Discrete Symmetries and Dark Matter in String/M theory

Bobby Samir Acharya $d\varphi = d * \varphi = 0$
King's College London $\partial^{\mu} F_{\mu\nu} = j^{\nu}$
and
ICTP Trieste $\bar{\Psi}(1 - \gamma_5)\gamma_{\nu}\Psi$

Unification and String Theory 01-05.10.2012
Bad Honnef
Talk Based on: arXiv:1204.2795(review), 1205.5789, 1102.0556 + to appear
Work with:
G. Kane, P. Kumar, R. Lu, B. Zheng

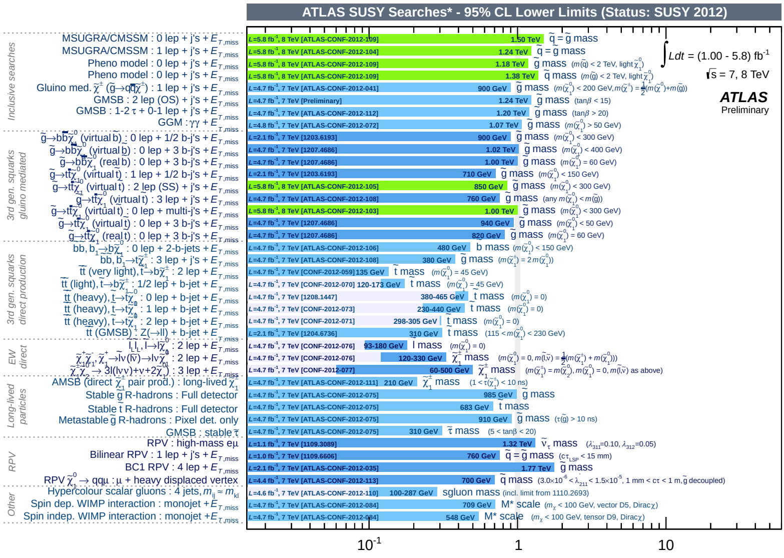
Introduction

- Discrete symmetries are prolific in BSM particle physics model building
- Required by proton stability and many other constraints
- If unbroken also provide a rationale for the stability of dark matter
- In string/M theory they arise as geometric symmetries of the extra dimensions
- There has been much work since 1984 on this topic
- This talk: what do our recent lessons about moduli physics teach us about discrete symmetries
- Goal in a slogan: "A (string) theory of R-parity violation"

Introduction: Fermi and LHC data

- Data from the LHC and Fermi/LAT are providing clues about dark matter
- The lack of BSM missing energy results might indicate that dark matter is NOT a visible sector WIMP
- The Higgs data suggests that scalar masses are order 10 - 100 TeV
- In our general approach to string/M theory the simplest models predicted a W-ino LSP and the correct Higgs mass
- The analysis of the Fermi data in arXiv:1203.1312, 1204.2797, 1205.1045, 1206.1616 $+$... suggest DM with large annihilation x-section
- The cross-section and peak is compatible with that of a 145 GeV W-ino (1205.5789)
- BUT: all MSSM wimps have been shown to produce too many low energy (10 GeV) photons (Buchmuller et al/Cohen et al/Cholis et al '2012)
- Suggests breaking of discrete symmetries

LHC SUSY Limits



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Outline

- Summary of predictions
- Comments on discrete symmetries
- Moduli vevs and breaking discrete symmetries
- Attempt "classification" of different possibilities
- All have very different DM and LHC phenomenology

Basic Predictions Summary (review:1204.2795)

- Early Universe (post-inflation but pre BBN) is **MATTER** dominated by moduli fields
  - Many phenomenologists assume that this era is radiation dominated (i.e. a thermal history)
  - String/M theory predicts a **non-thermal** history
- Dark matter consists of *both* axions and W-ino like WIMPS.
- The Fermi LAT experiment should see mono-chromatic photons somewhere in the few hundred GeV region.
- Scalar superpartners of quarks and leptons have masses in the 10's of TeV region i.e. are unobservable at the LHC
- Gauginos, including gluinos and W-inos will be observed at the LHC since their masses $\leq \mathcal{O}$(TeV)
- The Higgs mass, m_h: 115 GeV $\leq m_h \leq 129$, but in the M-theory G_2-manifold case:
- 122 GeV $\leq m_h \leq$ 129 GeV due to a correlation with Witten's solution of doublet-triplet splitting!

Summary of the Basic Predictions

- Note that both the 2011 ATLAS and CMS data may be indicating $m_h \sim 126$ GeV
- Recent analyses of the Fermi data (arXiv:1203.1312, 1204.2797, 1205.1045, 1206.1616 $+..$) are all concluding an excess of high energy, monochromatic galactic photons at $E_\gamma \sim 130$ GeV
- Both of these are included in the generic predictions above.

Why Discrete Symmetries?

- Discrete symmetries seem to be required, though they often seem "ad hoc"
- Bottom up: proton decay and the doublet triplet splitting problem
- They can arise in string/M theory as geometric symmetries of the extra dimensions (Strominger/Witten, Ibanez/Ross, Banks/Dine, Recent work in heterotic theory H.M. Lee,S. Raby,G. Ross,M.Ratz, R. Schieren, K. SchmidtHoberg P. Vaudrevange/ R. Kappl, B. Petersen, S. Raby, M.Ratz., R. Schieren P. Vaudrevange /M. Fallbacher, M.Ratz P. Vaudrevange /M.C. Chen, M.Ratz, C. Staudt P. Vaudrevange, /M. Fischer, M.Ratz, J. Torrado P. Vaudrevange)
- BUT: such symmetries MUST be broken, at least partially : μ and Higgsino mass ≥ 120 GeV.
- Moduli fields are charged under discrete symmetries and their VEVs $\langle z \rangle$ in the late time minimum of the potential where we are today $generically$ will spontaneously break the symmetry.

A (string) Theory of R-parity Breaking

- The "offending" operators are (flavour indices suppressed)
- $W_{RPV} \sim \lambda' LLE^c + \lambda'' LQD^c + \lambda''' U^c U^c D^c$
- $W_{RPV} \sim \epsilon \mu L H_u$
- Now that we have a better understanding of moduli potentials we can calculate the couplings generated via the moduli vevs

In M theory on a G_2-manifold

- Witten (hep-ph-0201018) showed that discrete symmetries (G) can
- Solve doublet triplet splitting and removing the "offending" operators
- Since $\mu = 0$ the symmetry must be broken
- In arXiv:1102.0556 we showed that μ is generated by moduli vevs which break G
- But, for generic breaking there are phenomenological constraints on the LSP lifetime

Consider this Z_{18} example

Q_L	U_R	D_R	L	E	H_u	H_d	T_u	T_d
4	15	7	10	1	17	7	9	9

The anomaly coefficients are:

$$A_3 = \frac{3}{2}\left(2q_{Q_L} + q_{U_R} + q_{D_R}\right) + \frac{1}{2}\left(q_{T_u} + q_{T_d}\right) = 54 = 0 \bmod 9$$

$$A_2 = \frac{3}{2}\left(3q_{Q_L} + q_L\right) + \frac{1}{2}\left(q_{H_u} + q_{H_d}\right) = 45 = 0 \bmod 9$$

$$A_1 = \frac{9}{5}\left(\frac{1}{6}q_{Q_L} + \frac{4}{3}q_{U_R} + \frac{1}{3}q_{D_R} + \frac{1}{2}q_L + q_E\right) + \frac{3}{10}\left(q_{H_u} + q_{H_d}\right) + \frac{1}{5}\left(q_{T_u} + q_{T_d}\right) = 63 = 0 \bmod 9$$

Z_{18} example

Q_L	U_R	D_R	L	E	H_u	H_d	T_u	T_d
4	15	7	10	1	17	7	9	9

NOTE: the charges of different elements of GUT matter multiplets are different!

This does not disturb gauge coupling unification

CF Mu-Chun Chen and Michael Ratz's talks – they assume that $L + D_R = \mathbf{5}$ both have the same charge. Similar for $\mathbf{10}$

So can have anomaly free *non-R*-symmetries.

The size of these couplings arXiv:1102.0556

- G sets the terms in W_{RPV} to zero
- The moduli vevs do not enter W perturbatively due to axion shift symmetries
- So, all couplings are generated by Kahler potential terms (Giudice-Masiero)
- Furthermore, $\frac{\langle z \rangle}{m_{pl}} \sim 0.1$ and $F_z \sim \frac{\alpha_{GUT}}{4\pi} m_{3/2} m_{pl}$
- Result : $\mu \sim \frac{\langle z \rangle m_{3/2}}{m_{pl}} \sim fewTeV$ and λ's $\sim \frac{\langle z \rangle m_{3/2}}{m_{pl}^2} \sim 10^{-15}$

New Results, to appear

- Since μ and λ's are known we can consider several possibilities
- Class A (General RPV): G is completely broken
- Class B (No RPV): G is partially broken to R-parity so only μ is allowed
- Class C (Leptonic RPV): G is partially broken to a subgroup which allows LH_u and LQD^c only e.g. $\mathbf{Z_{18}} \rightarrow \mathbf{Z_3}$
- Class D (Baryonic RPV): G partially broken and allows $U^cU^cD^c$ only
- Others?..

Phenomenology of Case A, "Generic RPV"

- G broken completely
- All operators are present
- Proton stability requires, in particular, that $\lambda''' \epsilon y_b \leq 10^{-25}$
- In particular, ϵ is required to be $\leq 10^{-10}$ TUNED
- If it were, then W-ino would decay quickly inside the LHC detectors
- The Fermi γ-ray line might then be produced via the hidden sector
- LHC limits on gluino mass are reduced to ~ 500 GeV.

Phenomenology of Case B, "No RPV"

- G broken to R-parity
- Only μ generated
- LSP is stable
- LHC predictions as reviewed in 1204.2794
- **Cannot** explain Fermi line

Phenomenology of Case C, "Leptonic RPV"

- G broken but allows μ, LH_u and QLD
- Proton stable
- Neutrino masses require $\epsilon \leq 10^{-3}$ (Banks,Grossman,Nadir,Nir hep-ph/9505248; Nilles, Polansky hep-ph/9606388; Hempfling ph/9511288)
- If μ and $B\mu$ are "aligned" in flavour space ϵ suppressed
- This happens in M theory and probably other moduli vacua in string theory (see next slide) due to suppressed F_z and slightly suppressed $\langle z \rangle$
- Now, LSP lifetime becomes order $10^{-8} - 10^{-10}$ seconds i.e. centimetres to metres
- So, W-ino decay will produced displaced charged tracks ($\tilde{W}^0 \rightarrow W^+\mu^- \rightarrow e^+\nu_e\mu^-$)
- Very interesting LHC phenomenology, under investigation.
- This case also allows the possibility of "explaining Fermi" with the hidden sector

$$
\begin{aligned}
\mu_\alpha &= m_{3/2}\, K_{H_u\alpha} - F^{\bar{k}}\, K_{H_u\,\alpha\,\bar{k}} \\
B\mu_\alpha &= (2\, m_{3/2}^2\, K_{H_u\alpha} - m_{3/2}\, F^{\bar{k}}\, K_{H_u\,\alpha\,\bar{k}} + m_{3/2}\, F^{k}\, K_{H_u\,\alpha\,k}) - \\
& (m_{3/2} F^m\, K^{n\bar{l}} K_{\bar{l}mH_u} K_{n\alpha} + (H_u \leftrightarrow L_\alpha)) - \\
& F^n\, F^{\bar{m}} (\frac{1}{2} K_{H_u\alpha n\bar{m}} - K^{j\bar{l}} K_{\bar{l}nH_u} K_{j\bar{m}\alpha} + (H_u \leftrightarrow L_\alpha)) \quad (1)
\end{aligned}
$$

From the leading contribution to the Kahler potential terms:

$$
K \supset P_\alpha \frac{(S^1)^\dagger}{m_{pl}}\, H_u\, L_\alpha + Q_\alpha \frac{(S^2)}{m_{pl}}\, H_u\, L_\alpha, \quad (2)
$$

where P_α, Q_α are $\mathcal{O}(1)$ coefficients in general, one finds :

$$
\begin{aligned}
\mu_\alpha &= P_\alpha \frac{(S^1)^\dagger}{m_{pl}}\, m_{3/2} + P_\alpha\, \frac{\langle F^{S_1} \rangle}{m_{pl}} \\
B\mu_\alpha &= 2P_\alpha \frac{(S^1)^\dagger}{m_{pl}}\, m_{3/2}^2 + P_\alpha \frac{(S^1)^\dagger}{m_{pl}}\, m_{3/2} + Q_\alpha\, \frac{\langle F^{S_2} \rangle}{m_{pl}}\, m_{3/2} \quad (3)
\end{aligned}
$$

Then, using the result that $\langle F^{S_i}\rangle \ll \langle S_i\rangle m_{3/2}$ [1102.0556] so that the terms proportional to $\langle F^{S_1}\rangle$ and $\langle F^{S_2}\rangle$ are negligible to a very good approximation, one gets:

$$\boxed{B\mu_\alpha \simeq 2\, m_{3/2}\, \mu_\alpha} \tag{4}$$

Conclusions

- In vacua with suppressed gaugino masses, the moduli potential allows one to estimate the size of R-parity violating effects
- This seems to require that discrete symmetries are only partially broken
- Leads to a rich phenomenology at the LHC
- Allows the possibility of finding a hidden sector explanation of the Fermi γ-ray line if it is DM

BACKUP

Example: Moduli Stabilization in M theory

- Basic (old, but great) idea that strong dynamics in the hidden sector:
  1. Generates the hierarchy between m_{pl} and M_W
  2. That supersymmetry breaking will also stabilize the moduli
- Realised for the first time in string/M theory by considering M theory on G_2-manifolds
- In fact, strong hidden sector dynamics generates the hierarchy, the moduli potential and supersymmetry breaking *simultaneously*!
- There are two INTEGER parameters P, Q which determine $\alpha_{GUT}, M_{GUT}, M_{pl}, m_{3/2}$ all *consistently*.

Moduli Stabilzation in M theory

- Moduli vevs $s_i \sim 3Q = \frac{1}{\alpha_{GUT}}$
- So, eg, Q=6,7,8,9
- $m_{pl}^2 = Vol(X)M_{11}^2 \sim \frac{1}{\alpha_{GUT}^{7/3}}M_{11}^2$
- $M_{GUT} = M_{11}\alpha_{GUT}^{1/3}$
- $m_{3/2} = m_{pl}\frac{\alpha_{GUT}^{7/2}}{\sqrt{\pi}}\frac{|Q-P|}{Q}e^{-\frac{P_{eff}}{Q-P}}$
- $P_{eff} = \frac{14(3(Q-P)-2)}{3(3(Q-P)-2\sqrt{6(Q-P)})} \sim 60$ when $Q-P=3$
- So, $m_{3/2} \sim O(50)$ TeV.Note: $Q-P \geq 3$, so $Q-P=4$ doesn't work.
- So, moduli can decay before BBN.
- There are two INTEGER parameters P, Q which determine $\alpha_{GUT}, M_{GUT}, M_{pl}, m_{3/2}$ all *consistently*.

The Spectrum in String/M theory

- In string/M theory in the classical limit a positive cosmological constant is not possible.
- 'Pure moduli dynamics has an anti de Sitter vacuum'
- Therefore, the field which dominates supersymmetry breaking is not a modulus
- e.g. a matter field
- In M theory this is a hidden sector matter field
- $F_{moduli} \sim \alpha_{GUT} m_{3/2} m_{pl}$
- Leads to a Wino LSP
- Note: this is NOT pure AMSB in the gaugino sector, but similar to it.

A New Mass Scale

- Direct consequences of having moduli with masses of order 10 - 100 TeV include:
- The upper limit on the axion decay constant is lifted to close to the GUT scale.
- This solves a long outstanding problem in string/M theory. Hence, axions will make up a significant fraction of dark matter *without* fine tuning!
- If the LSP is stable, it will be produced when the moduli decay.
- The relic density comes out about right for a 100-200 GeV W-ino like LSP.
- This is a non-thermal WIMP 'Miracle'.So dark matter is mixed: W-ino and axion.
- The W-ino has the right annihilation cross-section to explain the gamma line 'signal' (eg arXiv:1204.2797) in Fermi data (see arXiv:1205.5789)

Axion-Wino dark matter and the Fermi 'signal'

- Several recent analyses of the Fermi data (arXiv:1203.1312, 1204.2797, 1205.1045, 1206.1616) are all concluding an excess of high energy, monochromatic galactic photons at $E_\gamma \sim 130$ GeV
- The cross-section for DM annihilation for the photon signal is roughly $\sigma v(\chi\chi \rightarrow \gamma X) \sim 10^{-27}$ cm^{3}s^{-1}.
- Thermal WIMP relics have $\sigma v_{total} \sim 3 \times 10^{-26}$ cm^{3}s^{-1}. Since annihilation to photons is a one-loop process this implies that typical thermal WIMPs *cannot* produce the required number of photons.
- Non-thermal WIMP relics, such as a W-ino with mass 145 GeV have a much larger total σv of the right order to produce the 130 GeV γ-line by 1-loop annihilating to $Z\gamma$.
- Further: fitting the signal in detail shows that roughly 50% of dark matter is W-ino like. The rest is interpreted as axions!!