NEW PHYSICS @ THE LHC

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U. of Hawaii

LHC IS EXPECTED TO TURN ON SOON

Beam

Collisions

Physics

Luminosity

Understanding of detectors

Jets, electrons, muons, photons

W, Z Physics

Top quarks

TeV Scale NEW PHYSICS

HIGGS BOSON-LIKE OBJECTS

✡ REMINDER ✡

If we have elementary scalars in the low energy spectrum, and if we require that the predictions of the low energy theory (weak scale) are not wildly sensitive to details of high scale physics, THERE MUST BE NEW DEGREES OF FREEDOM NOT CONTAINED IN THE SM "JUST ABOVE" THE WEAK SCALE.

WE HOPE THAT

- These will be excited at LHC energy - See new particles
- At least see effects of tails of these excitations
- Unexpectedly large scattering amplitudes in EWSB sector

MANY PROPOSALS FOR NEW PHYSICS

- Eliminate the elementary scalar
  Higgs appears as a composite of new fermions bound by "new interactions". Many bnd states @ LHC

- Strong gravity @ "Weak Scale"
  Gravity appears weak because flux is lost in extra dimensions
  Compactified Extra dim^{ns} KK excit^{ns}
  Warped Dimensions

- Postpone the scale of excit^{ns}
  Arrange for sensitivity to UV physics to appear @ Multi-loops
  Scale of newphysics $\uparrow \sqrt{16\pi^2}$

- Obviate perturbative arguments by strongly coupled longitudinal W_L's, Z_L's. Resonances

- Introduce a symmetry that stabilizes scalars in the same way that chiral/gauge symmetries stabilize fermions/gauge bosons.

Supersymmetry

- Weakly coupled to high scales (agreement of LEP with SM)
- Sensible extrapolation to high scale (unif^{n} of gauge couplings, m_b/m_τ)

- Accept the strong sensitivity to UV physics L-word & All that.

Rather than go model-by-model & make a list of LHC capabilities for each in a Workshop on DM & Colliders, I'll focus only on WEAK SCALE SUPERSYMMETRY

- Where we are today.
- What we can hope to probe at the LHC
- Assuming neutralinos are stable, what does WMAP tell us about LHC expectation?
- What are the prospects for CDM detection in non-collider experiments?

LEP2 LIMITS

$\tilde{e}, \tilde{\mu}, \tilde{\tau}$ $\gtrsim$ 99 GeV, 94 GeV, 85 GeV $\Delta m > 10$ GeV

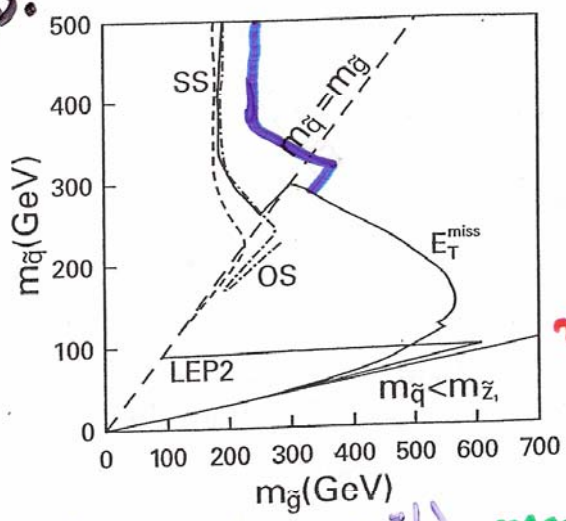
$\tilde{t}_1, \tilde{b}_1$ $\gtrsim$ 94-99 GeV depending on mixing θs.

$\tilde{W}_1$ > 103.5 GeV, $m_{\tilde{q}} > 300$ GeV, $\Delta m > 106$ GeV, $M_1/M_2 \simeq 1/2$

$\tilde{W}_1$ > 91 GeV, $m_{\tilde{\nu}_e} > 500$ GeV for small Δm

TEVATRON

IMPROVED!
Nachtmann



$m_{\tilde{g}} \gtrsim 200$ GeV indep of $m_{\tilde{q}}$

$m_{\tilde{q}} \simeq m_{\tilde{g}} \gtrsim 260$ GeV

DØ Run II (310 pb^{-1}) $m_{\tilde{g}} > 240$ GeV

$m_{\tilde{g}} \simeq m_{\tilde{q}} \gtrsim 325$ GeV

leptonic & E_T^{miss} Searches Competetive

WHAT WILL WE SEE AT THE LHC?

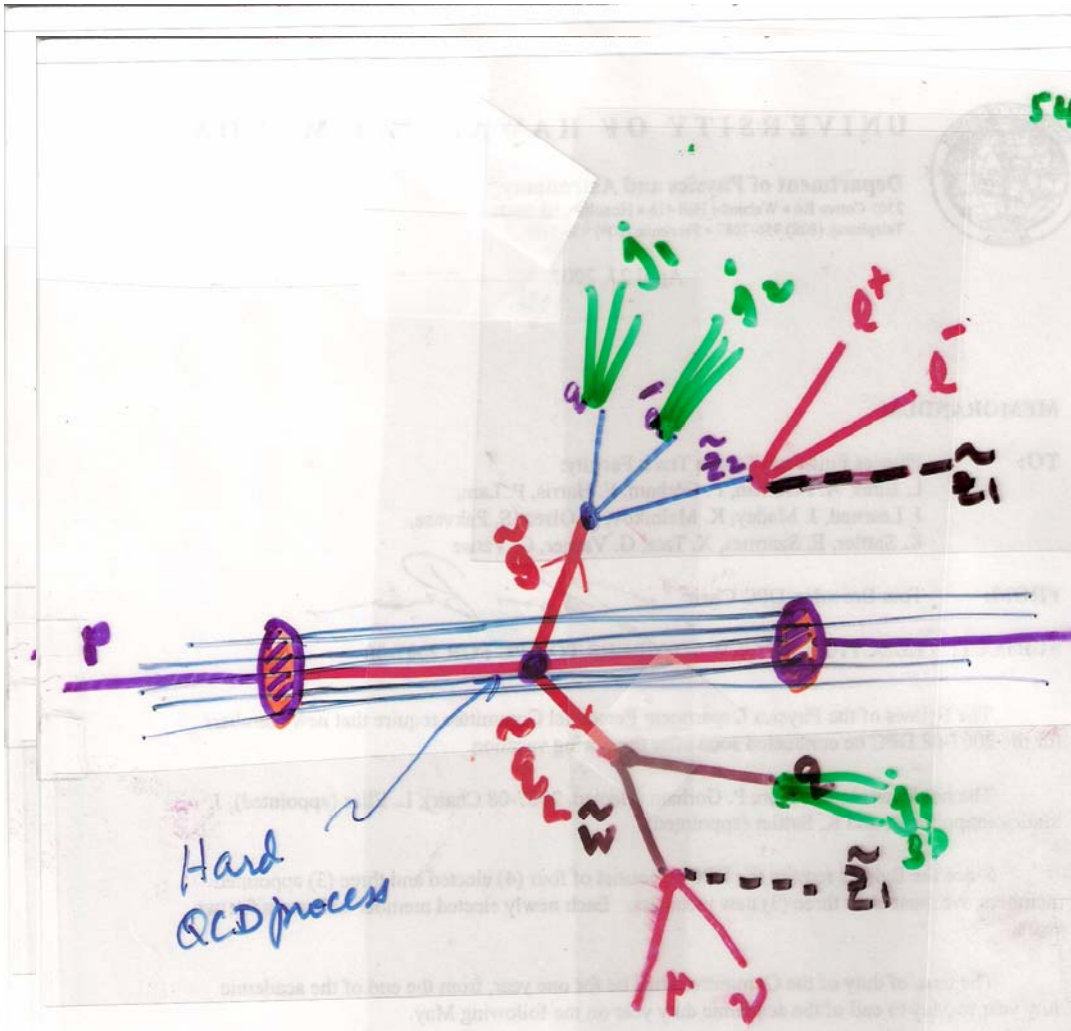
- Superpartners with QCD interactions most likely to be dominantly produced $\tilde{q}, \tilde{g}$
- Superpartners with SU(2) int^{ns} $\tilde{W}, \tilde{Z}$
- Superpartners with "only" $U(1)_Y$ int^{ns} $\tilde{B}$

[Of course, this hierarchy can be upset by kinematics]

Decays of whatever is produced also depend on the mass spectrum of superpartners.

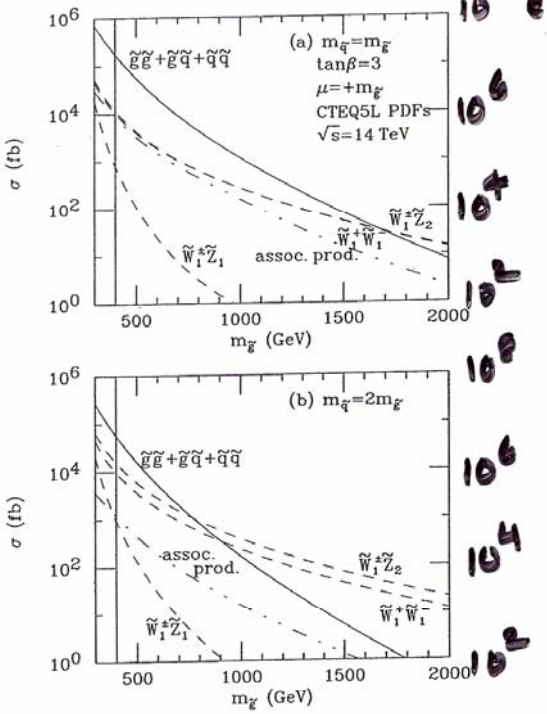
AGNOSTIC ANALYSIS INTRACTABLE

Resort to models of superpartner masses


Hard
QCD process

LHC: SUSY FACTORY

10^8 evts per $100 fb^{-1}$



Strong production dominates out to $m \gtrsim 1.7$ TeV if $m_{\tilde{q}} = m_{\tilde{g}}$ even though coloured particles are heavy!

For heavy squarks, dominance out to 800 GeV.

SPARTICLE MASSES DEPEND ON HOW SUPERPARTNERS "FEEL" SUSY BREAKING.

GRAVITY + technical assumptions	mSUGRA
GAUGE INT^{NS}	GMSB
WEYL ANOMALY	AMSB
⋮	
Mixture of gravity med. by moduli + AMSB	MM-AMSB (Mirage Unif^{n}) Mirage Mediation

mSUGRA $m_0, m_{\frac{1}{2}}, \tan\beta, A_0$ Sgn μ

HIGH SCALE UNIVERSALITY

mGMSB Λ, M_{mess}, n_5, $\tan\beta$, Sgn μ, C_{grav}

$m_i \propto g_i^2$

mAMSB m_0, $m_{3/2}$, $\tan\beta$, Sgn μ

$m_i \propto \beta_i$

MMAMSB $m_{3/2}$, α, $\tan\beta$, Sgn μ, n_i ← discrete

• HANDFUL OF PARAMETERS FIX EVERYTHING

(because of underlying assumptions)

Most likely wrong

TRACTABLE MODELS WHICH SERVE TO GUIDE OUR THINKING.

ATLAS $10 fb^{-1}$

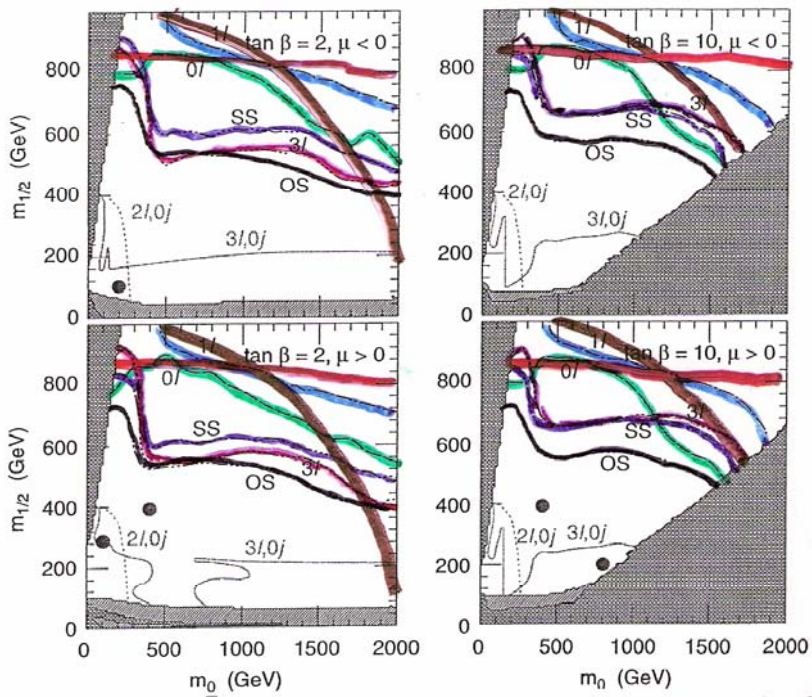


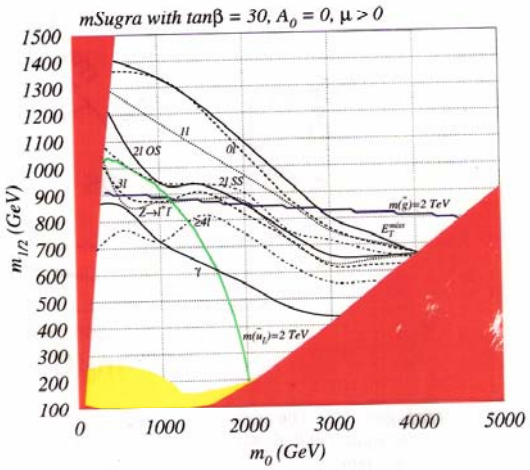
Figure 20-3 Reach for $S/\sqrt{B} > 5$ for various SUSY signatures in the SUGRA parameter space with $A_0 = 0$. 0l: Jets, E_T^{miss}, and no leptons. 1l: Jets, E_T^{miss}, and 1 lepton. SS: Same-sign dileptons. OS: Opposite-sign dileptons. 3l: trileptons. 3l,0j: trileptons with jet veto. 2l,0j: dileptons with jet veto. See Figure 20-1 for the explanation of the shaded regions.

SUSY SIGNAL IN MANY CHANNELS

Relative rates have info on parameters

Reach out to $m_{\tilde{g}} \approx 1.7 - 1.8$ TeV with $10 fb^{-1}$

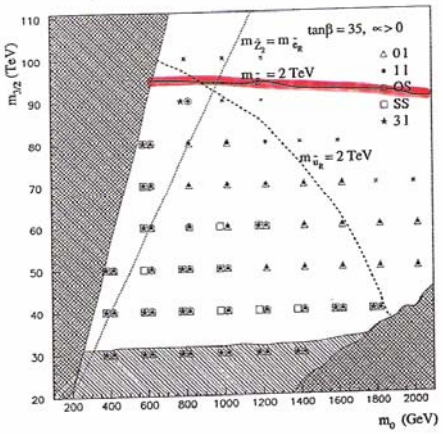
Alternative more involved strategy CMS
$100 fb^{-1}$



Notice
γ signal

Figure 1.6: The 5σ reach of the CERN LHC in the $m_0 - m_{1/2}$ plane of the mSUGRA model for an integrated luminosity of 100 fb^{-1}. The shaded regions are excluded by theoretical and experimental constraints.

AMSB MODEL , $10 fb^{-1}$



Reach qualitatively similar when expressed in terms of $(m_{\tilde{g}}, m_{\tilde{q}})$ as in mSUGRA.

$\tilde{g}$, $\tilde{q}$ dominant signal source

Signal determined by "kinematics" as long as Δm, the "mass gap" is large enough, so that daughters give visible jets, leptons, ... & E_T^{miss}

- DETAILS OF RELATIVE TOPOLOGIES ARE MODEL-DEPENDENT.

The CDM Density is well determined today

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

Assuming Standard Big Bang Cosmology & thermal production,

$$\Omega_{\tilde{Z}_1} h^2 \lesssim 0.13$$

Typically, $\Omega_{\tilde{Z}_1} h^2 \sim 0.1 \left(\frac{M_{SUSY}}{100\,GeV}\right)^2$

For $M_{SUSY} \simeq$ few 100 GeV, this is a bit too high UNLESS $\tilde{Z}_1^s$ CAN ANNIHILATE VERY EFFICIENTLY IN THE EARLY UNIVERSE

SPECIAL REGIONS OF PARAMETERS PICKED OUT

JACKING UP $\sigma_{\tilde{\chi}\tilde{\chi}_1 \to \text{STUFF}}$

- **MASS ADJUSTMENT**

1) $2m_{\tilde{\chi}_1} \gtrsim m_A, m_H, m_h, M_Z$

Resonance enhancement

2) $m_{\tilde{\chi}_1} \simeq m(\tilde{P}^{\pm})$ $[\tilde{\tau}, \tilde{t}_1, \tilde{W}]$

If $\tilde{\chi}_1$ is close in mass to a charged or coloured particle, and remains in thermal equilibrium with it, its density will be reduced because charged sparticles annihilate fast.

3) Enhanced annihilation to $t\bar{t}$ via "not so heavy" $\tilde{t}$

"COMPRESSED SUSY SPECTRUM"

$m_t < m_{\tilde{\chi}_1} \lesssim m_{\tilde{\chi}_1} + 100\,\text{GeV}$ Steve Martin

$m_{\tilde{\chi}_1} + 25\,\text{GeV} \lesssim m_{\tilde{t}_1} \lesssim m_{\tilde{\chi}_1} + 100\,\text{GeV}$

- COMPOSITION ADJUSTMENT Park.

$\tilde{Z}_1$ typically $\simeq \tilde{B}$ $\Rightarrow$ Small cross-sections because of suppressed couplings to Z

IF WE CAN INCREASE HIGGSINO or WINO CONTENT, ANNIHILATION RATE CAN BE INCREASED.

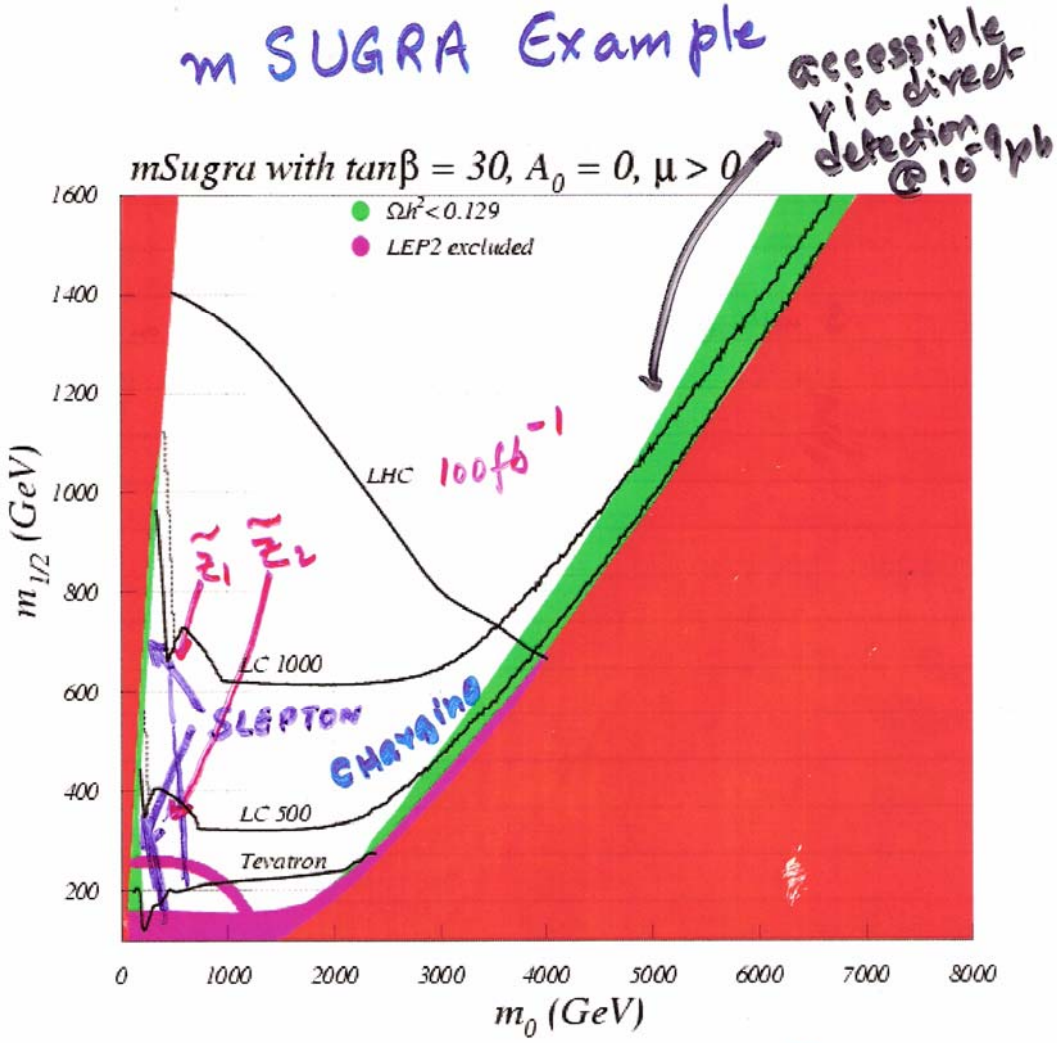
MIXED HIGGSINO DM (MHDM)

MIXED WINO DM. (MWDM)

VIOLATES GAUGINO MASS UNIFN.

BINO-WINO CO-ANNIHLATION (BWCA) FROM PREV. PAGE

m SUGRA Example



LHC can beat ~~charg~~ L.C.
Except in the small μ-sliver
D.M. favoured region.

HOW ROBUST ARE THESE REGIONS TO SMALL CHANGES OF THE FRAMEWORK?

Relax mSUGRA universality in controlled ways.

1) Higgs matter scalar universality

2) Gaugino mass universality.

(Auxilliary) Field that breaks SUSY also breaks GUT symmetry.

Non-Universal Higgs Mass NUHM

$m_{H_u}^2, m_{H_d}^2 \neq m_0^2$

NUHM1 $m_{H_u}^2 = m_{H_d}^2$ $m_0, m_{1/2}, m_0^2, A_0, \tan\beta$, sgn μ

NUHM2 $m_{H_u}^2 \neq m_{H_d}^2 \Leftrightarrow \mu^2, m_A^2$

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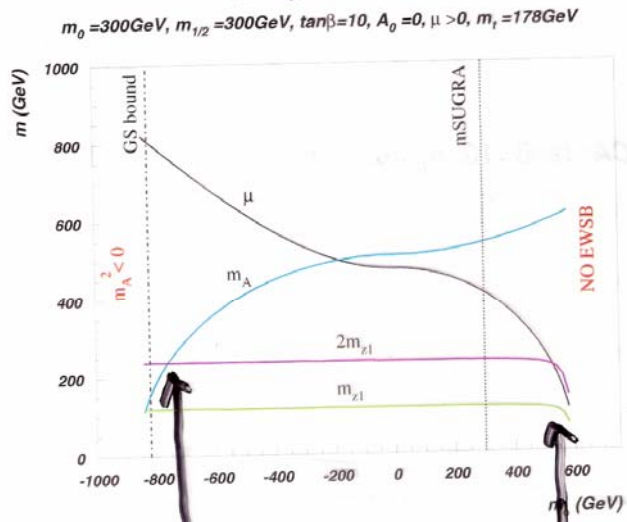
NUHM1



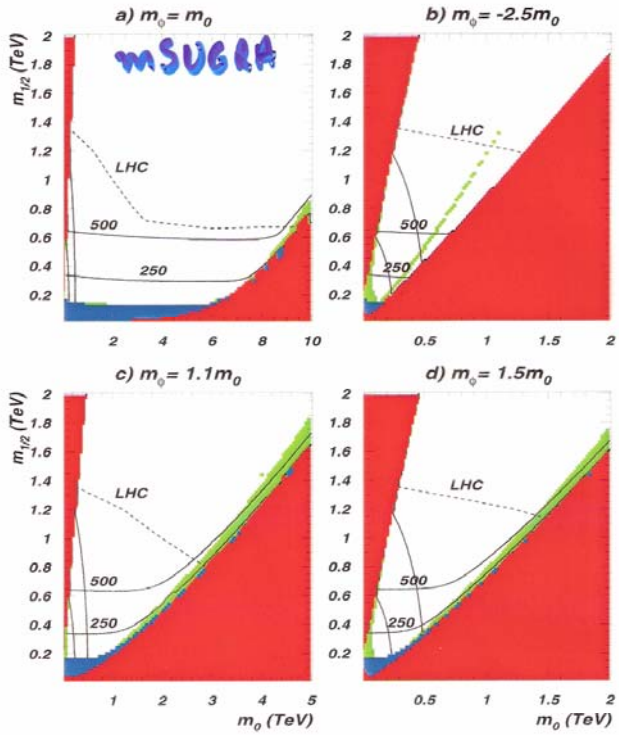
Resonance annihilation in early universe

Higgsino-like $\tilde{Z}_1$

In NUHM1 model can have "A-funnel" annihilation or MHDM for all values of tan β & m_0.

Even more freedom in NUHM2!

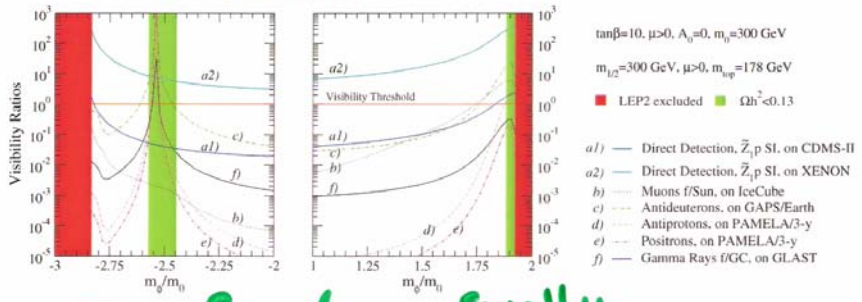
tanβ=10



Look @ Horizontal Scale!

- Higgs funnel for low tan β
- FP/HB region for modest m_0
- LHC covers most of the WMAP region except along the HB/FP part.
- b-tagging increases reach by ~20% in $m_{\tilde{g}}$

NUHM1



Higgs funnel small μ

- Observable signal @ Stage 3 Direct Detection Expt a2)
- Anti-particle & γ ray searches c, d, e, f) Burkert profile in resonance region, + possibly in low μ region
- IceCube Signals possible in MHDM case – no guarantees!

$\boxed{\text{MHDM = DM that couples to } Z^0}$

Santoso

NUHM 2

- $\tilde{u}_R$, $\tilde{c}_R$ can be very light - even accessible @ Tevatron - while other squarks are heavy
- $\tilde{\tau}_1 \simeq \tilde{\tau}_L$, $\tilde{e}_L$ light.

  "Pseudo bulk region" - bino-like LSP.
- LC reach can be "enormous" if μ is small

NON-UNIVERSAL GAUGINO MASSES

- The VEV of SUSY BRKING FIELD NOT A GUT SINGLET

$$\langle F_{ab} \rangle \neq \delta_{ab}$$

- If $M_1^{WEAK} \simeq M_2^{WEAK}$

$\tilde{Z}_1$ gets a significant $\tilde{W}$ component

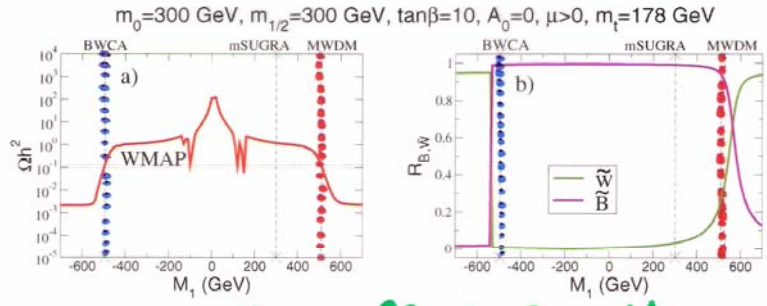
[$M_1 = M_2 \Rightarrow \tilde{Z}_1 = \tilde{B}\cos\theta_W + \tilde{W}\sin\theta_W \equiv \tilde{\gamma}$]

MIXED WINO DM.

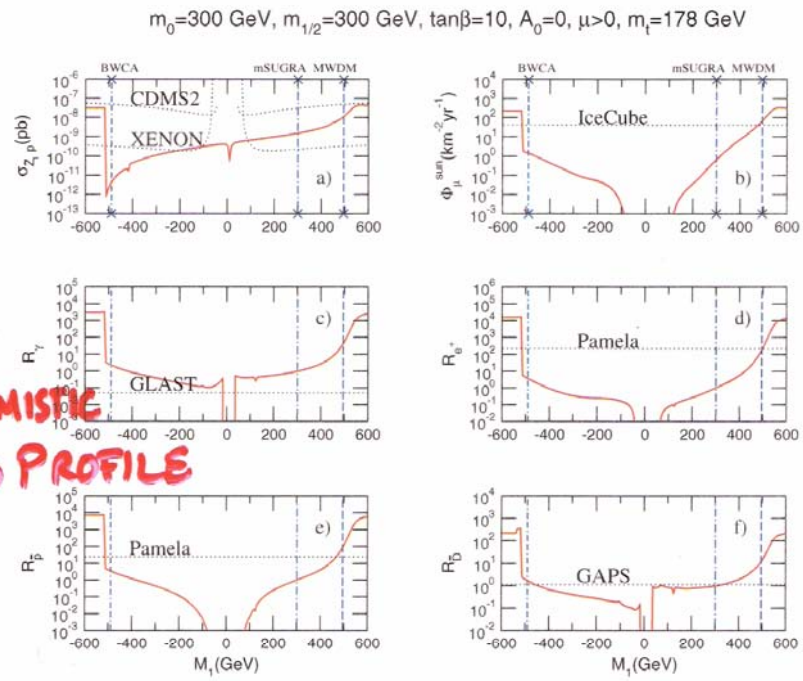
- If $M_1^{WEAK} \simeq -M_2^{WEAK}$

$\tilde{Z}_1 = \tilde{B}$, $\tilde{Z}_2 = \tilde{W}$

CLOSE IN MASS $\Rightarrow$ $\tilde{B}$-$\tilde{W}$ Co-annihilation



Similar effect for M_2 varying



OPTIMISTIC HALO PROFILE

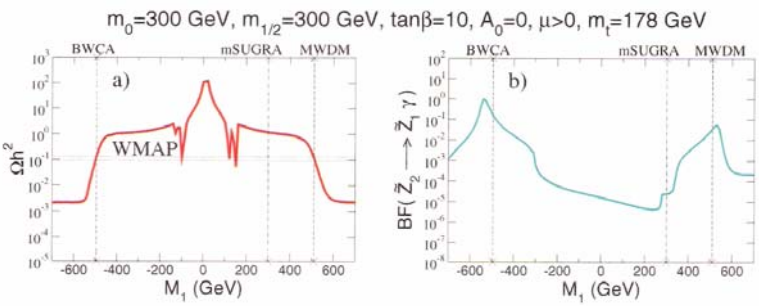
Bino DM hard to see

Wino DM may just be possible

In both MWDM & BWCA scenarios

$m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$ is small

$\Rightarrow$ 2 body decays strongly preferred over "lower order" three body decays by phase space.



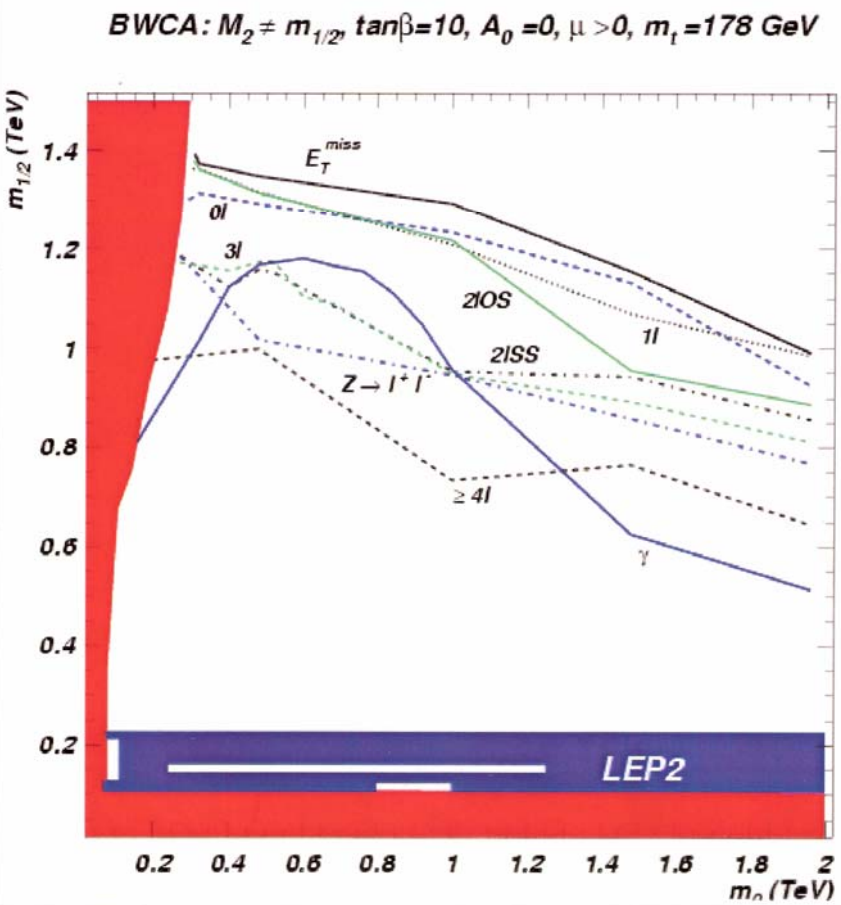
$B(\tilde{Z}_2 \to \tilde{Z}_1 \gamma)$ enhanced.

BWCA – no $\tilde{W}^{\pm} W^{\mp}$ loop

Value of $\tilde{Z}_2 \to \tilde{Z}_1 \gamma$ BF sensitive to dynamical & Kinematic details.

- Because of smallness of mass gap, $\tilde{\chi}_2 \to \tilde{\chi}_1 \ell\bar{\ell}$ dilepton edge present all over parameter space.

- Notice signal with hard isolated photons - will not be confused with gauge-mediated SUSY brking.



- If $M_1^{GUT} = M_2^{GUT}$ can be violated why not mess around with M_3^{GUT}?

- Who cares as far as WMAP goes?

If $M_3^{GUT} \downarrow$ we can get smaller $|\mu|$, and hence mixed higgsino DM.

[Belanger et. al; Nezri & Mambrini]

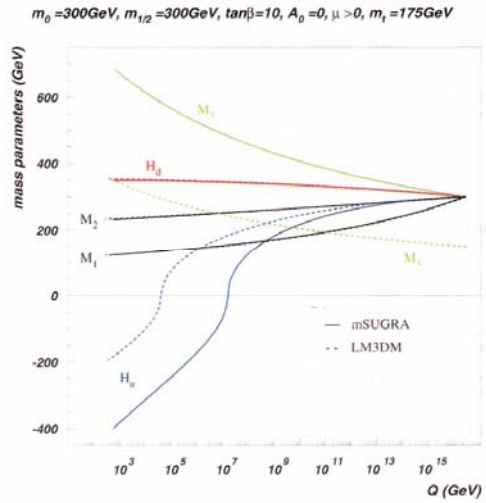
$$\frac{dm_{H_u}^2}{dt} = \frac{1}{8\pi^2}\left[-\frac{3}{5}g_1^2 M_1^2 - 3g_2^2 M_2^2 + 3f_t^2\left(m_{Q_3}^2 + m_{\tilde{t}_R}^2 + A_t^2 + m_{H_u}^2\right)\right]$$

Small $|M_3| \Rightarrow$ smaller red term.

So $m_{H_u}^2$ not driven AS NEGATIVE!

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

So μ^2 is smaller!

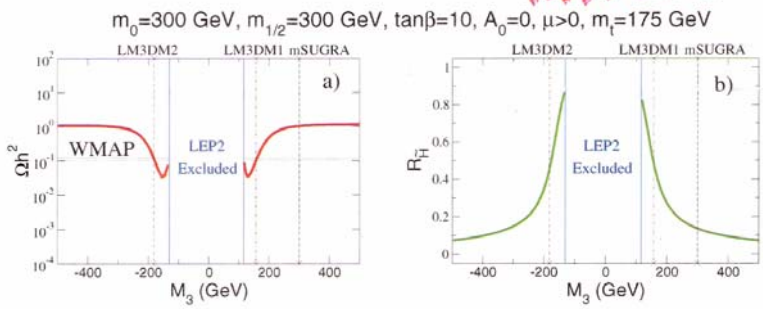


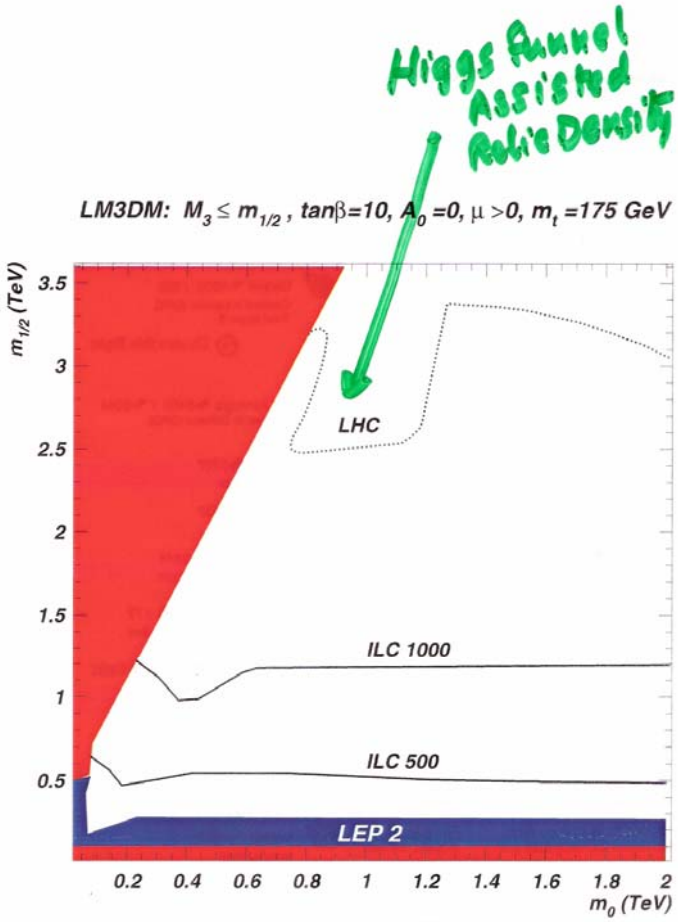
Solid lines mSUGRA

Dashed lines Low M_3 DM

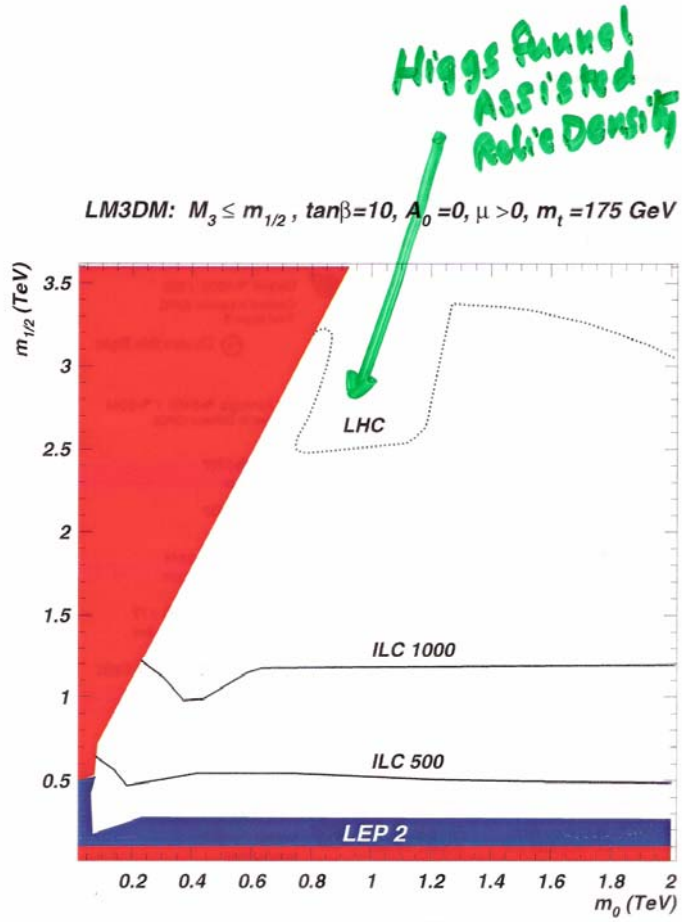
LM3DM

Small $m^2_{H_u}$(Weak) ⇒ Small μ^2
⇒ Agreement with WMAP
MHDM.





- Observable $\tilde{\chi}_2 \to \tilde{\chi}_1 l \bar{l}$ mass edge due to reduced μ. Violation of $M_1 : M_2 : M_3$
- Reduction of SS dilepton rate from $\tilde{g}$ if radiative decays enhanced.



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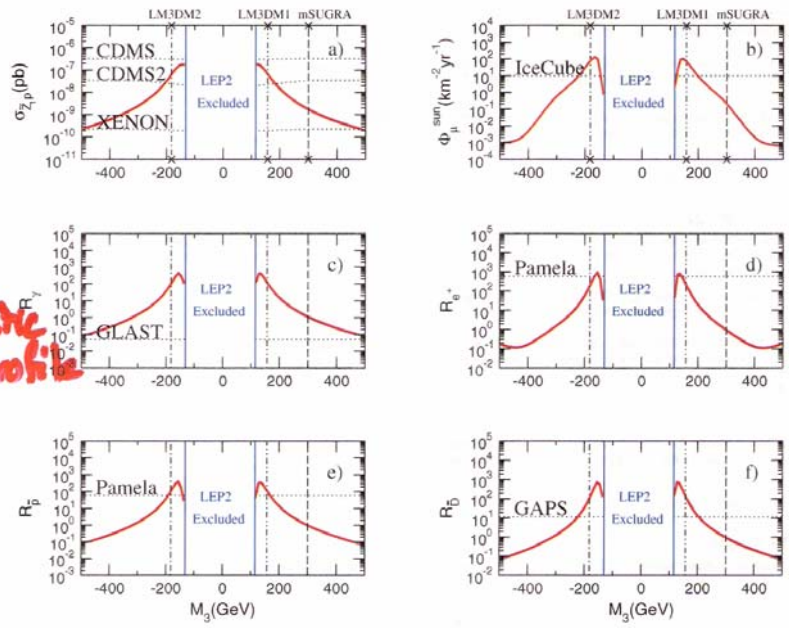
m_0=300 GeV, $m_{1/2}$=300 GeV, tanβ=10, A_0=0, μ>0, m_t=175 GeV



Optimistic halo profile

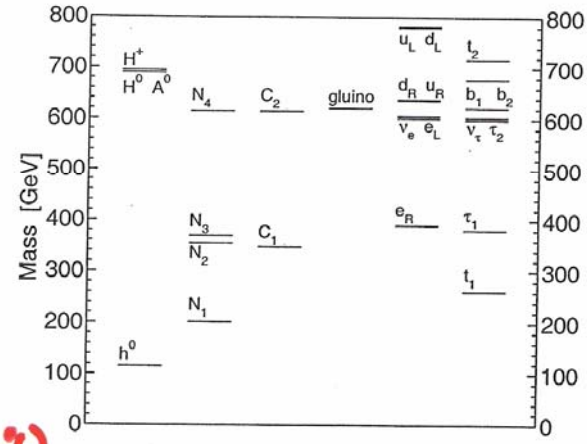
Possibly observable Signals in indirect detection, but not guaranteed

Good prospects for Direct Detection

MHDM.

Steve Martin's "Compressed SUSY"

ANOTHER LMSDM VARIANT – "Small μ"



$\tilde{\chi}_1 \tilde{\chi}_1 \to t\bar{t}$

$\tilde{q}_R \to q\tilde{\chi}_1$

$\tilde{q}_L \to q\tilde{g}$

$\to q\tilde{W}_2$ (22%)

$\tilde{g} \to t\tilde{t}_1$

$\tilde{t}_1 \to \tilde{\chi}_1 c$ (bW $\tilde{\chi}_1$ closed)

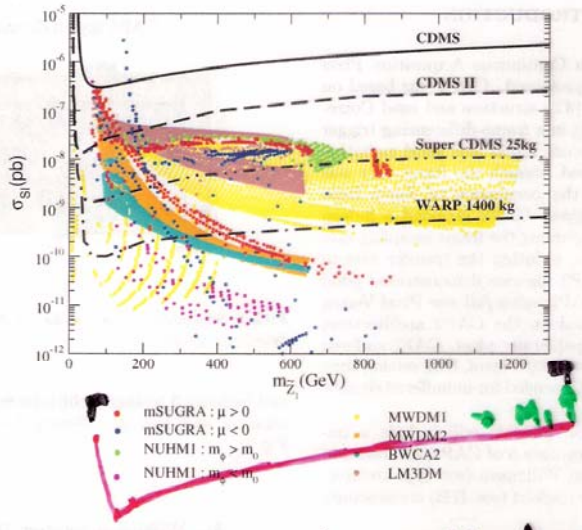
$\boxed{\text{Novel feature } \tilde{W}_1 \to \tilde{t}_1 b}$

SUSY rich in b & c jets.

Leptons mostly only from τ-decays

Bino DM – Bad for direct/indirect detection.

WMAP RELIC DENSITY CONSISTENT MODELS



XENON 10
APS meeting

- Mixed Higgsino DM typically has $\sigma \gtrsim 10^{-8}$ pb : IMPORTANT BENCHMARK.
- Many models detectable by WARP 1400 kg
- Bino DM case is the most difficult

MIXED MODULUS-ANOMALY MEDIATED SUSY BRKNG

AKA

MIRAGE UNIFICATION AKA MIRAGE MEDIATION

- IN MODELS WITH GRAVITY-MEDIATED SUSY BREAKING, MODULI-MEDIATED CONTRIBUTIONS (tree-level) DOMINATE THE LOOP-LEVEL AMSB CONTRIBUTIONS.

- IN MM-AMSB, these are comparable

- Inspired by KKLT construction of a string compactif^{n} with fluxes that leads to a
  - calculable ground state
  - positive cosmological constant
  - SUSY breaking

Inspired a novel model-building exercise.

Choi, Falkowski, Nilles, Olechowski, Pokorski
Choi, Jeong, Okumura; Falkowski, Lebedev,
Mambrini; ....

SSB Parameter Pattern

$$M_a = (\alpha + b_a g_a^2) M_s$$

$$A_{ijk} = ((+\beta - n_i - n_j - n_k)\alpha + \gamma_i + \gamma_j + \gamma_k) M_s$$

$$m_i^2 = ((1-n_i)\alpha^2 + 4\alpha\xi_i - \dot{\gamma}_i) M_s^2$$

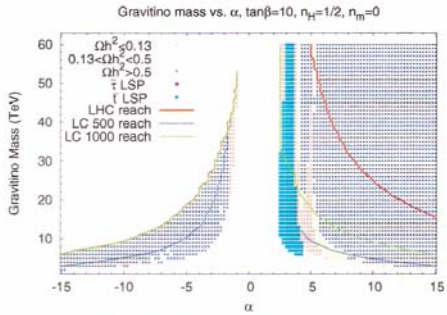
$$M_s \equiv \frac{m_{3/2}}{16\pi^2}$$

$$\boxed{m_{\frac{3}{2}}, \alpha, \tan\beta, \mathrm{Sgn}\,\mu ; n_i}$$

α : Phenom. parameter that fixes ratio of AMSB & modulus-mediated contrib^{ns}

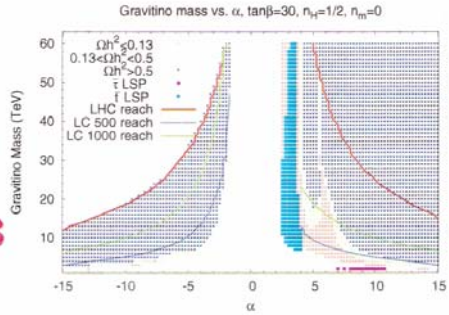
n_i - discrete #^{s} $0, \frac{1}{2}, 1, \frac{2}{3}, \ldots$

BWCA

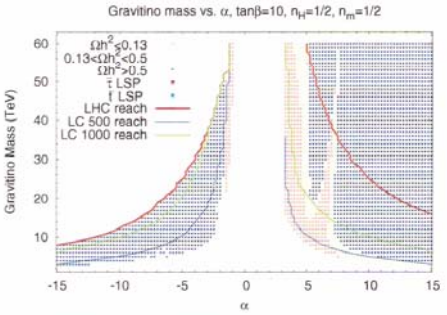


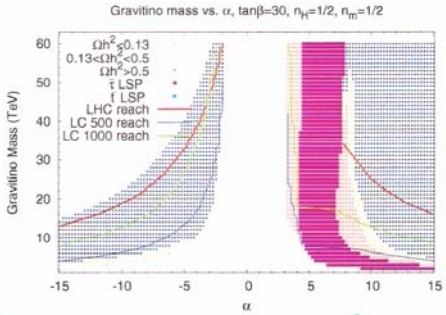
$\tilde{t}$ - Co-annih.
Higgs funnel
Tevatron $\tilde{t}$ opportunity

Probably no EW scale Baryogenesis via light $\tilde{t}_1$



Also MHDM



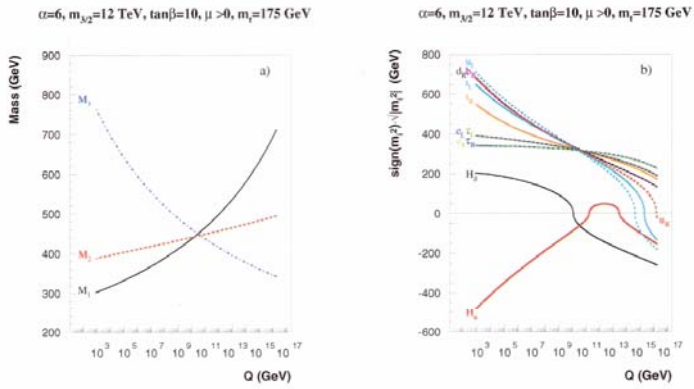


$\tilde{\tau}$ - Co-annih.

Mixed $\tilde{W}$ - $\tilde{B}$ - $\tilde{H}$ DM

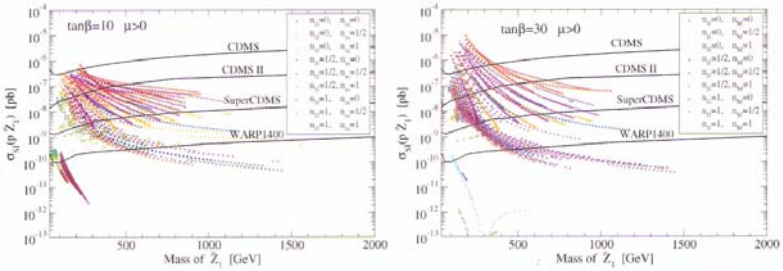
LHC Covers most allowed region

WHY MIRAGE UNIFICATION?



3rd Gen. & Higgs unify special

DIRECT DARK MATTER DETECTION HAS EXCELLENT PROSPECTS IN THIS CLASS OF MODELS



FEW ISOLATED CASES OF $\tilde{B}$ LSP via BWCA

SUMMARY OF MODELS

		D.D.	LHC
MHDM	FP/HB NUHM LM3DM	$\sigma \gtrsim 10^{-8}$ pb	heavy $\tilde{q}$; ino spectrum accessible $\tilde{q}$; ino spec. "Light $\tilde{g}$"; Enhanced $\tilde{g} \to g \tilde{\chi}_i$
A-funnel	mSUGRA NUHM	Maybe below even WARP 1400 for $m_{\tilde{\chi}_1} \gtrsim 350$ GeV	Several Higgs bosons [tan β]
BinoDM	$\tilde{\tau}$-coann BWCA $\tilde{t}$-ann.	σ_{SI} falls off v. fast with $m_{\tilde{\chi}_1}$	γ signals [Dutta et. al] Spectrum, Enhanced γ Signal Excess of b, t.
MWDM		Sensitive to $M_1 \uparrow$ or $M_2 \downarrow$	Spectrum, Enhanced γ Separate @ LC
MM-AMSB		Mostly Good prospects WARP 1400 out to $m_{\tilde{\chi}_1} \gtrsim 1200$ GeV [almost min @ 500 GeV]	MIRAGE UNIF. [LC needed]

INDIRECT DETECTION

- Have to exercise caution in making strong statements bcs. of halo modelling uncertainties. [IceCube is an exception.]

- Signal @ IceCube ⇒ Higgsino Comp. a.k.a Coupling to Z.

- In general, if the relic density is obtained by adjusting the Composition of the neutralino, the Direct Detection rate is increased.

⇓

"Generic parameters" underestimate $\sigma_{SI}(\tilde{Z}, P)$.

- Collider, DD and indirect detection signals will provide independent information that will guide us to the underlying framework. 10^{-8} pb a BENCHMARK!
- LC essential diagnostic tool if it has enough oomph.
- Important to sort out if DM has more than one component. LC is essential! [Balt3]

(except p'haps in special cases)

- Knowing we have seen <u>all</u> the DM will be really cool.
- Direct Detection from multiple nuclei may be very helpful.