Supersymmetry, dark matter and the LHC

XERXES TATA
University of Hawaii
Although Fayet had been working on it before all of us, supersymmetry phenomenology 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 the only rationale for the sparticle mass scale to be in the TeV region......of interest to the LHC.

TODAY THE SITUATION IS DIFFERENT.

LEP has measured the 3 gauge couplings, and these unify well in 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 mass scale is around a TeV....**Thermal DM, Standard Big Bang cosmology.**

A REMARKABLE TRIPLE COINCIDENCE OF SCALES!!!
GAUGE COUPLING (NON)-UNIFICATION

\[ \frac{1}{\alpha_1}, \frac{1}{\alpha_2}, \frac{1}{\alpha_3} \]

\( Q \text{ (GeV)} \)

\( \alpha_1^{-1}, \alpha_2^{-1}, \alpha_3^{-1} \)

a) SM

b) MSSM-2HD
c) MSSM-4HD

X. Tata, “Workshop on Low Energy Precision EW Physics in the LHC Era”
GENERIC SUSY CREATES NEW PROBLEMS

1) Renormalizable baryon and lepton number violating operators
Fixed by imposing conserved $R$-parity

[Other phenomenological fixes possible. Lose natural DM candidate!]

178 arbitrary parameters, mostly in the SUSY breaking sector! ⇒ Intractable phenomenology.

2) Flavour violation in hadron and lepton sectors
Problem generic to ANY theory with many scalars

$$\bar{q}_f \Gamma \tilde{g} \tilde{q}_f \rightarrow \bar{q}_m U^\dagger \Gamma \tilde{g} \tilde{U} \tilde{q}_m,$$
where $q_f = U q_m, \tilde{q}_f = \tilde{U} \tilde{q}_m$.

Problem: $U^\dagger \tilde{U}$ is not diagonal, so every quark couples to every squark ⇒ Unwanted quark FCNC processes at 1 loop level.

Analogous situation for leptons.

CANNOT WORK WITH GENERIC MODELS ⇒ VITAL CLUE ABOUT HOW MSSM SPARTICLES “FEEL” SUSY BREAKING.
Solutions to the flavour problem

★ Arrange $U^\dagger \tilde{U} = I$ $\implies$ ALIGNMENT
★ $\tilde{U}$ arbitrary if $\tilde{q}$ with same Q Nos. are degenerate! $\implies$ DEGENERACY
★ Suppress unwanted FC effects by making sparticles heavy $\implies$ DECOUPLING

Many well studied models use the degeneracy option. What scale degeneracy?

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.
For tractable phenomenology, we are forced to resort to models. Based on untested assumptions about high scale physics. However, these assumptions will be testable if sparticles are discovered and their properties determined.

MSSM parameters fixed in terms of a handful of parameters, usually renormalized at a much higher scale $\Rightarrow$ Not directly measurable.

MSSM parameters depend on how MSSM sparticles feel SUSY breaking, and not so much on the dynamics of SUSY breaking.

MODELS ARE CHARACTERIZED BY THE MECHANISM FOR THE MEDIATION OF SUSY BREAKING (between the SUSY breaking and MSSM sectors).

Sparticle spectrum characteristic of the model.
★ Gravity-mediated SUSY breaking. Always present because gravity exists.
Problem with flavour needs a technical assumption about Kähler potential.
mSUGRA model UNIVERSAL SSB parameters at $Q = M_{GUT}$

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

★ Gauge-mediated SUSY breaking. GMSB model $m_i \propto g_i^2 \implies$ Coloured
sparticles heaviest, sparticles with just hypercharge interactions lightest.
GRAVITINO MAY BE THE LSP.

$\Lambda, M, n_5, \text{sign}(\mu), C_{grav}$

★ Anomaly-mediated SUSY breaking Problem with sfermion mass squared
mAMSB model $m_i \propto \beta_i \implies$ neutral wino LSP. Tiny mass gap with chargino.

$m_0, m_{3/2}, \tan \beta, \text{sign}(\mu)$
Generalize high scale scalar SSB parameters so that these are not a new source of flavour violation.

\[ m_{Q,L}^2 = m_{(Q,L)}^2 I, \]
\[ m_{U,D,E}^2 = m_{(U,D,E)}^2 [c_{U,D,E} I + R_{U,D,E} f_{u,d,e}^T f_{u,d,e}^* + S_{U,D,E} (f_{u,d,e}^T f_{u,d,e}^*)], \]
\[ a_{u,d,e} = f_{u,d,e} [A_{(u,d,e)} I + W_{u,d,e} f_{u,d,e}^* f_{u,d,e} + X_{u,d,e} (f_{u,d,e}^* f_{u,d,e})], \]
\[ R_\bullet = S_\bullet = W_\bullet = X_\bullet = 0, \quad c_\bullet = 1 \]
in usually considered models.

Doublet sfermion mass matrices need to be universal, but singlet sfermion mass matrices and \( a \)-parameter matrices can be generalized.

Again, be cautious about drawing strong conclusions from flavour constraints.
Mixed Modulus-Anomaly Mediated SUSY Breaking

Mixture of 1 and 3 MM-AMSB mediation, Mirage-mediation, Mirage unification

Universality of SSB parameters at a scale $\mu_{\text{mirage}}$ where there is no physical threshold. NOVEL PHENOMENOLOGY POSSIBLE.

Usually, AMSB $\ll$ modulus-mediated SUSY breaking.

MM-AMSB structure of MSSM soft SUSY breaking terms arises if the moduli of type IIB superstring are stabilized because space curls up with fluxes (non-zero field strengths) along the extra dimensions. (Kachru, Kallosh, Trivedi and Linde toy scenario)

KEY POINT

Scale of modulus-mediated contributions to MSSM SSB parameters, $m_{\text{SUSY}} \ll m_3/2$, so may be comparable or smaller than loop AMSB which is $\sim m_3/2 \times \text{loop factor}$.

In original KKLT construction, $m_3/2 \simeq m_{\text{SUSY}} \ln\left(\frac{M_P}{m_3/2}\right)$. 
No concrete realization of KKL T idea with an explicit C-Y space and choice of fluxes that leads to a ground state with all the required properties (e.g. SM, dS spacetime)!

**PHENOMENOLOGICAL APPROACH.**

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

Generalize the ratio between anomaly and modulus mediated SUSY breaking contributions to be arbitrary.

Parametrize this ratio by $\alpha$. Since it is a ratio of products of VEVs, $\alpha$ can take either sign, BUT CAN BE $O(1)$.

**Warning:** There are two conventions for $\alpha$ in the literature!

\[
\alpha_{\text{Our}} = \alpha_{\text{FLM}} = \frac{16\pi^2}{\ln(M_P/m_{3/2})} \frac{1}{\alpha_{\text{Choi}}}
\]
MSSM sparticle mass scale \( \sim \frac{m_{3/2}}{16\pi^2} \equiv M_s \)

Ratio of modulus-mediated and anomaly-mediated contributions set by a phenomenological parameter \( \alpha \)

Modulus-mediated contributions depend on so-called “modular weights” of the fields, which (for toroidal compactifications) are determined by where these fields are located in the extra dimensions.

Matter modular weights \( n_i = 0 \) \((1)\) for matter on D7 \((D3)\) branes.  
Gauge kinetic function indices \( l_a = 1 \) \((0)\) on \(D7\) \((D3)\) branes.

Model completely specified by

\[ m_{3/2}, \alpha, \tan \beta, \text{sign}(\mu), n_i, l_a \]

Radiative EWSB determines \( \mu^2 \) as usual.
More on modular weights

The modular weights, 0 (1) for chiral superfields on D7 (D3) branes (1/2 on brane intersections) were obtained in examples with toroidal compactifications. Ibañez and collaborators

These modular weights are generic for adjoint superfields.

But for chiral superfields, this is not so. Recent analysis with Calabi-Yau compactification shows that modular weight 2/3 is possible. Conlon, Quevedo and collaborators

We will take \( n_i = 0, 1/2, 1 \) as choices that guide our phenomenological analyses. The choice 2/3 will give a phenomenology somewhere “in between”.

X. Tata, “Workshop on Low Energy Precision EW Physics in the LHC Era”
Soft SUSY Breaking Terms

The soft terms renormalized at $Q \sim M_{\text{GUT}}$ are given by,

\begin{align*}
M_a &= M_s (\ell a \alpha + b_a g_a^2), \\
A_{ijk} &= M_s (-a_{ijk} \alpha + \gamma_i + \gamma_j + \gamma_k), \\
m_i^2 &= M_s^2 (c_i \alpha^2 + 4 \alpha \xi_i - \dot{\gamma}_i),
\end{align*}

with

\begin{align*}
c_i &= 1 - n_i, \\
a_{ijk} &= 3 - n_i - n_j - n_k, \\
\xi_i &= \sum_{j,k} a_{ijk} \frac{y_{ij}^2}{4} - \sum_{a} l_a g_a^2 C_a^2 (f_i), \text{ and } \dot{\gamma}_i = 8 \pi^2 \frac{\partial \gamma_i}{\partial \log \mu}.
\end{align*}

Note that if $n_i = 0$, $A_{ijk}^2 \sim 9 m_i^2$ for the modulus-mediated contribution. Large A-parameters $\implies$ light $\tilde{t}_1$ possible.
\( \alpha = 0 \) gives us the AMSB Model with wino-like neutralino LSP.

For large \(|\alpha|\), AMSB terms subdominant. With universal \( l_a(n_i) \) we will have common gaugino (scalar) masses.

Generation-independent modular weights for MSSM multiplets ensures FCNC OK. SUSY \( CP \) problem also ameliorated.

Models potentially have smaller fine tuning: even for heavy stop, \( m_{H_u}^2 \) can be modest at weak scale. (Lebedev, Nilles, Ratz; Choi et al; Kitano and Nomura).

Possibility of a compressed sparticle spectrum.
True Unification and Mirage Unification

Mirage unification

Low mirage unification scale

NOTE: $M_1(\text{weak}) = \pm M_2(\text{weak})$ is possible, depending on $\alpha$. This has implications for dark matter.
Mirage unification for scalar masses also, but spoiled by Yukawa couplings (NZMW model is an exception). Note low value of $m_{\tilde{t}_R}$. Anticipate light $\tilde{t}_1$. 

X. Tata, “Workshop on Low Energy Precision EW Physics in the LHC Era”
Strongly-interacting gluinos and squarks most copiously produced.

If left- and right-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)

mSUGRA (100 fb\(^{-1}\))


mAMSB (10 fb\(^{-1}\))

Cascade decays \(\implies\) Multiple Signals

Note photon signal also

X. Tata, “Workshop on Low Energy Precision EW Physics in the LHC Era”
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 rate for the various event topologies 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 $E_T$ spectrum, so hard $E_T$ 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 tracks.

★ Long-lived charged sparticles may leave stubby tracks with kinks, e.g. $\tilde{W}_1^+ \to \tilde{Z}_1 \pi^+$ with $\tau(\tilde{W}_1) \sim 10^{-9}$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 2010-2020

★ Establish a clear New Physics signal.
★ Make the case it is SUSY. The case will be circumstantial.

• Rates vs. mass. Strong vs. EW $\Rightarrow$ Q. Nos.
• Same sign dileptons+jet+$\not{E}_T$ signal $\Rightarrow$ strongly interacting Majorana particles. $(N(\ell^+\ell^+) \text{ vs. } N(\ell^-\ell^-))$
• 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.

\[ m_{\tilde{Z}_2} - m_{\tilde{Z}_1} \text{ or } \sqrt{m_{\tilde{Z}_2}^2 - m_{\tilde{\ell}}^2} \sqrt{1 - \frac{m_{\tilde{Z}_1}^2}{m_{\tilde{\ell}}^2}} \]  

\( h \) in SUSY events

X. Tata, “Workshop on Low Energy Precision EW Physics in the LHC Era”
Determination of other mass edges allow reconstruction of event chains in the favourable situation of a sequence two body decays, modulo ambiguities of interpretation.

Mass edges typically give $\Delta m$. 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 $m_{TGen}$) 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.
The $m_{T2}$ variable

$m_{max}^{T2}(m_{\tilde{Z}_1}^{trial})$ is a different function of masses, depending on whether $m_{\tilde{Z}_1}^{trial}$ is smaller/bigger than the true value of $m_{\tilde{Z}_1}$.
CURRENT CONSTRAINTS

We need consistency with measurements of,

- flavour changing neutral currents in down, and now also up, sectors;
- $g_\mu - 2$
- Determination of the relic density of CDM

$$\Omega_{CDM} h^2 = 0.111^{+0.006}_{-0.008}$$

- Direct limits from LEP and Tevatron
Interpreting the relic density measurement

Assuming standard Big Bang cosmology, and thermal production in the BB, the relic density of any stable particle is unambiguously determined.

It is possible to get a different answer if these conditions (which are not tested) are relaxed, but it is reasonable to see how far we can go without invoking new hypothesis.

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.

$$\langle v\sigma \rangle \propto \frac{g_X^4}{M_X^2}$$

has to be in the right range.

Weak scale couplings together with weak scale masses work! (WIMP MIRACLE) (see, however, Feng and Kumar.)
Assuming that the LSP is a neutralino, we strictly conclude that

\[ \Omega \tilde{Z}_1 h^2 \lesssim 0.12 \ (2\sigma). \]

Then, generic SUSY models are bang-on if sparticles are light and the LSPs bino-like with \( m_{\text{SUSY}} \sim \mathcal{O}(100) \) GeV ("bulk" region).

This bulk region is being constrained by direct searches and constraints on rare processes, which force the SUSY scale to go up, and hence, \( v\sigma(\text{annihilation}) \sim 1/m_{\text{SUSY}}^2 \) to come down, \( \Rightarrow \) neutralino 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 $\tilde{Z}_1$ (usually $\tilde{\tau}_1$ or $\tilde{t}_1$)
  
  If $M_1 \simeq -M_2$, $m_{\tilde{Z}_1} \simeq m_{\tilde{W}_1} \simeq m_{\tilde{Z}_2}$ 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 $2m_{\tilde{Z}_1} \simeq m_\phi$, 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 $\mu$ 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)

\[ m_{1/2} \text{(GeV)} \]

\[ m_0 \text{(GeV)} \]

\[ \tan \beta = 45, \mu < 0 \]

**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
  \[ m^2_\phi \equiv m^2_{H_u} = m^2_{H_d} \neq m^0 \]

- Non-universal gaugino mass parameters
  \[ M_1(\text{weak}) \simeq M_2(\text{weak}) \implies \text{Mixed wino DM (MWDM)}; \]
  \[ M_1(\text{weak}) \simeq -M_2(\text{weak}) \implies \text{bino-wino co-annihilation (BWCA)}; \]
  \[ \text{Low } |M_3| \text{ or large } M_2 \implies \text{Low } |\mu|, \text{ so mixed higgsino DM (MHDM)}. \]

**BY ADJUSTING THE ONE ADDITIONAL PARAMETER, ANY POINT IN THE**
\[ m_0 - m_{1/2} \] **MSUGRA PLANE BECOMES RELIC-DENSITY-ALLOWED!**

**View relic density implications with care.**
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 $f_\nu$ in the RG evolution of MSSM parameters. [Remember $f_\nu$ is related to $f_u$.]

\[
f_\nu(M_{\text{GUT}}) = f_t(M_{\text{GUT}})
\]

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.

HOWEVER, ALMOST NO IMPACT ON DM SEARCHES (Mustafayev).
Non-Universal Higgs masses

Relax scalar mass universality. FCNC $\implies$ 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 $\mu$ for large $m_{\phi} > m_0$ Higgs funnel anihilation for $m_{\phi} < 0$
COLLIDER PROSPECTS in NUHM: $\tan \beta = 10$

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

Baer, Mustafayev, Profumo, Belyaev, XT
Non-Universal Gaugino Masses

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

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

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

Taking $|M_2$(GUT)$| \simeq (2.5 - 3)m_{1/2}$ $\implies$ small $|\mu|$ (mixed higgsino DM in High $M_2$ DM model)

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

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

X. Tata, “Workshop on Low Energy Precision EW Physics in the LHC Era”
Illustrate in situation where we vary $M_1$ from its unified value.
Small $m_{\tilde{Z}_2} - m_{\tilde{Z}_1} \Rightarrow$ enhanced $B(\tilde{Z}_2 \rightarrow \tilde{Z}_1 \gamma) \sim 10 - 20\%$.

(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 $m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$.
LOWERING $M_3$(GUT) relative to $m_{1/2}$ also LOWERS $\mu$.

For every value of $(m_0, m_{1/2})$ we can find the hyperbolic branch region by adjusting $M_3$(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??

X. Tata, “Workshop on Low Energy Precision EW Physics in the LHC Era”
LHC will overwhelm $e^+e^-$ colliders for reach.

\[ M_3 \leq m_{1/2}, \ \text{tan}\beta = 10, \ \text{A}_0 = 0, \mu > 0, m_t = 175 \text{ GeV} \]

$M_3$ 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 $\tilde{q} \rightarrow q\tilde{g}$, gluino studies at ILC!
WMAP consistency via stop and stau co-annihilation, via mixed bino-wino-higgsino SM, Higgs funnel or BWCA

LHC probes *almost* all the WMAP allowed regions. LC probe all BWCA regions.
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.
In many models $\tilde{Z}_2$ decays via three-body decays, so that the location of the dilepton mass edge at $m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$ may be possible at the LHC.

In MHDM models, $\tilde{Z}_3$ 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 of dark matter

Detect recoils of nuclei from their collisions with DM in our galactic halo we move through it.

DAMA experiment has claimed a signal which is not seen by other experiments with greater sensitivity.

\[ \sigma_{\text{SI}}(\tilde{Z}_1 p) \approx (5 - 10) \times 10^{-8} \text{ pb for } m_{\tilde{Z}_1} = 100 \text{ GeV.} \]
Current searches at CDMS and Xenon-10 beginning to cut into models.
Notice the branch from MHDM models where $\sigma_{SI}(Z_1p)$ 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
Annihilation of neutralinos accumulating in the sun give high energy neutrinos that can be detected in IceCube.

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. IS THERE A SIGNAL IN PAMELA DATA?

★ 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).
WARNING: THE SIGNAL FROM INDIRECT DETECTION EXPERIMENTS (EXCEPT ICECUBE) IS SENSITIVE TO THE UNKNOWN DISTRIBUTION OF THE NEUTRALINOS IN OUR GALACTIC HALO. STILL MAY BE ABLE TO INFER INFORMATION ABOUT THE WIMP BY CORRELATING THESE SIGNALS.

I will not show these results here.
mSUGRA Prejudices

★ Relic-density-consistent “bulk region” ⇒ 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 $Q = M_{\text{GUT}}$. 

X. Tata, “Workshop on Low Energy Precision EW Physics in the LHC Era”
Features of relic-density-consistent models

★ Most models accessible at the LHC

★ Frequently, the mass edge in $\tilde{Z}_2 \rightarrow \tilde{Z}_1 \ell \bar{\ell}$ 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**
LHC experiments each have $\sim 4 \text{ fb}^{-1}$ of data with some significant fraction well-processed.

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.

GLAST and PAMELA.....are all arguing about whether they are seeing DM, and if so how it 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 $2.6\sigma$ 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.
The distinction between particle type and cosmology type will be fuzzy as plots like these will exist with real data!

Baltz, Battaglia, Peskin, Wizansky. Arnowitt et al.

See also, Nojiri, Polesello and Tovey.

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

This may well be the only way to know DM consists of a single component. A peaked plot like this (with real data) would truly be a consumation of the HEP-Cosmology union.
WE ARE ENTERING A DECADE OF NEW OPPORTUNITIES WITH THE ADVENT OF THE LHC AND OF OTHER FACILITIES THAT WILL ALLOW US TO STUDY STUFF FROM THE SKY.

PARTICLE PHYSICS AND COSMOLOGY WILL BE INTER-RELATED AT AN UNPRECEDENTED LEVEL.

I DO NOT KNOW WHAT NATURE HAS IN STORE FOR US, BUT WE MUST LOOK TO SEE WHAT WE FIND.
FCNC constraints suggest particles with same gauge quantum numbers are (roughly) degenerate ⇒ intergenerational universality of sfermion masses; 
\[ m(\tilde{u}_L) = m(\tilde{c}_L) = m(L), \text{ etc.} \]

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

\[ m_{H_u}^2 (\text{GUT}), m_{H_d}^2 (\text{GUT}) \neq m_0^2 \]

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

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

NUHM1 model completely specified by

\[ m_0, m_\phi, m_{1/2}, A_0, \tan \beta, \text{sign}(\mu) \]
NUHM2 can lead to funny SUSY spectra because $S \neq 0$.

$m_{\tilde{f}}=300\text{GeV}$, $m_{\tilde{g}}=300\text{GeV}$, $\tan\beta=10$, $A_0=0$, $\mu>0$, $m_Z=178\text{GeV}$

PSPS2: $m_{\tilde{f}}=1450\text{GeV}$, $m_{\tilde{g}}=300\text{GeV}$, $\tan\beta=10$, $A_0=0$, $\mu>0$, $m_Z=178\text{GeV}$

"Pseudo-bulk" region annihilation via LEFT staus; part of negative $\Delta m_H$ 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 $\tilde{Z}_1\tilde{Z}_2$ cross section in BWCA directly traced to $M_1/M_2 < 0$.

$\gamma + \not{E}_T$ events from $\tilde{Z}_1\tilde{Z}_2$ production and $\gamma\gamma + \not{E}_T$, $jj$ or $\bar{\ell}\ell + \gamma + \not{E}_T$ events from $\tilde{Z}_2\tilde{Z}_2$ production.
How can gluinos make a difference to the relic density? (Belanger et al.; Mambrini and Nezri.)

Small $M_3$(GUT) $\Rightarrow$ smaller evolution of squark mass squared as well as $A_t$ parameters from gauge-gaugino loops $\Rightarrow$ smaller values for

$$X_t = m_{Q_3}^2 + m_{t_R}^2 + m_{H_u^2} + A_t^2.$$ 

Then, because

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

small $X_t$ means $m_{H_u^2}^2$ 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 $M_3$(GUT) $\Rightarrow$ reduced $\mu$! $\Rightarrow$ MHDM
Remember that $\Delta a_\mu \propto \tan \beta$ which is fixed to be $\tan \beta = 10$ (except in mSUGRA).
$b \rightarrow s\gamma$ in relic density consistent models

Here, $\tan \beta$ is fixed to be $\tan \beta = 10$ (except in mSUGRA).