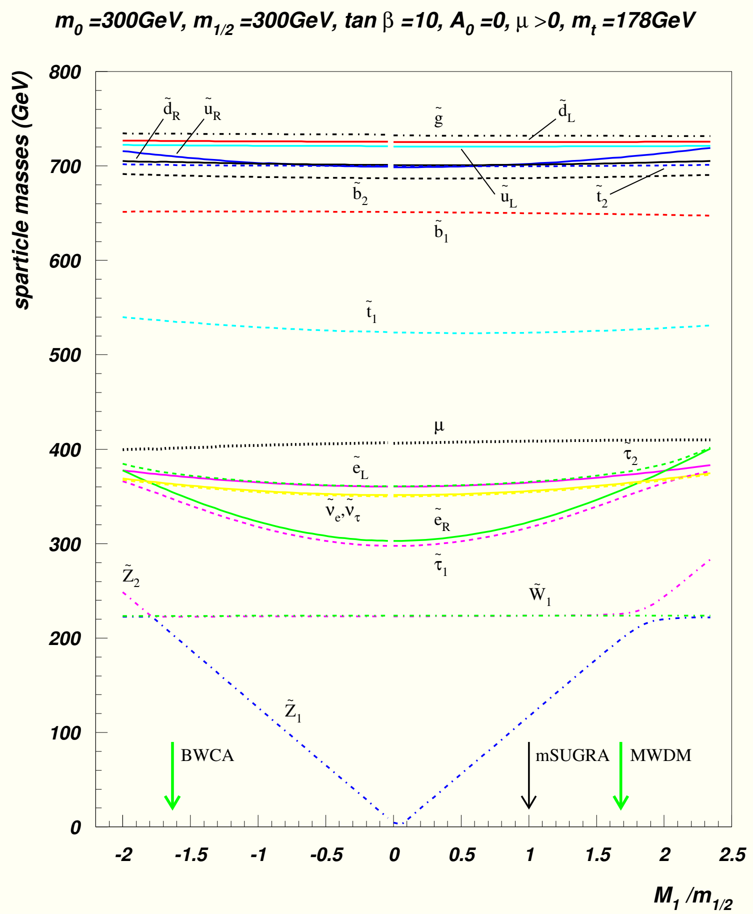
If $M_1(\text{weak}) \simeq -M_2(\text{weak})$, very little bino-wino mixing. But bino and wino states have about the same physical mass. $\Rightarrow$ bino-wino coannihilation (BWCA).

Taking $|M_2(\text{GUT})| \simeq (2.5-3)\text{m}_{1/2} \Longrightarrow$ small $|\mu|$ (mixed higsino DM in High M_2 DM model)

$$m_0, m_{1/2}, M_1 \text{ or } M_2, A_0, \tan\beta, sign(\mu)$$

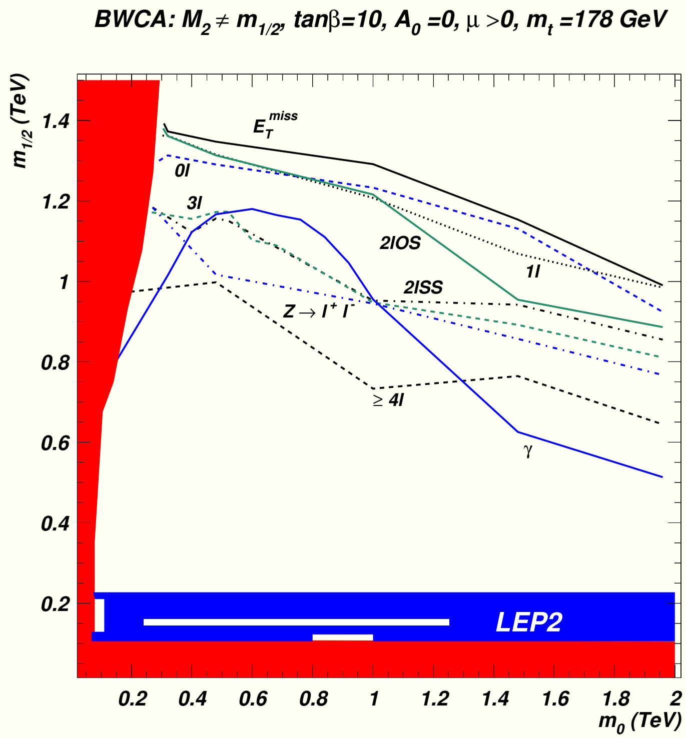
BWCA is realized in the mixed modulus-anomaly mediated SUSY breaking model.

Illustrate in situation where we vary M_1 from its unified value.



Small $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1} \Rightarrow$ enhanced $B(\widetilde{Z}_2 \to \widetilde{Z}_1\gamma) \sim 10 - 20\%$.

(Vector boson-gaugino loops decouple in BWCA case, but not in MWDM case.)



Baer, Krupovnickas, Mustafayev, Park, Profumo, XT

Observable rate for photon signals at LHC.

Observable dilepton mass edges with small $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$.

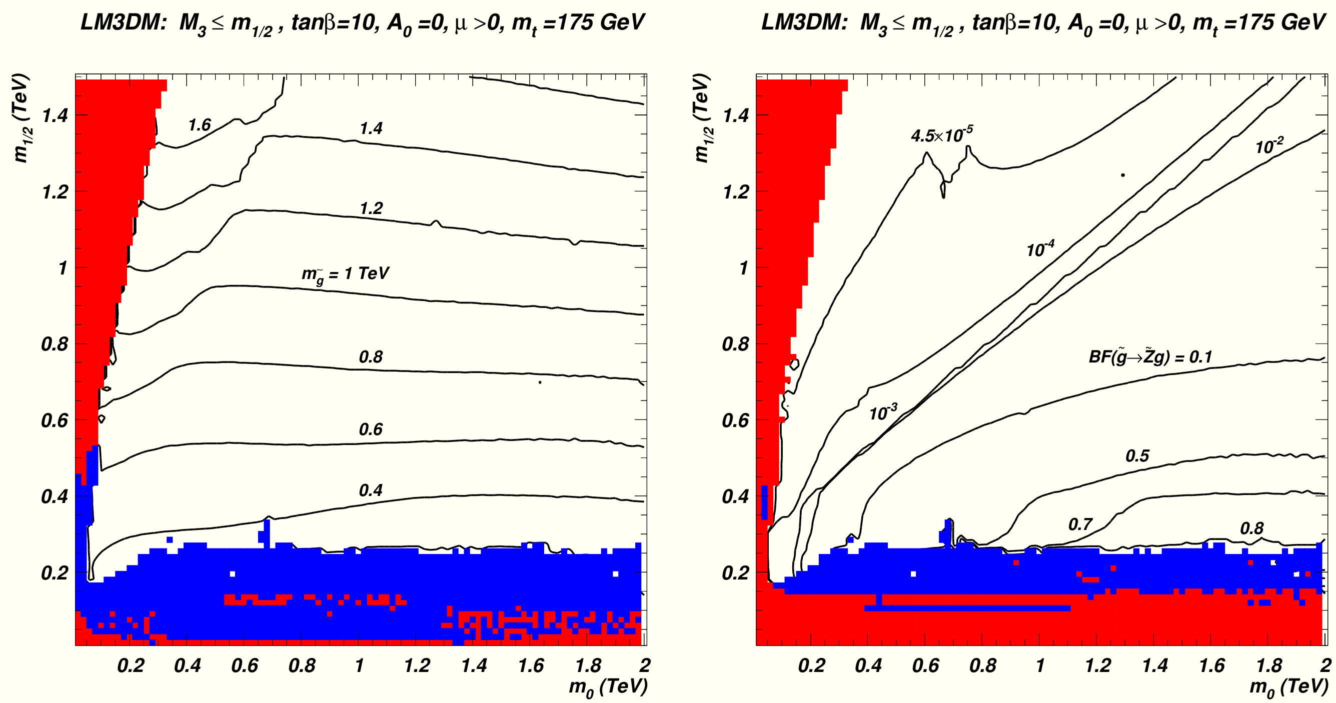
LOWERING $M_3(\mathrm{GUT})$ relative to $m_{1/2}$ also LOWERS μ.

For every value of $(m_0,\ m_{1/2})$ we can find the hyperbolic branch region by adjusting $M_3(\mathrm{GUT})$, and so get the right relic density.

Small $M_3 \Rightarrow$ Lighter gluinos (and also squarks) relative to uncoloured sparticles.

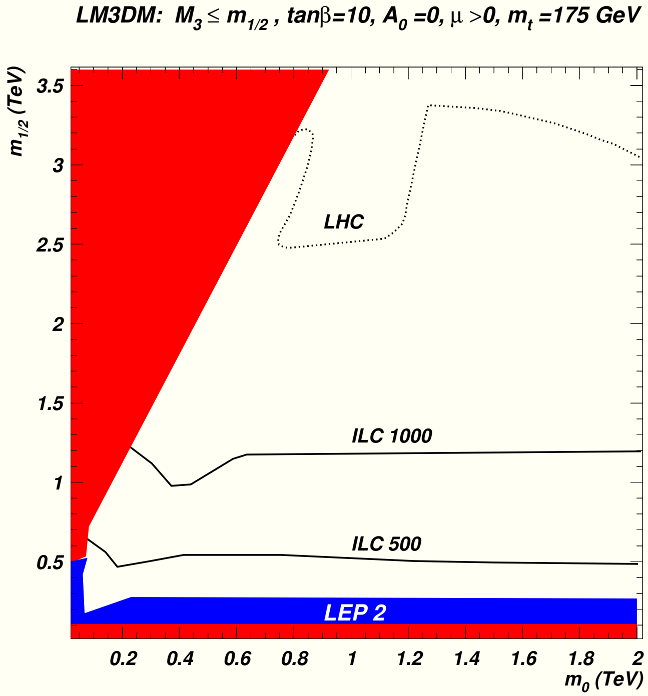
Enhanced Radiative decays of the gluino.

Baer,Mustafayev,Park,Profumo,XT



Opportunity for Tevatron!! Low jet multiplicity??

LHC will overwhelm e^+e^- colliders for reach.



M_3 is everywhere adjusted to reproduce central value of the relic density.

Dilepton mass edges.

ILC contours are composites of stau and chargino contours.

All inos may be accessible at ILC $\Rightarrow$ detailed study of ino sector.

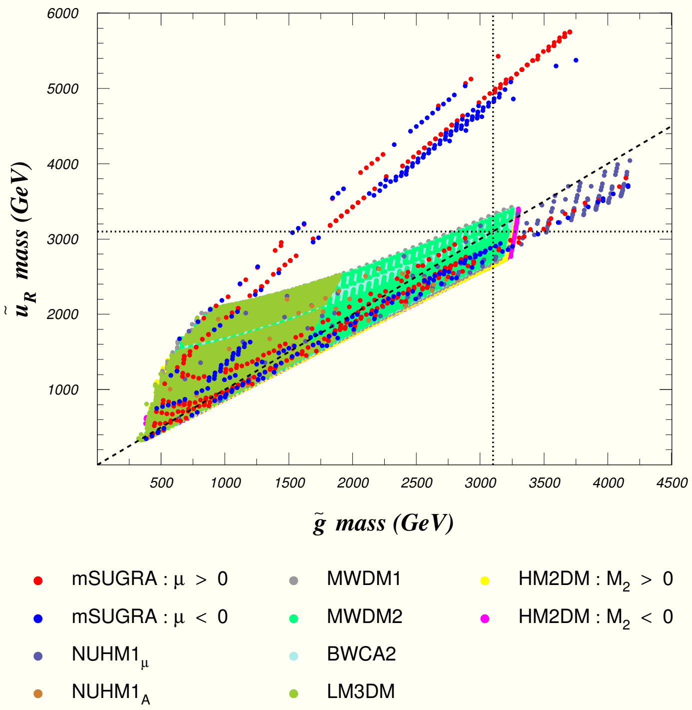
Squarks may be accessible at especially a TeV collider, and since $\tilde{q} \to q\tilde{g}$, gluino studies at ILC!

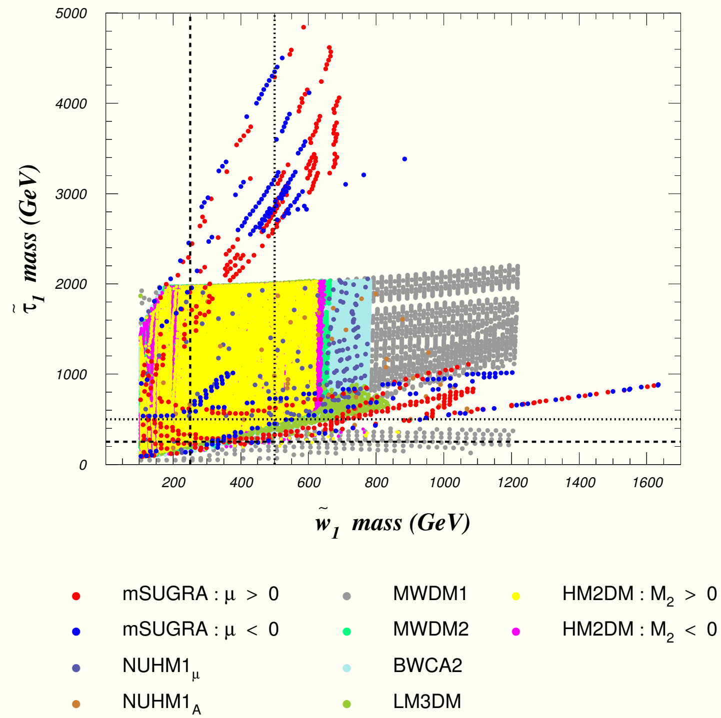
What I zoomed by on the last few slides

We saw that even in 1-parameter extensions of mSUGRA, the entire $m_0 - m_{1/2}$ plane could be made compatible with the relic-density measurement?

DOES THE RELIC DENSITY ALLOW FOR ANY ROBUST CONCLUSIONS?

Examine various relic-density-consistent extensions of the mSUGRA model to look for trends. Analysis does not mean that there are no models where these trends will not hold.



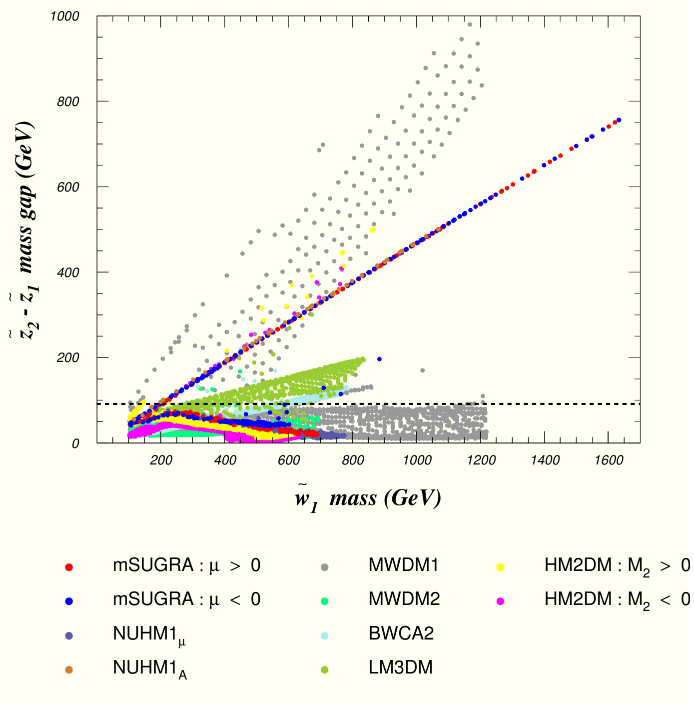


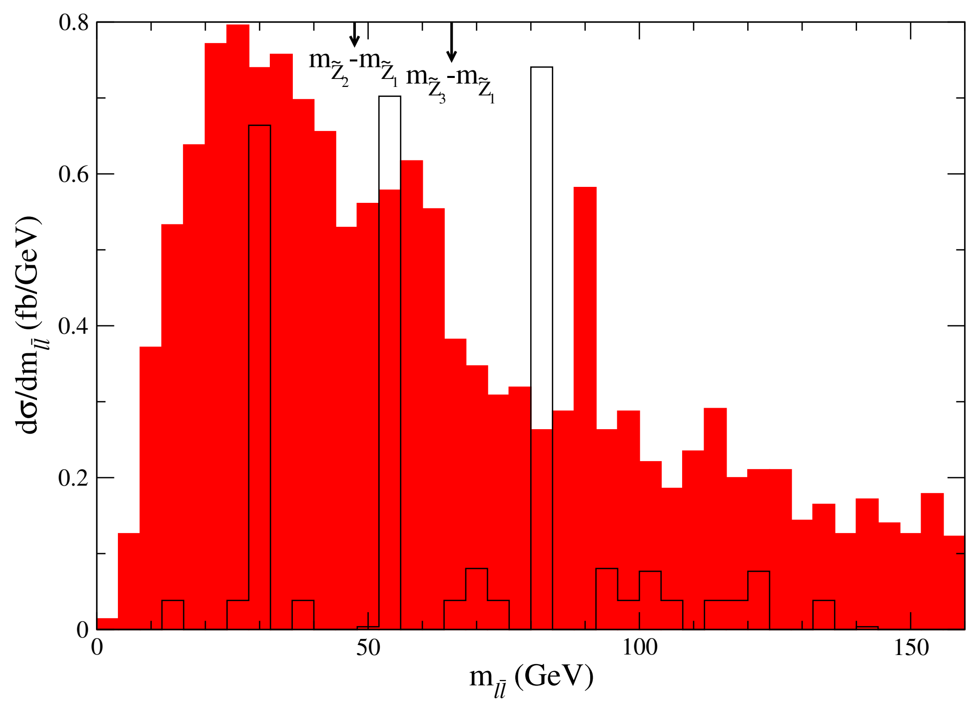
Many models with the correct neutralino RD should be accessible at the LHC.

The HB/FP region of SUGRA is an exception.

Accessibility of sparticles not guaranteed at even a 1 TeV linear collider.

m_{ll} dist. in a high M_2 DM model



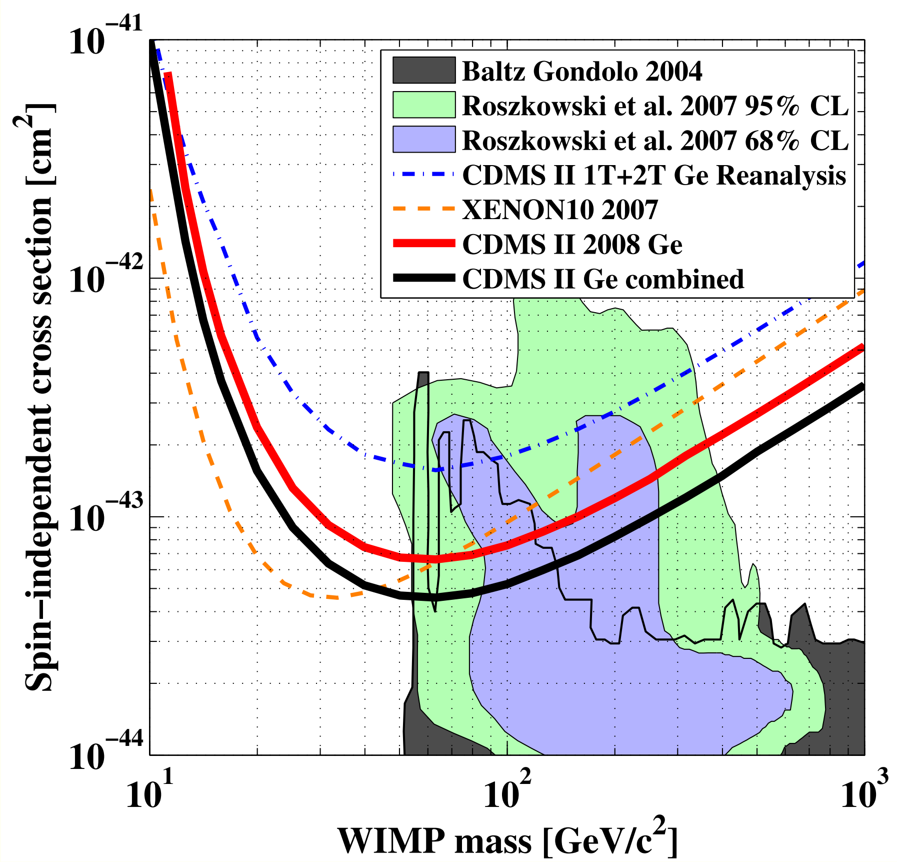


In many models $\widetilde{Z}_2$ decays via three-body decays, so that the location of the dilepton mass edge at $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ may be possible at the LHC.

In MHDM models, $\widetilde{Z}_3$ may also be light, allowing multiple mass edges to be measured.

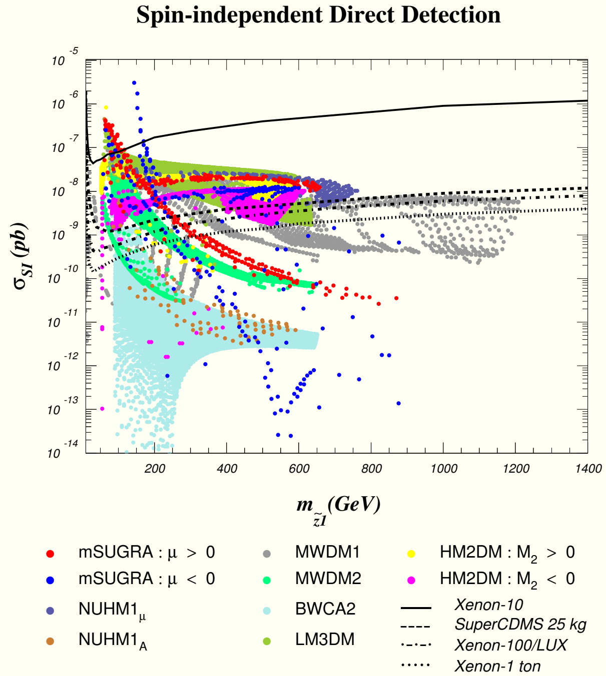
Notice the different shapes of the "two humps" in the right frame.

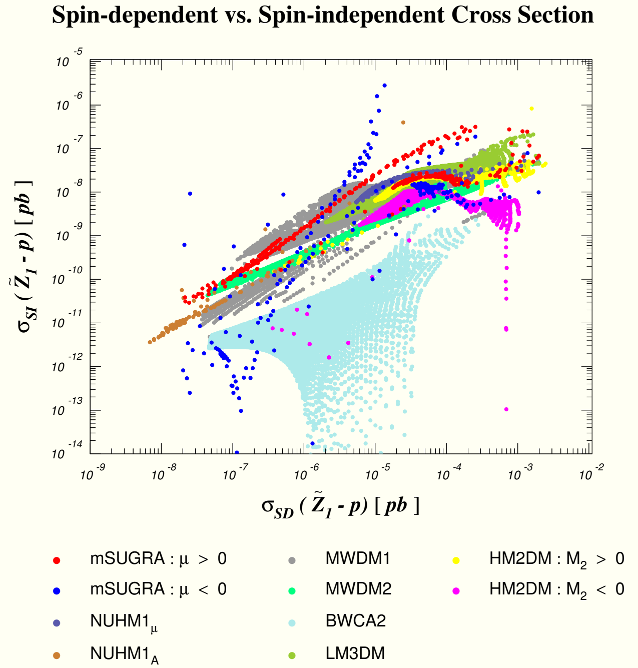
Direct Detection Limits



CDMS and Xenon-10 are running neck and neck. Probing $\sigma_{\rm SI}(\widetilde{Z}_1 p) \sim (5-10)\times 10^{-8}$ pb for $m_{\widetilde{Z}_1} = 100$ GeV.

DIRECT DETECTION OF DARK MATTER





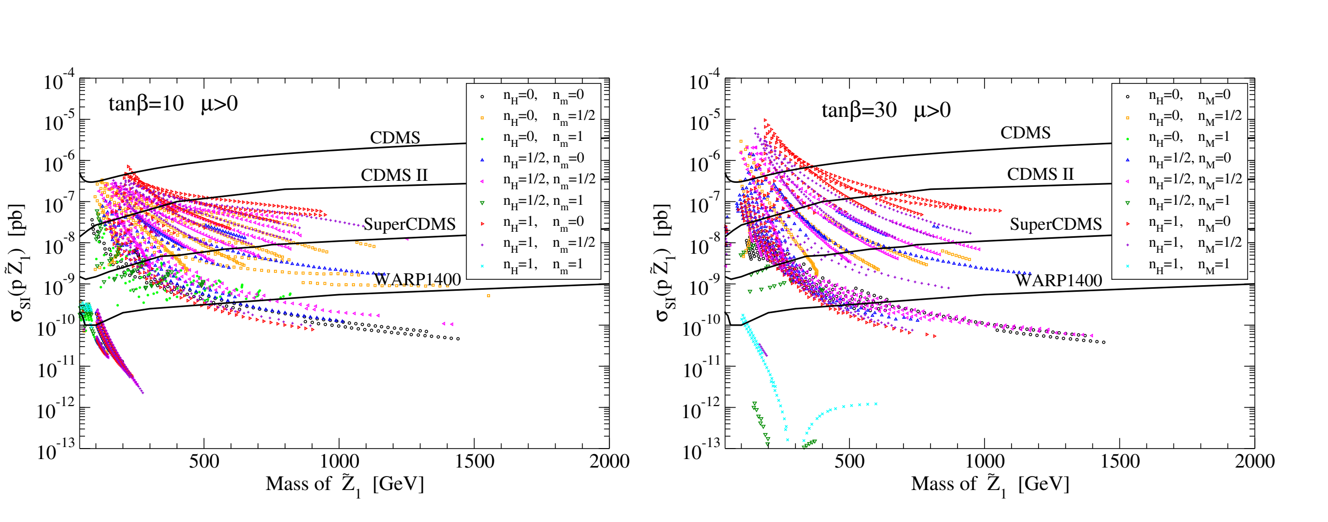
Current searches at CDMS and Xenon-10 beginning to cut into models.

Notice the branch from MHDM models where $\sigma_{\rm SI}(\widetilde{Z}_1 p)$ asymptotes to about 10^{-8} pb, within reach of the next round of DD searches. superCDMS, XENON-100, LUX

Ton-sized detectors essential for bino-like LSPs. 1t-xenon WARP, COUPP....

Targets using multiple nuclei can reveal multiple WIMP components.

Direct Detection also leads to observable signals over much of the parameter space of mirage unification models.

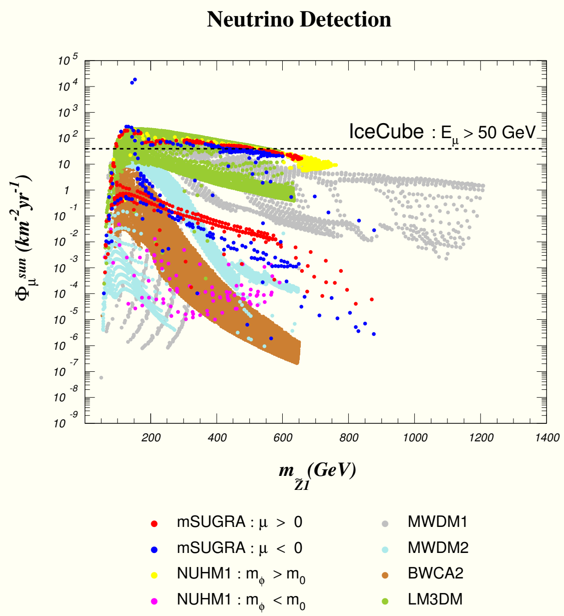


Relic-density-consistent mirage unification models

Indirect detection of dark matter

★ Annihilation of neutralinos accumulating in the sun give high energy neutrinos that can be detected in IceCube.

Baer,Mustafayev,Park,XT



IceCube has interesting sensitivity to models with mixed higgsino DM as LSP can be trapped in the sun and annihilate rapidly enough.

INDIRECT DETECTION OF DARK MATTER: COMMENTS

- ⋆ IceCube should be sensitive to MHDM neutralino WIMPS accumulated in the sun up to WIMP masses of 500-600 GeV.
- ⋆ Signals from WIMP annihilation to anti-particles in our halo are sensitive to WIMP distribution and to how anti-particles propagate in the not-well-known magnetic field. Greatest sensitivity in anti-deuterons (GAPS) and anti-protons (Pamela), and again for MHDM.
- ⋆ Gamma ray signals from our galactic centre extremely sensitive to halo profile. A signal at GLAST may serve to determine this profile!
- ⋆ Halo-annihilation signals tend to be enhanced in the Higgs-funnel region (though not always to observable levels).

mSUGRA Prejudices

- ⋆ Relic-density-consistent "bulk region" $\Rightarrow$ many light sparticles.
- ⋆ Higgs-funnel occurs only for large $\tan\beta$ values.
- ⋆ MHDM occurs only if scalars are essentially decoupled at the LHC
- ⋆ Lighter $\tilde{b}_1 \sim \tilde{b}_L$, lighter $\tilde{\tau}_1 \sim \tilde{\tau}_R$.

Each of these statements is false in one-parameter-extensions of mSUGRA that allow non-universality.

- ⋆ Rapid neutralino annihilation possible via very light $\tilde{u}_R/\tilde{c}_R$ or light $\tilde{\tau}_1 \sim \tilde{\tau}_L$ (with other scalars heavy) in NUHM models.
- ⋆ Higgs-funnel annihilation can be arranged for all values of $\tan\beta$, and MHDM for small values of scalar matter masses.
- ⋆ $\tilde{b}_L$ is very heavy if $M_2 \gg M_{1,3}$ at $Q = M_{\rm GUT}$.

Features of relic-density-consistent models

- ⋆ Most models accessible at the LHC
- ⋆ Frequently, the mass edge in $\widetilde{Z}_2 \to \widetilde{Z}_1 \ell\bar{\ell}$ decays should be observable at the LHC.
- ⋆ The mechanism that enhances neutralino annihilation in the early universe also tends to enhance the direct detection rate. MHDM models should be accessible in the next round of direct detection experiments, and possibly also at neutrino telescopes.
- ⋆ Indirect detection may facilitate the determination of the DM halo profile.

In the next several years, we hope there will be a lot of new data as we have many beautiful experiments running/coming on.

- ⋆ LHC, Direction WIMP detection searches: CDMS, XENON10, COUPP, larger noble gas/liquid detectors....
  Indirect detection: IceCube, PAMELA, GLAST,......
- ⋆ Probes of flavour physics in the b and c meson systems....also at the LHC. Must also probe lepton flavour violation. REMEMBER THAT WE DO NOT UNDERSTAND FLAVOUR CONSERVATION IN THE SUSY CONTEXT. Even if flavour violation is only in the Yukawa sector, KM matrix may not completely encode it!
- ⋆ We do not understand the goodness of CP in the SUSY context. Push experiments in meson systems to see if we can break the KM tyranny. Probe neutron and electron EDMs.
- ⋆ Planck Satellite, Probes of acceleration of the Universe

Dream Situation in Summer 2010

- ⋆ LHC experiments each have analysed ~ 3 fb^{-1} of data.
- ⋆ We may have data from the first year of the Planck Mission.
- ⋆ Our friends on direct detection WIMP searches are confused by their data because they have not realized the recoils they are seeing are caused by collisions from more than one halo DM component that they barely can resolve! Need experiments with several nuclei with range of masses.
- ⋆ The IDD searches, GLAST, PAMELA.....are all arguing about how the DM is distributed, but not saying anything about what the stuff is! Map our galactic halo.
- ⋆ BELLE data are showing some discrepancy with the KM model.
- ⋆ Rumours about 2.6σ effect suggesting an electron EDM.

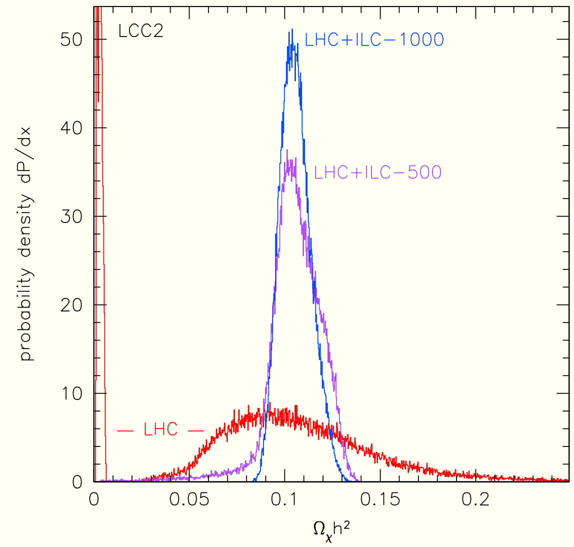
Fast-forward to 2020

- ⋆ At Snowmass 2019 we will have developed a tentative consensus about the new physics discovered at the LHC. *LC approved for construction

  I hope that we will have archived LHC data for subsequent re-analysis.

- ⋆ We will still be wondering what dark energy is.

We will ultimately have plots like this with real data.



Baltz, Battaglia, Peskin, Wizansky.

It is remarkable that determinations at the LHC can get the right order of magnitude for $\Omega_{\widetilde{Z}_1}$.

This may well be the only way to know DM consists of a single component.

A peaked plot such as this (with real data) would truly be a consumation of the HEP-Cosmology union.

CONCLUSIONS

- ⋆ WE ARE ENETERING A DECADE OF OPPORTUNITY WITH THE ADVENT OF THE LHC AS WELL AS OTHER FACILITIES THAT WILL ALLOW US TO STUDY STUFF FROM THE SKY.
- ⋆ PARTICLE PHYSICS AND COSMOLOGY WILL BECOME INTER-RELATED AT AN UNPRECENDENTED LEVEL.
- ⋆ I DO NOT KNOW WHAT NATURE HAS IN STORE FOR US, BUT WE MUST LOOK TO SEE WHAT WE FIND.

NON-UNIVERSAL HIGGS MASS PARAMETERS

FCNC constraints suggest particles with same gauge quantum numbers are (roughly) degenerate $\Rightarrow$ intergenerational universality of sfermion masses; $m(\tilde{u}_L) = m(\tilde{c}_L) = m(_{\mathrm{L}})$, etc.

Simple anstätz: Maintain high scale sfermion mass universality, but,

$$m_{H_u}^2(\mathrm{GUT}), m_{H_d}^2(\mathrm{GUT}) \neq m_0^2$$

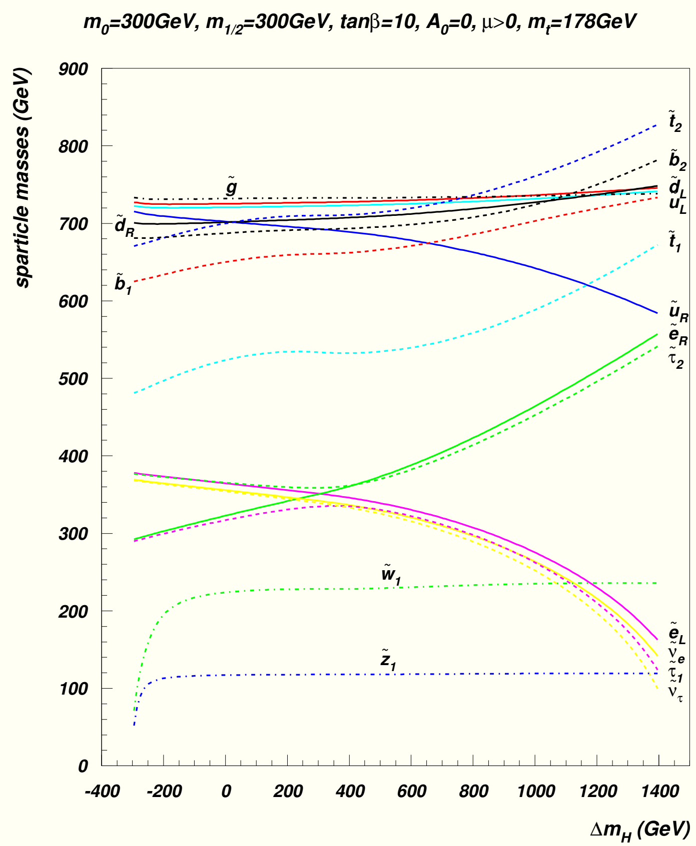
$$m_{H_u}^2 = m_{H_d}^2 \equiv sign(m_\phi)|m_\phi^2| \text{ (NUHM1 model)}$$

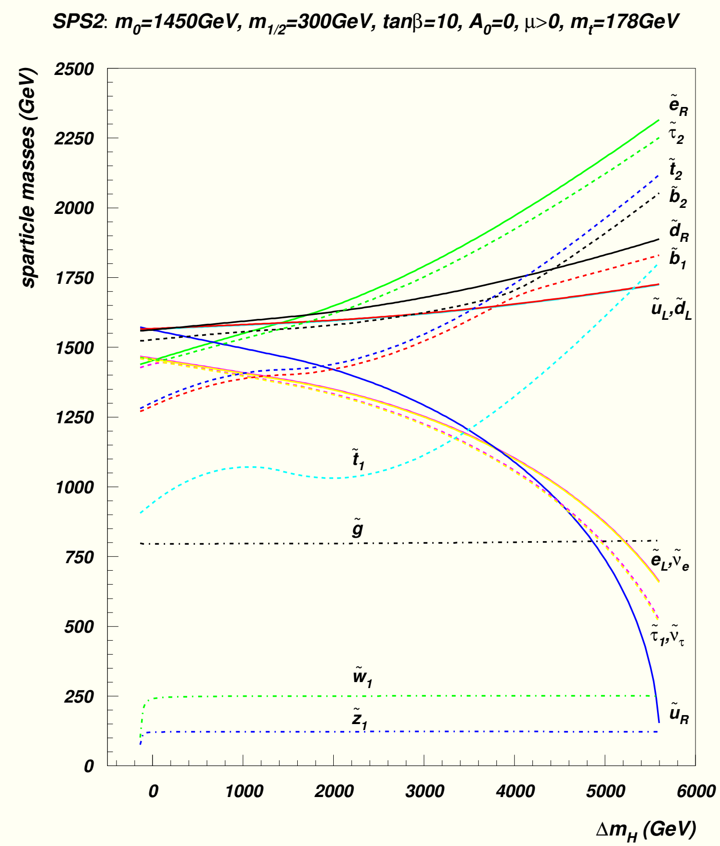
$$m_{H_u}^2 \neq m_{H_d}^2 \text{ (NUHM2 model)}$$

NUHM1 model completely specified by

$$m_0,\ m_\phi,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$$

NUHM2 can lead to funny SUSY spectra because $S \neq 0$.

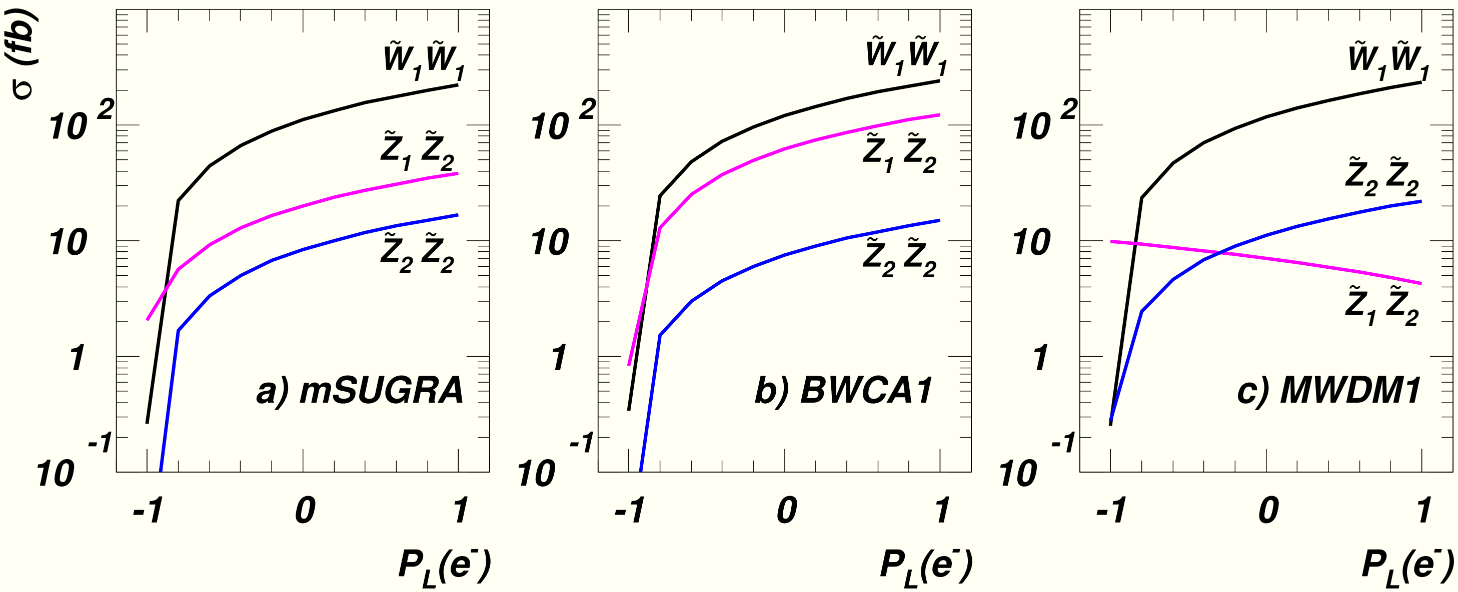




"Pseudo-bulk" region annihilation via LEFT staus; part of negative Δm_H region already probed at CDMS 2004!

"Pseudo-bulk" region annihilation via $\tilde{u}_R$, $\tilde{c}_R$ in right frame.

Distinction between mSUGRA, MWDM and BWCA "easy" at Linear colliders.



Large size of $\widetilde{Z}_1\widetilde{Z}_2$ cross section in BWCA directly traced to $M_1/M_2 < 0$.

$\gamma+ \not{E}_T$ events from $\widetilde{Z}_1\widetilde{Z}_2$ production and $\gamma\gamma+ \not{E}_T$, jj or $\bar{\ell}\ell + \gamma+ \not{E}_T$ events from $\widetilde{Z}_2\widetilde{Z}_2$ production.

Lower $M_3(\mathrm{GUT})$ w.r.t $M_1 = M_2$

How can gluinos make a difference to the relic density? (Belanger *et al.*; Mambrini and Nezri.)

Small $M_3(\mathrm{GUT}) \Rightarrow$ smaller evolution of squark mass squared as well as A_t parameters from gauge-gaugino loops $\Rightarrow$ smaller values for $X_t = m_{Q_3}^2 + m_{\tilde{t}_R}^2 + m_{H_u^2} + A_t^2$.

Then, because

$$\frac{dm_{H_u}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2 M_1^2 - 3g_2^2 M_2^2 + \frac{3}{10}g_1^2 S + 3f_t^2 X_t\right),$$

small X_t means $m_{H_u}^2$ evolves to LESS NEGATIVE values. Finally, because

$$\mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{(\tan^2\beta - 1)} - \frac{M_Z^2}{2}$$

small $M_3(\mathrm{GUT}) \Rightarrow$ reduced μ! $\Longrightarrow$ MHDM

Raise $M_2(\mathrm{GUT})$ with respect to $M_1 = M_3$

$$\frac{dm^2_{H_u}}{dt} = \frac{1}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2 S + 3f_t^2 X_t^2\right)$$

Usually, the last term drives $m^2_{H_u}$ to large negative values, so that $\mu^2 - \sim m^2_{H_u}$ is large.

However, if $M_2^2(\mathrm{GUT})$ is very large, it first drives $m^2_{H_u}$ upwards, before the top-Yukawa term takes over and drives it down, causing EWSB.

As a result of this initially "upward evolution", the weak scale magnitude of $-m^2_{H_u}$ is not as large, so that the resulting value of $|\mu|$ is smaller $\Longrightarrow$ MHDM.

LHC $\simeq$ ILC(1 TeV) as far as reach goes.

Large $\tilde{f}_L \tilde{f}_R$ splitting.

$m^2(\tilde{b}_R) < m^2(\tilde{b}_L)$!

Multiple mass edges.

Large DD cross section.