Generic Predictions from String/M theory for the LHC and Dark Matter

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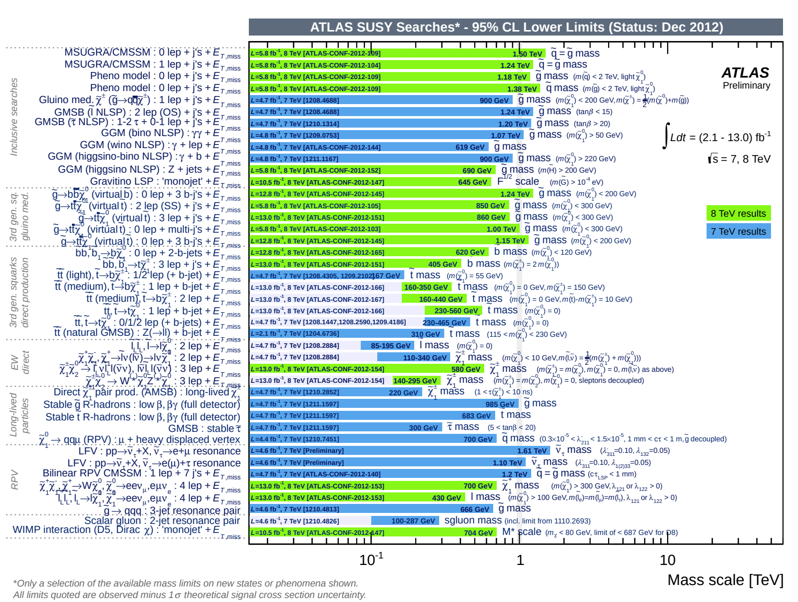
King's College London $\partial^\mu F_{\mu\nu} = j_\nu$

and

ICTP Trieste $\bar{\Psi}(1-\gamma_5)\gamma_\nu\Psi$

Seminar 08.02.2013
UCL HEP
Based on Review - arXiv:1204.2795
of work with several collaborators:
G. Kane, P. Kumar, K. Bobkov, E. Kuflik, S. Watson, R. Lu, B. Zheng

LHC SUSY Limits



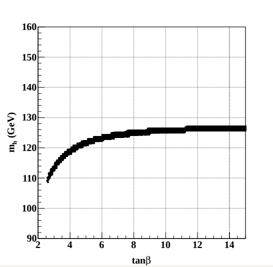
Why String Theory ?

- Supersymmetry introduces hundreds of new parameters.
- It is very difficult to navigate theoretically and experimentally
- UV complete models such as string/M theory tend to lead to low energy models with very few parameters
- They provide motivation for looking at particular models
- Though of course we should try and look "everywhere" for susy and other ideas.

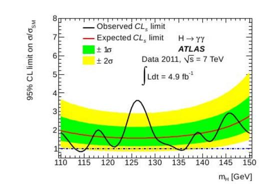
Key Points

- A consistent cosmology for these moduli correlates strongly with LHC physics!
- There is a beautiful correlation between the mass of the moduli and the Higgs boson mass.

M theory, G_2-manifolds and the LHC data



Prediction for m_h from M theory on a G_2-manifold. Plot made summer 2011.



Data from ATLAS from December 2011

Summary of the Basic Predictions

- The very 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 axions and W-ino like WIMPS. Axion decay constants are GUT scale!!!
- The Fermi satellite experiment should see mono-chromatic photons somewhere in the 100-200 GeV range.
- 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 was predicted to be 122 GeV $\leq m_h \leq$ 129 GeV

Moduli/Axion physics

- The key insights are provided by moduli and string axion physics — i.e. are due to the extra dimensions
- Understanding the moduli potential is key to all of this

What is "Generic"?

- We are interested in "generic" properties of string/M theory vacua with all moduli stabilised and a realistic observable sector
- "Generic": not a theorem, might be avoided in "special cases"
- One would have to work fairly hard to construct a "non-generic" example.

What is "Generic?", an example

- Asking what the generic predictions of QFT are is **NOT** a good question (CPT, spin , stats, aside).
- The Standard Model is one of infinitely many QFT's.
- The SM describes very precisely the results of all particle physics experiments and that is good enough
- A better question: what are the generic predictions of non-Abelian gauge theories with chiral fermions and hierarchical Yukawa couplings and spontaneous symmetry breaking?
- Answer: Charged currents, massive vector bosons and a rich spectrum of three-body decays of heavier fermions into lighter ones.
- The discovery of the muon, the tau, the W-boson and their decay properties represents a verification of these generic predictions.
- **We will elicit similarly generic predictions about BSM physics not from QFT but from string/M theory.**

How can we justify our assumptions?

- How do we justify our assumption that solutions of string/M theory exist which reduce to the Standard Model at low energies?
- In 1984 (Candelas, Horowitz, Strominger and Witten) showed that a generic 4d solution of heterotic string theory is described by
  - A non-Abelian gauge theory with
  - Multiple generations of Chiral fermions
  - Hierarchical Yukawa couplings
- Similar statements are true in other perturbative limits eg Type IIA (Berkooz/Douglas/Leigh, Cvetic/Shiu et al), Type IIB (Ibanez et al, Blumenhagen/Lust) or M theory on a G_2-manifold (BSA/Witten).
- The assumptions about low energy supersymmetry and unification are well motivated.

Moduli Problems and Solutions

- Moduli are scalar fields with m_{pl} suppressed couplings to matter.
- They are the low energy description of the extra dimensions and "generic".
- Classically, in the supersymmetric limit, they are massless.So their masses are expected to be of order the susy breaking scale ($m_{3/2}$).
- It is *very* difficult to arrange m_ϕ much larger than $m_{3/2}$ for all the moduli fields (Denef/Douglas, Louis/Gomez-Reino/Scrucca, pheno-implications: BSA/Kane/Kuflik) .
- Has quite far reaching consequences as we will see.
- No known counterexamples?
- **Henceforth assume that there is at least one modulus field with $m_\phi \sim m_{3/2}$.**

Moduli Problems, Solutions and a New Mass Scale

- In the early Universe, when the Hubble scale H decreases to be of order m_ϕ, the moduli begin to oscillate in their potential and quickly dominate the energy density of the Universe:
- Hence, the early Universe is matter dominated:a non-thermal history.
- But, when H decreases to the decay width $\Gamma_\phi \sim \frac{m_\phi^3}{m_{pl}^2}$, the moduli decay
- In general they can decay to any (allowed) Standard Model particle.
- If $m_\phi \sim$TeV, this happens during Big Bang Nucleosynthesis.BAD!
- **If $m_\phi \geq$30 TeV, it happens just before and is consistent with all constraints.**

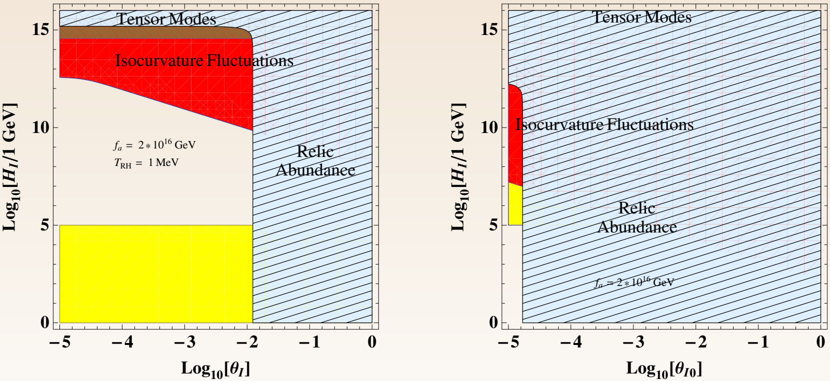
A New Mass Scale

- 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'.
- This has the about the right annihilation cross-section to explain the cosmic positron excess measured by PAMELA.
- Photon excess in Fermi data ? (see later)

A New Mass Scale: the LHC

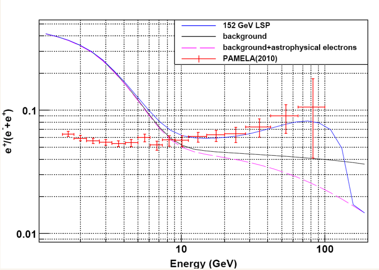
- **Finally, for the LHC, supergravity couplings between the moduli and scalar superpartners (squarks and sleptons) give them a large mass also, of order m_ϕ. Thus, squarks and sleptons will not be produced directly.**
- **However, gauginos could be!**
- All of this has a simple origin in one of the best understood classes of examples: M theory on a G_2-manifold
- Serves as a benchmark from which to draw more "generic" conclusions.

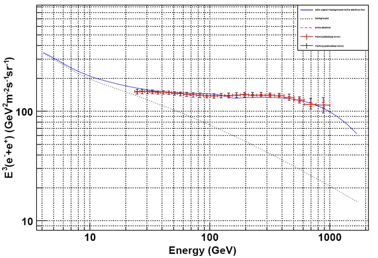
Non-anthropic Axion Physics



Non-thermal is the case on the Left.

Wino DM and PAMELA Data





Left: $e^+/(e^+ + e^-)$ Right: Energy Spectrum of $e^+ + e^-$

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*.

Moduli Masses in Supergravity

- Supergravity potential $V \sim F^i F_i - 3|W|^2$
- In vacuum this is $V_o \sim< F^i F_i > -3m_{3/2}^2 m_{pl}^2$
- Therefore $m_{3/2} \sim \frac{F}{m_{pl}}$ where F dominates susy breaking.
- *Generically* F/m_{pl} sets the mass scale of *ALL SCALARS* in the theory
- This not only includes the moduli, but also charged scalars: Higgses and Squarks and Sleptons
- eg $V \sim \cdots + K^i K_i |W|^2 + ... \sim \phi^i \phi_i |W|^2 ... \sim m_{3/2}^2 \phi_i^2$
- Therefore $m_\phi \sim m_{3/2}$
- The G_2 M theory model has $m_\phi \sim m_{3/2}$.

The Spectrum

- *Generically* Supersymmetry breaking must be gravity mediated with all scalars masses of order $m_{3/2} \geq 10\mathrm{TeV}$
- What about the Higgsino and Gaugino masses ?
- For Higgsinos, Giudice-Masiero typically gives $\mu \geq m_{3/2}$, though can be smaller.
- But, $m_f \leq m_{3/2}$ for gauginos
- Why? Because *there is no reason why the field which has the largest F-term is the field whose vev is the gauge coupling*.
- These arguments suggest a spectrum in which
- All scalar particles and vector like fermions have masses of order $m_{3/2} \geq 10\mathrm{TeV}$
- Gauginos ie gluinos, Winos and Binos have $m_{1/2} \leq m_{3/2}$
- This all comes from simple cosmological constraints plus EFT

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.

The Spectrum

Spectrum at the LHC

Microscopic Constants

Light Gluino, Neutralinos
Charginos, Higgs

Stop Right Lightest Squark

Heavy Squarks/Sleptons

parameter	Point 1	Point 2	Point 3	Point 4
δ	-6	-6	-6	-7
$Q-P$	3	3	3	3
$P_{\rm eff}$	75	83	73	70
V_7	90	21.6	220	220
C_2	5	5	5	1
α_{unif}^{-1}	26.1	26.4	26.5	26.1
$Z_{\rm eff}$	1.94	1.66	1.92	2.08
$m_{3/2}$	19266	35262	30032	16261
$\tan\beta$	1.40	1.45	1.39	1.39
μ	26488	45751	41585	22708
$m_{\tilde{g}}$	638.0	732.0	1048	734.5
$m_{\tilde{\chi}_1^0}$	116.0	110.6	224.7	157.2
$m_{\tilde{\chi}_2^0}$	152.5	228.2	258.2	157.7
$m_{\tilde{\chi}_1^\pm}$	116.2	110.7	224.9	157.4
$m_{\tilde{u}_L}$	19269	35264	30037	16266
$m_{\tilde{u}_R}$	19269	35264	30037	16265
$m_{\tilde{t}_1}$	4462	9003	7469	3475
$m_{\tilde{t}_2}$	13974	25712	21870	11752
$m_{\tilde{b}_1}$	13974	25712	21870	11752
$m_{\tilde{b}_2}$	19252	35230	30011	16251
$m_{\tilde{e}_L}$	19267	35263	30033	16262
$m_{\tilde{e}_R}$	19267	35263	30033	16261
$m_{\tilde{\tau}_1}$	19259	35246	30021	16251
$m_{\tilde{\tau}_2}$	19263	35254	30027	16258
m_h	117.5	120.7	118.8	115.5
m_A	40218	70182	63191	34388
A_t	2015	6199	3380	1427
A_b	798	1635	1199	665
A_τ	466	988	714	382

Non-thermal Dark Matter

- Energy density of Universe when moduli decay is
- $\rho_{decay} \sim {\Gamma_\phi}^2 m_{pl}^2 = \frac{m_\phi^6}{m_{pl}^2}$
- The number density of DM particles is thus
- $n_\chi^i \sim \frac{Br_{\phi\to\chi}\rho_d}{m_\chi} \sim 10^{-10}\mathrm{GeV}^3 Br_{\phi\to\chi}(\frac{100\mathrm{GeV}}{m_\chi})(\frac{m_\phi}{100\mathrm{TeV}})^6$
- We can compare this with $\frac{H}{\sigma v}$ to evaluate if n_χ^i is large enough to allow χ particles to annihilate
- $\frac{H}{\sigma v} \sim \frac{\Gamma_\phi}{\sigma v} \sim 10^{-16}\mathrm{GeV}^3(\frac{m_\phi}{100\mathrm{TeV}})^3\frac{\sigma_o}{\sigma v}$
  where $\sigma_o = 10^{-7}\mathrm{GeV}^{-2}$
- Unless $\mathrm{Br}_{\phi\to\chi}$ is small, χ particles will annihilate until $n_\chi \sim \frac{H}{\sigma v}$
- The Branching ratio is large since 'χ is a gaugino' and moduli couple like gravitons.

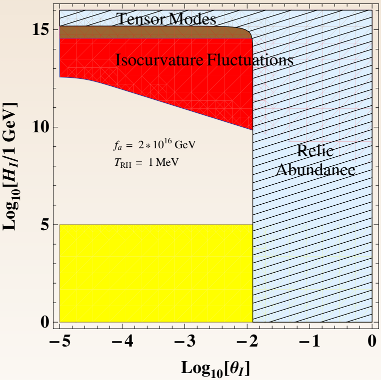
Miracles can be Non-thermal!

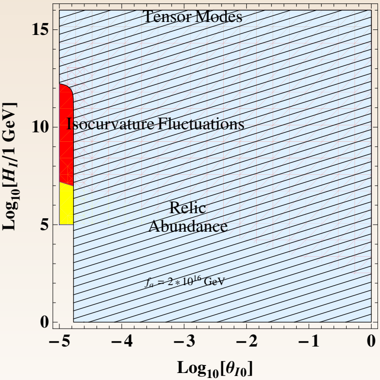
- Reheat temperature
  $T_{rh} \sim (\Gamma_\phi m_{pl})^{1/2} \sim \frac{m_\phi^{3/2}}{m_{pl}^{1/2}} \sim 10\mathrm{MeV}(\frac{m_\phi}{50\mathrm{TeV}})^{3/2}$
- So BBN can occur after the moduli have decayed!
- Entropy at decay time $s_{decay} \sim s_{rh} \sim g_* \frac{m_\phi^{9/2}}{m_{pl}^{3/2}}$
- Non-thermal relic abundance is therefore predicted to be
- $\frac{\rho}{s}|_{today} = \frac{m_\chi H}{s \ \sigma v}|_{decay} \sim \mathcal{O}(\mathrm{eV}) \ \frac{m_\chi}{100\mathrm{GeV}} \frac{10.75}{g_*} \frac{\sigma_o}{\sigma v} \ (\frac{100\mathrm{TeV}}{m_\phi})^{3/2}$
- **This is the Non-thermal WIMP 'Miracle'**
- First realised by Moroi-Randall that this happens in 'AMSB $+$ heavy scalars' ten years ago.
- In M theory, because $M_\chi \sim c\frac{\alpha_{GUT}}{4\pi} m_{3/2}$, $\rho/s \sim m_{3/2}^{3/2}$ so upper limit $m_{3/2} \leq 250$TeV.

Non-anthropic Axion Physics

- Coherent Axion oscillations produced during non-thermal moduli domination have (cf Fox, Pierce, Thomas '04).
  $\Omega_{a_k} h^2 = \mathcal{O}(10) \left(\frac{\hat{f}_{a_k}}{2\times 10^{16}\mathrm{GeV}}\right)^2 \left(\frac{T_{RH}^{X_0}}{1\,\mathrm{MeV}}\right) \langle \theta_{I_k}^2 \rangle$
- Due to large amount of entropy dilution from the moduli decay
- Independent of axion mass
- Much less tuning required (10^{-2})

Non-anthropic Axion Physics with GUT scale decay constants





Non-thermal is the case on the Left.

Planck experiment: Isocurvature perturbations? YES.

Tensor Modes: NO.

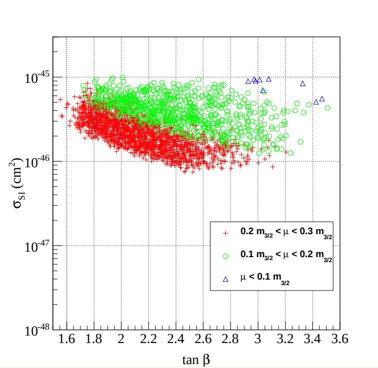
Caveats

- A late period of pre-BBN inflation with $H < m_{3/2}$ can inflate away the energy density of the moduli and their decay products.
- Is this possible in string/M theory?
- Is it "generic" in the same sense that a non-thermal history is "generic"?
- Note: In gauge mediated supersymmetry breaking $m_{3/2} <<$TeV
- So late inflation is *required* in gauge mediation because the moduli lifetimes are too long and $\rho/s \sim (m_{3/2} m_{pl})^{1/2}$

Lots of testable predictions!

- LHC: events with up to four top quarks plus missing energy
- LHC: short track stubs from the $SU(2)$ partners of the Wino
- Isocurvature perturbations but no tensor modes
- PAMELA/Fermi already consistent
- No signals at existing Axion search experiments
- Xenon 100: Calculation of μ in M theory leads to no signal, but observable at a Xenon 1000 detector or similar. (work with Gordy Kane, Eric Kuflik and Ran Lu)

Direct Detection of DM



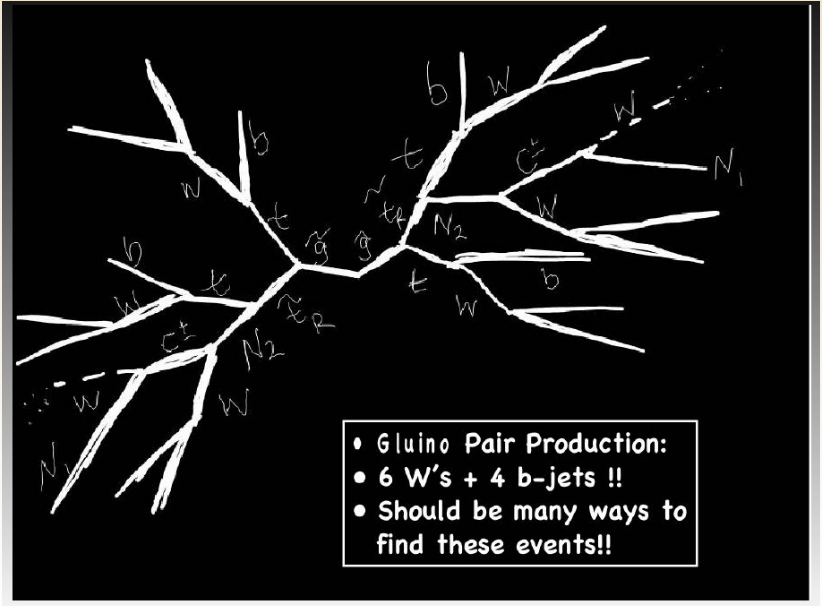
The G2 models are out of reach of Xenon 100.

Xenon 1000 or equivalent will be sensitive to this signal though.

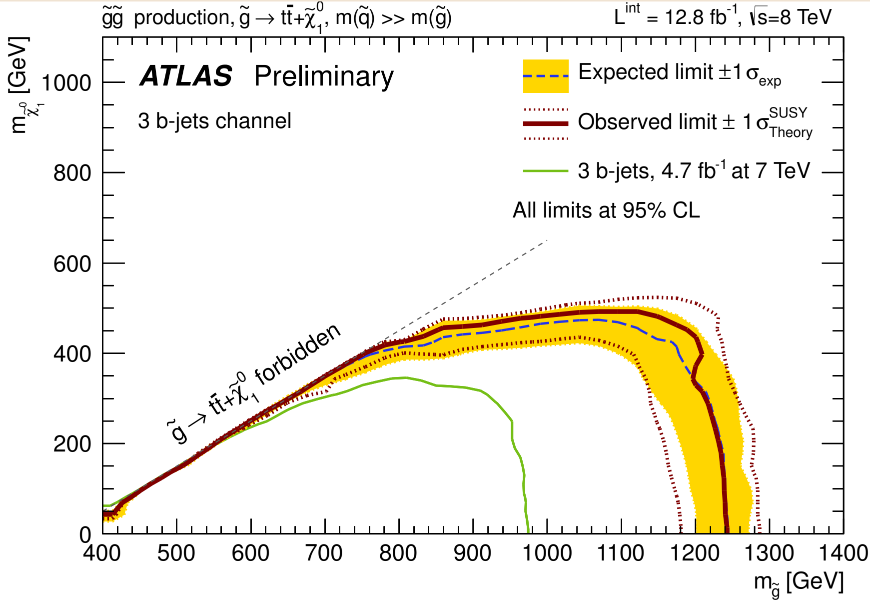
LHC predictions

- There is only one light, SM-like Higgs boson with a mass of between 122 and 129 GeV.
- The other supersymmetric Higgses will not be produced.
- Renormalising the scalar masses from the GUT to the TeV scale typically means that the stops and sbottoms are lighter than the other squarks.
- Though the squarks cannot be produced, this has an impact on gluino decays.
- $\tilde{g} \to t\bar{t} + MET$
- $\tilde{g} \to b\bar{b} + MET$
- $\tilde{g} \to t\bar{b} + MET + soft$
- These channels will have signficant branching fractions.
- So, multi-top, multi-b, plus MET is a characteristic signature.

Multi-Top Quark Events!



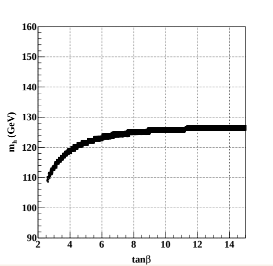
Being Challenged by the LHC!!



LHC predictions

- If the LSP is wino-like (as in most G_2-MSSM models) then the lightest chargino is almost degenerate with the LSP
- There will be "short track-stubs" from the chargino (lifetime at rest is about 5 cm).
- These will be present in some of the multi-top and multi-b events as well as in "direct chargino pair and chargino-neutralino" events
- These latter require an additional jet to trigger, though the pT thresholds are way to high now (at high luminosity). These are hard to find!

G_2-manifolds and the LHC data



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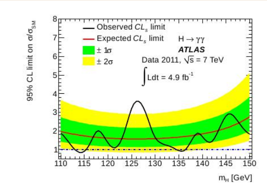

Data from the ATLAS from December 2011

Evidence for the Higgs boson and G_2-manifolds

Summary of "Generic" Predictions

- The gravitino and moduli masses are of order 30 TeV:
- String axions have a non-fine tuned cosmology and make up a significant fraction of dark matter W-ino like particles are also a component of dark matter.
- Only one, SM-like Higgs with a mass around 115 to 127 GeV will be observed at the LHC (122 - 127 GeV in M theory).
- Squarks and Sleptons will not be produced directly
- Gluinos, charginos and neutralinos could be produced
- The main discovery channel is gluino pair production with top and bottom rich high multiplicity final states.
- A search with at least three b-jets, MET and a single high pT lepton is one way to find evidence for such a signal at the LHC.

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

Other possibilities?

- What is implied if the data provides a different picture?
- One possibility is that we are "unlucky" and that the gaugino masses are just beyond the LHC
- In this case the LHC would observe a single Higgs and that's all
- What about "natural" susy and other models
- From the point of view of string/M theory, "natural susy" seems *u*nnatural and tuned
- Similarly of other models with sub-TeV (non-Higgs) scalars.

Higgs Branching Ratios

- There are some preliminary indications that the Higgs is not the Standard Model Higgs
- Say, for arguments sake, that the Higgs BR's are different from the SM
- This implies new particles and/or Higgs interactions
- The minimal, simplest string/M theory model of the type considered about would then be ruled out
- Staus are too heavy for instance
- But with a spectrum beyond the MSSM, new fermions and/or gauge bosons could modify the Higgs BRs

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
- $m_{pl}^2 = Vol(X)M_{11}^2 \sim \frac{1}{\alpha_{GUT}^{7/3}} M_{11}^2$
- $M_{GUT} = M_{11}\alpha_{GUT}^{1/3}$
- $m_{3/2} = m_{pl}\frac{\alpha_{GUT}^{7/2}}{\sqrt{\pi}}\frac{|Q-P|}{Q}e^{-\frac{P_{eff}}{Q-P}}$
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- So, $m_{3/2} \sim O(50)$ TeV.Note: $Q-P \geq 3$, so $Q-P=4$ doesn't work.
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- 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 $\sigma v(\chi\chi \to \gamma X) \sim 10^{-27}$ 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!!