Compactifying M-theory on a G2 manifold to describe/explain our world – Predictions for LHC (gluinos, winos, squarks), and dark matter

Gordy Kane

CMS, Fermilab, April 2016

OUTLINE

- **Testing theories in physics – some generalities - Testing 10/11 dimensional string/M-theories as underlying theories of *our* world *requires* compactification to four space-time dimensions!**
- **Compactifying M-theory on "G2 manifolds" to describe/ explain *our* vacuum – underlying theory - fluxless sector!**
- **Moduli – 4D manifestations of extra dimensions – stabilization - supersymmetry breaking – changes cosmology** first 16 slides
- **Technical stuff –** 18-33 - quickly
- **From the Planck scale to EW scale –** 34-39
- **LHC predictions – gluino about 1.5 TeV – also winos at LHC – but not squarks -** 40-47
- **Dark matter – in progress – surprising –** 48
- **(Little hierarchy problem –** 49-51**)**
- **Final remarks 1-5**

String/M theory a powerful, very promising framework for constructing an underlying theory that incorporates the Standard Models of particle physics and cosmology and probably addresses all the questions we hope to understand about the physical universe – we hope for such a theory! – probably also a quantum theory of gravity

Compactified M-theory generically has gravity; Yang-Mills forces like the SM; chiral fermions like quarks and leptons; softly broken supersymmetry; solutions to hierarchy problems; EWSB and Higgs physics; unification; small EDMs; no flavor changing problems; partially observable superpartner spectrum; hidden sector DM; etc

Simultaneously – generically

Argue compactified M-theory is *by far* the best motivated, and most comprehensive, extension of the SM – gets physics relevant to the LHC and Higgs and superpartners right – no ad hoc inputs or free parameters

☺ Take it very seriously ☺

So have to spend some time explaining derivations, testability of string/M theory

Don't have to be somewhere to test theory there

– E.g. no one at big bang, or dinosaur extinction, or not traveling faster than speed of light - but tests fully compelling

– Don't need experiments at Planck scale – always relics

-- If world supersymmetric, can connect EW scale data and Planck scale theory

String/M theory must be formulated in 10 (11) D to be a possible quantum theory of gravity, and obviously must be projected to 4D ("compactified") for predictions, tests

Many string theorists do not know the techniques to study or evaluate compactified string/M-theories in 4 D

Most of what is written on this is very misleading, even by experts(!) – string theorists do not think much about it ("string theorists have temporarily given up trying to make contact with the real world" - 1999)

But string/M-theory's potential to provide a comprehensive underlying theory is too great to ignore it

String/M-theory is too important to be left to string theorists

Ideally theory would determine what corner of string/M theory to compactify to (heterotic? Type II? M-theory? Etc), and gauge group and matter content , and type of manifold etc – but not yet – small finite number – can try one at a time

Nevertheless, can address most issues – **many major results do not depend on manifold, on details**

COMPACTIFIED STRING THEORIES GIVE 4D TESTABLE RELATIVISTIC SUPERGRAVITY QUANTUM FIELD THEORIES – can calculate lots of predictions

There is a standard well-defined procedure to "compactify" (procedure for going to 4D)

- Choose Planck scale size manifold to compactify to
- Choose corner of string/M theory, e.g. heterotic, Type II, M-theory, etc, and gauge group, matter (e.g. SU(5)-MSSM)
- Write action, metric – project to 4D
  - Determine "superpotential", essentially Lagrangian
  - Determine "gauge kinetic function", metric for "gauge fields"
  - Determine "Kahler potential", essentially metric for "scalar" fields"
- Calculate potential energy, minimize it → 4D ground state

Compactified string theory is analogous to Lagrangian of a system

In all areas of physics one specifies the particular "theory" by giving the Lagrangian (Hamiltonian)

Physical systems are described not by the Lagrangian but by *solutions* to the equations – look for set of solutions that might describe our world

Normally find the ground state of a system, calculate energy levels and transitions

Analogous for string theory – our world corresponds to a metastable (or stable) ground state – called "vacuum"

Curled up dimensions contain information on our world – particles and their masses, symmetries, forces, dark matter, superpartners, more – nature of compact dimensions observable indirectly via superpartner masses, etc

What would we need to understand and calculate to say we had an underlying theory ("final theory") of our world?

- ➢ What are we made of? Why quarks and leptons?
- ➢ What is light?
- ➢ Why are there protons and nuclei and atoms? Why 3-2-1?
- ➢ What is the origin of mass for fundamental particles (q, l, W and Z)?
- ➢ Are the forces unified in form and strength?
- ➢ Why are quark and charged lepton masses hierarchical?
- ➢ Why are neutrino masses small and not hierarchical?
- ➢ Is nature supersymmetric near the weak scale?
- ➢ How is supersymmetry broken
- ➢ ***How is the hierarchy problem solved – stabilize hierarchy? – size of hierarchy? - μ?***
- ➢ Why matter asymmetry?
- ➢ Quantum theory of gravity
- ➢ What is an electron?
- ❑ What is dark matter? Ratio of DM to baryons?
- ❑ One and only one quark with Yukawa coupling ~ 1
- ❑ Why families? Why 3?
- ❑ What is the inflaton? Why is the universe old and cold and dark?
- ❖ Which corner of string/M-theory? Are several equivalent?
- ❖ Why three large dimensions?
- ❖ Why is there a universe? More populated universes?
- ❖ Are the rules of quantum theory inevitable?
- ❖ Are the underlying laws of nature (forces, particles, etc) inevitable?
- ❖ CC problems?

➢ Answered (more or less) in compactified M-theory - simultaneously

❑ Addressable in compactified M-theory

❖ **Can work on these**

Three new physics aspects:

- “Generic” – crucial to be predictive
- “Gravitino”- sets scale of superpartner masses
- “Moduli”
  - moduli 4D manifestation of existence of extra dimensions – generically present in all compactifications
  - New physics from compactifying
  - Describe sizes and shapes and metrics of small manifolds
  - Have definite values in vacuum – “stabilized” – if not, laws of nature time and space dependent
  - Supersymmetry breaking generates potential for all moduli, stabilizes
  - Dominate energy density of universe after inflation ends – oscillate, fall into minimum – we begin there
  - Can show lightest eigenvalue of moduli mass matrix about equal to gravitino mass
  - Decay of lightest moduli may determine matter asymmetry, and decay into DM

GENERIC methods, results:

- **Probably not a theorem (or at least not yet proved), might be avoided in special cases**

- **One has to work at constructing non-generic cases**

- ***No (or very few) adjustable parameters, no tuning***

- ***Predictions NOT subject to qualitative changes from small input changes***

GRAVITINO

-- In theories with supersymmetry the graviton has a superpartner, gravitino – if supersymmetry broken, gravitino mass (**$M_{3/2}$**) splitting from the massless graviton is determined by the form of supersymmetry breaking

– Gravitino mass sets the mass scale for all superpartners, for some dark matter

"Naturalness" – superpartners should have masses like W,Z, top to solve hierarchy and other problems

"Naturalness" does suggest should have found superpartners at LHC Run 1, but naturalness is what you invoke if you *don't* have a theory – all superpartner predictions before about a decade ago were based on naturalness, not theory – some of our predictions were already made then, more recently

Theories need not be "natural" - Actual compactified string theories imply should *not* have found superpartners at LHC Run 1 (see below) – hierarchy problem etc still solved, in interesting ways

M-theory compactified on G2 manifold

PAPERS ABOUT M-THEORY COMPACTIFICATIONS ON G_2 MANIFOLDS (11-7=4)

Earlier work 1995-2004 (stringy, mathematical) ; Witten 1995

- Papadopoulos, Townsend th/9506150, compactification on 7D manifold with G_2 holonomy → resulting quantum field theory has N=1 supersymmetry!!!
- Acharya, hep-th/9812205, non-abelian gauge fields localized on singular 3 cycles
- Atiyah and Witten, hep-th/0107177, analyze dynamics of M-theory on manifold of G_2 holonomy with conical singularity and relations to 4D gauge theory
- Acharya and Witten, hep-th/0109152, chiral fermions supported at points with conical singularities (quarks and leptons)
- Witten, hep-ph/0201018 – M-theory embedding SU(5)-MSSM, solves doublet-triplet splitting in 4D supersymmetric GUT, GENERIC discrete symmetry sets $\mu=0$
- Beasley and Witten, hep-th/0203061, generic Kahler form
- Friedmann and Witten, hep-th/0211269, SU(5) MSSM, scales – Newton's constant, GUT scale, proton decay – no susy breaking
- Lukas, Morris hep-th/0305078, generic gauge kinetic function
- Acharya and Gukov, Physics Reports, 392(2004)2003

Particles and forces!

Basic framework established – powerful, rather complete

➢ Acharya and I (and students, postdocs, collaborators) began there

We make a few discrete assumptions, calculate

- Compactify M-Theory on manifold with G_2 holonomy in fluxless sector – *well motivated* and *technically robust*

- Compactify to gauge matter group SU(5)-MSSM – can try others, one at a time

- Use generic Kahler potential and generic gauge kinetic function

- Assume needed singular mathematical manifolds exist – considerable progress recently – Simons Center workshops, Acharya, Simon Donaldson et al, etc

- **CC issues not relevant** - solving it doesn't help learn our vacuum, and not solving it doesn't stop learning our vacuum

We started in 2005 – since LHC coming, focused on moduli stabilization, supersymmetry breaking, etc → LHC physics, Higgs physics, dark matter etc

[Acharya, Bobkov, GK, Piyush Kumar, Kuflik, Shao, Watson, Lu, Zheng, S. Ellis – over 20 papers, over 500 arXiv pages]

- Indeed we showed that in M theory supersymmetry automatically was spontaneously broken via gaugino and chiral fermion condensation
- Simultaneously moduli stabilized, in unique de Sitter vacuum for given manifold
- Calculated supersymmetry soft-breaking Lagrangian → radiative electroweak symmetry breaking, Higgs boson – precise prediction of M_h/M_Z and h decays (in decoupling sector) – gluino and wino masses, etc

Get 4D effective supersymmetric field theory – in usual case coefficients of all operators are independent, so many coefficients – here all coefficients DETERMINED, calculable and connected

NO adjustable parameters – sometimes coefficient of term hard to calculate, so constrained parameter, e.g. of order 1 but could be off □ factor 2

Generically two hidden sector 3D submanifolds do not intersect in a 7D space, so no light matter fields charged under both SM gauge group and hidden sector gauge groups → supersymmetry breaking *generically gravity mediated* in these vacua

Technical aspects:

MODULI STABILIZATION

- All moduli geometric, equivalent – All G_2 moduli fields s_i have axionic partners t_i which have a shift symmetry in the absence of fluxes (different from heterotic or IIB) – such symmetries can only be broken by non-perturbative effects

- So in zero-flux sector only contributions to superpotential are non-perturbative, from "strong dynamics" (e.g. gaugino condensation or instantons) – focus on former

- In M theory superpotential and gauge kinetic function depend on all the moduli– all moduli on equal footing

  – so only need one term in W to stabilize all moduli

  -- in practice use at least two to be sure supergravity approximation good numerically

  -- not racetrack

- The hidden sector gaugino condensation produces an effective potential that stabilizes all moduli

A set of Kahler potentials, consistent with G_2 holonomy and known to describe some explicit examples, was given by Beasley-Witten th/0203061; Acharya, Denef, Valandro th/0502060, with

$$K = -3\ln(4\pi^{1/3} V_X)$$

$$V_X = \prod_{i=1}^{N} s_i^{a_i}, \text{ with } \sum_{i=1}^{N} a_i = 7/3$$

We assume we can use this.

The gauge kinetic functions here are integer linear combinations of all the moduli (Lukas, Morris th/0305078),

$$f_k = \sum_{i=1}^{N} \underline{N_i^k}\, z_i \,.$$

Focus on the (well-motivated) case where two hidden sector gauge kinetic functions are equal (the corresponding three-cycles are in the same homology class)]

Include massless hidden sector chiral fermion quark states Q with N_c colors, N_f flavors, $N_f<N_c$ -- then (Affleck, Dine, Seiberg PRL 51(1983)1026, Seiberg hep-th/9402044, hep-th/9309335, Lebedev,Nilles, Ratz th/0603047), $a=2/(N_c-N_f)$

$$W = A_1\, e^{i\frac{2\pi}{N_c-N_f}\sum_{i=1}^{N} N_i^{(1)} z_i} \det(Q\tilde{Q})^{-\frac{1}{N_c-N_f}} = A_1 \boxed{\phi^a} e^{ib_1\, f_1}$$

and define an effective meson field

$$\phi \equiv \left(\det(Q\tilde{Q})\right)^{1/2} = \phi_0 e^{i\theta}$$

- For pure SU(Q) super Yang-Mills hidden sector, non-perturbative dynamics generates an effective moduli superpotential of form $W=AM_{Pl}^{3}e^{i2\pi bf}$ where f is the hidden sector gauge kinetic function $f=\Sigma N_i z_i$ and b=1/Q
- Integers N_i determined by homology class of the 3-cycle

- Hidden sectors with SU(P+1) gauge group with chiral charged matter, which arises from isolated conical singularities in the G2 manifold, also are included – superpotential from Seiberg et al

- Such a superpotential will stabilize all moduli, in de Sitter space

- Get unique de Sitter vacuum for a given manifold, and sector with Q-P=3 has no high scale solutions, only $M_{3/2} \approx 50$ TeV for number of moduli larger than about 60

gauge kinetic function

SUPERPOTENTIAL

Complex moduli

$$W = \sum_{k=1}^{M} A_k e^{i b_k f_k} \square \sum_k e^{i b_k \sum N_i^k z_i}$$

Keep two terms – enough to find solutions with good properties such as being in supergravity regime, simple enough to do most calculations semi-analytically (as well as numerically) – check some things with more terms numerically

Imagine expanding exponential – all terms get interactions

$b_k = 2\pi / c_k$ where c_k are dual coxeter numbers of hidden sector gauge groups --- A_k are constants of order unity, and depend on threshold corrections to gauge couplings, some computed by Friedmann and Witten

The microscopic constants a_i, b_k, A_k, N_i^k are determined for a given G_2 manifold (but not yet known for all relevant ones) --they completely characterize the vacua – not dependent on moduli

Finally mostly work with

$$W = A_1 \phi^a \, e^{ib_1 f} + A_2 e^{ib_2 f}$$

$$K = -3 \ln(4\pi^{1/3} V_X) + \phi\bar{\phi}$$

Can often get semi-analytic forms, and aproximations good

We also looked at chiral families in both hidden sectors, more chiral families in each – no changes in qualitative results (in paper)

The N=1 SUGRA scalar potential is then given by:

$V_X=V_7$

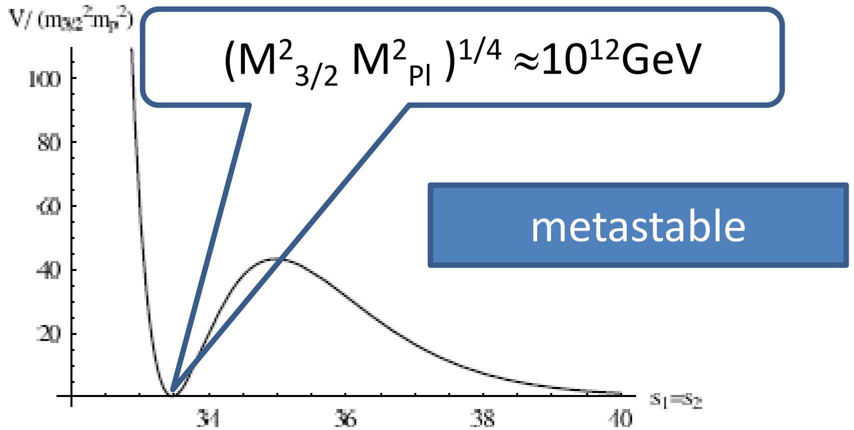
$$
\begin{aligned}
V \;=\; & \frac{e^{\phi_0^2}}{48\pi V_X^3}\Big[\big(b_1^2 A_1^2 \phi_0^{2a} e^{-2b_1\vec{\nu}\cdot\vec{a}} + b_2^2 A_2^2 e^{-2b_2\vec{\nu}\cdot\vec{a}} + 2b_1 b_2 A_1 A_2 \phi_0^{a} e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}} \cos((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta)\big) \\
& \times \sum_{i=1}^{N} a_i(\nu_i)^2 + 3(\vec{\nu}\cdot\vec{a})\big(b_1 A_1^2 \phi_0^{2\alpha} e^{-2b_1\vec{\nu}\cdot\vec{a}} + b_2 A_2^2 e^{-2b_2\vec{\nu}\cdot\vec{a}} + (b_1+b_2) A_1 A_2 \phi_0^{a} e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}} \\
& \times \cos((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta)\big) + 3\big(A_1^2 \phi_0^{2a} e^{-2b_1\vec{\nu}\cdot\vec{a}} + A_2^2 e^{-2b_2\vec{\nu}\cdot\vec{a}} + 2A_1 A_2 \phi_0^{a} e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}} \qquad (101) \\
& \times \cos((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta)\big) + \frac{3}{4}\phi_0^2 \Big(A_1^2 \phi_0^{2\alpha} \left(\frac{a}{\phi_0^2}+1\right)^2 e^{-2b_1\vec{\nu}\cdot\vec{a}} + A_2^2 e^{-2b_2\vec{\nu}\cdot\vec{a}} \\
& + 2A_1 A_2 \phi_0^{a} \left(\frac{a}{\phi_0^2}+1\right) e^{-(b_1+b_2)\vec{\nu}\cdot\vec{a}} \cos((b_1-b_2)\vec{N}\cdot\vec{t}+a\theta)\Big)\Big].
\end{aligned}
$$

Minimize

Results:

$m^2_{scalar} \approx M^2_{3/2} + V_0 + $ small corrections calculable from W,K,f

V_0 is value of potential at minimum≈cosmological constant, set it to be small for any particular vacuum



So scalar masses essentially equal to gravitino mass

DE SITTER VACUUM, GAUGINO MASSES SUPRESSED

$$M_{1/2} \sim K_{mn} F_m \partial_n f_{SM}$$

Standard Model gauge kinetic function

-- f_{SM} doesn't depend on chiral fermions, whose F-term gives the largest contribution to supersymmetry breaking

-- $F_{chiral\ fermion} \sim V_7$ but $F_{moduli} \sim V_3$, $V_7 >> V_3$

-- matter Kahler potential does not enter, so results more reliable

-- moduli dependence is entirely in Volume factors, so same for all G2 manifolds for tree level gaugino masses

- **Including μ parameter in string theory**($W=\mu H_u H_d + \ldots$ so $\mu \sim 10^{16}$ GeV ?)

- Normally μ and tanβ treated as parameters, constrained to get EWSB
- Ultimately want to derive them from first principles
- If μ in W then it should be of order string scale
- Need symmetry to set μ=0

arXiv:1102.0556, Acharya, Kane, Kuflik, Lu

- **Witten, hep-ph/0201018 – found generic discrete symmetry for G_2 compactifications, closely connected to doublet-triplet splitting problem proton lifetime**
- **Unbroken discrete symmetry so μ≡0 – but when moduli are stabilized the effects generally not invariant so in M-theory with moduli stabilized the symmetry is broken**
- **μ proportional to $M_{3/2}$** since $\mu \to 0$ if susy unbroken
- **μ proportional to moduli vev since μ→0 if moduli not stabilized**
- Stabilization led to moduli vevs/M_{pl} □ 0.1
- **So finally expect μ □ 0.1 $M_{3/2}$**
- But answer for residual symmetry not known – interesting mathematics – value of μ depends on manifold – maybe $0.04 M_{3/2}$

MAIN RESULTS, PREDICTIONS FOR M-THEORY SO FAR, and in progress – **ONE THEORY**

- **Moduli stabilized** – vevs calculable and □ 1/10 M_{pl}, masses multi TeV √
- Calculate **gravitino mass** approximately, from Planck scale ~ 50 TeV
- **Scalars heavy** (squarks, higgs sector, sleptons) ~ gravitino mass (2006) PREDICTION, LHC
- **Gaugino masses suppressed** (by volume ratios), ~ factor 40 PREDICTION, LHC
- **Hierarchy problem solved** √
- **Non-thermal cosmological history** via late time moduli decay (before BBN) PREDICTION
- Moduli decay can provide **ratio of baryogenesis *and* DM** PREDICTION
- Axions stabilized, give solution to **strong CP problem**, spectrum of axion masses √
- **Anticipated Higgs boson mass *and* BR** (SM-like) before data PREDICTION √
- SM quark and lepton charges, Yang-Mills 3-2-1 forces, parity violation, generic
- Gauge coupling unification, proton decay all right
- **No flavor problem, weak CPV ok**
- **EDMs calculable**, smallness explained (could have been wrong) PREDICTION √
- **$\mu \approx$ 2-3 TeV** – included in theory, approximately calculable
- **$\tan\beta \approx$ 5-7** PREDICTION
- LHC predictions – **gluinos ~ 1.5 TeV**, 3rd family decays enhanced
  -- **wino, bino** ~ ½ TeV
- Need future collider for **higgsinos, scalars – not at LHC** PREDICTION
- Hidden sector DM, under study – **LSP decays, LSP generically never dark matter**

ALL FOLLOW FROM few DISCRETE ASSUMPTIONS – no free parameters – all **SIMULTANEOUS**

Scales

M-THEORY COMPACTIFIED ON G2 MANIFOLD, TO MSSM

Planck scale

GUT~$2\text{x}10^{16}$

String, KK, etc

$\Lambda \approx 10^{14}$GeV — **gaugino, chiral fermion condensation, F-terms $\neq 0$** (susy broken)

$\Lambda \approx \exp\{-2\pi V_3/3Q\}\, M_{Pl}/V_7^{1/2}$

($V_3 \sim Q$ so not sensitive)

Supersymmetry breaking dynamical, automatic!

Hierarchy problem solved

$M_{3/2}$~50 TeV — **Gravitino mass** (so squarks heavy) $M_{3/2}=e^{K/2}W/M_{Pl}^2$, $W \sim \Lambda^3$

μ~ 2-3 TeV

TeV scale

Gaugino mass suppression

$M_{1/2} \sim F_{mod} \partial f_{vis}/\partial F_{mod}$

~~$+F_{ChiFerm} \partial f_{vis}/\partial F_{ChiFerm}$~~

and $F_{mod}/F_{ChiFerm} \sim V_3/V_7 << 1$

gluino~1.5 TeV, wino, bino 0.5 TeV

REWSB

$\mu \approx \langle mod \rangle M_{3/2}$ (Witten+mod stabilization) ~ few TeV

$M_{Hu} \sim f_{M0}(t)\, M_0^2 - f_{A0}(t)\, A_0^2 << M_{3/2}$ ($f_{M0} \approx f_{A0}$; $A_0 \gtrsim M_0$)

Qualitative gravitino and gluino masses

$$W \sim \Lambda^3$$

$$M_{3/2} = \frac{e^{K/2} W}{{M_{Pl}}^2} \approx \left(\frac{\Lambda}{M_{Pl}} \right)^3 \frac{1}{V_3} M_{Pl}$$

$$M_{gluino} \approx \left(\frac{\Lambda}{M_{Pl}} \right)^3 \frac{1}{V_3} \frac{V_3}{V_7} M_{Pl}$$

+ anomaly mediation terms

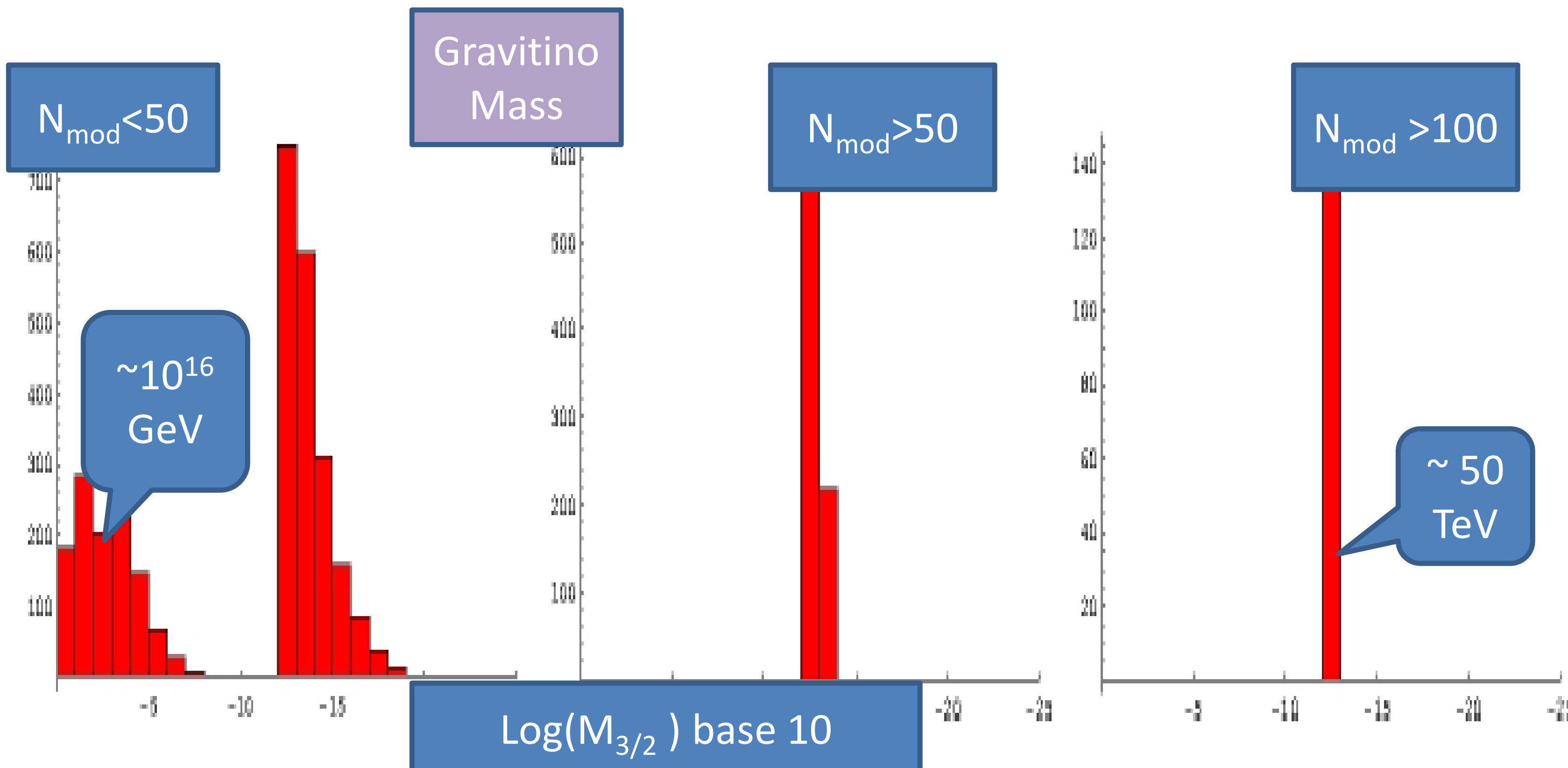
[Acharya, Bobkov calculated cross term between matter and moduli Kahler potential – coefficient C of order 1 but C hard to calculate – we include that term in careful calculation of gaugino masses – use Higgs mass to help fix C≈1/2

[Φ visible sector matter, φ moduli, $\kappa_{\alpha\beta}$ Kahler metric]

$$K = -3\ln(4\pi^{1/3}V_7) + \kappa_{\alpha\beta}\frac{\Phi_\alpha^\dagger \Phi_\beta}{V_7} + \frac{\bar{\varphi}\varphi}{V_7} + \frac{C}{3}\kappa_{\alpha\beta}\frac{\bar{\varphi}\varphi}{V_7}\frac{\Phi_\alpha^\dagger \Phi_\beta}{V_7}$$

Use M_h value to pin down $M_{3/2}$ rather precisely, $M_{3/2}$ =35 TeV]

Hierarchy problem solved IF number of moduli (b_3) large enough!



This is after setting potential to zero at minimum – do not have to separately set V_0 to zero and also $M_{3/2}$ to TeVs – does not happen in other corners !

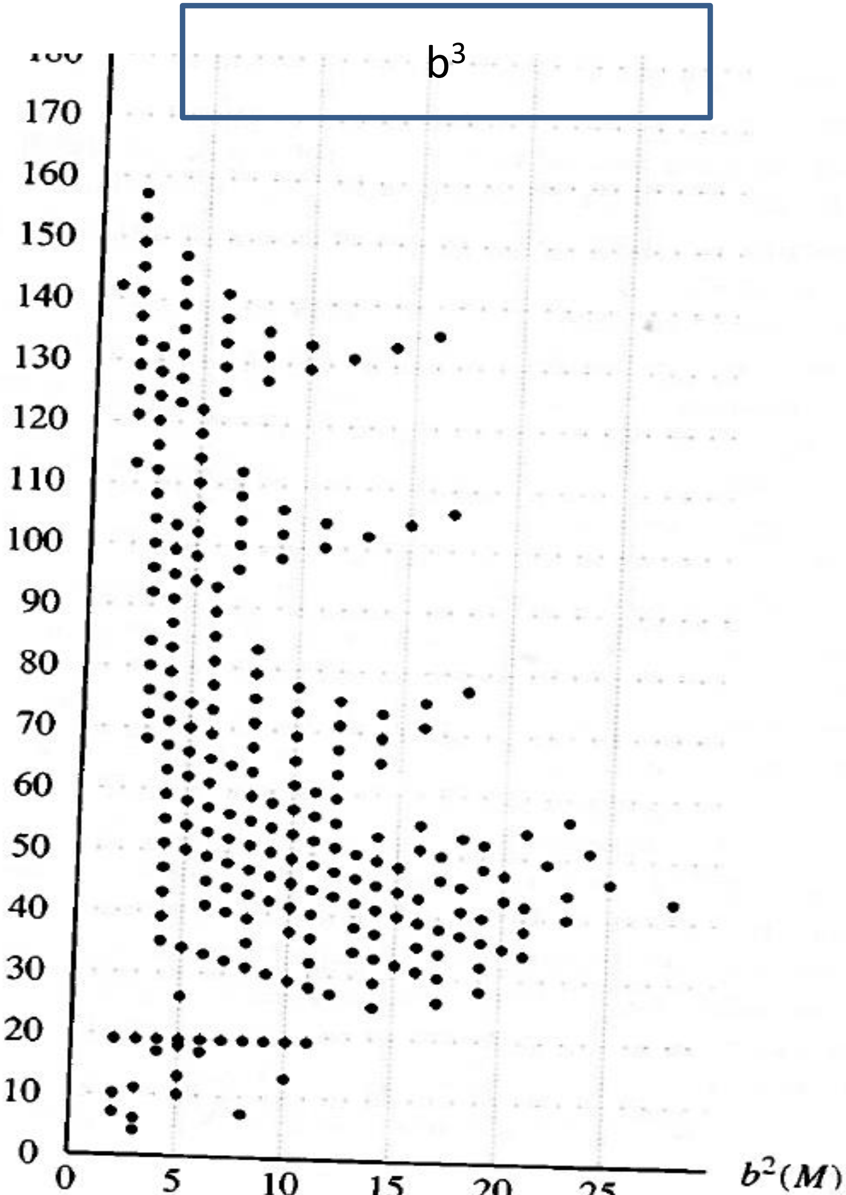


Figure 12.3. Betti numbers $(b^2(M), b^3(M))$ of compact, simply-connected 7-manifolds with holonomy G_2

Dominic Joyce, "Compact Manifolds with Special Holonomy" – graph for non-singular manifolds

HIGGS MASS, DECAYS

Two Higgs doublets in supersymmetry – large scalar terms in soft-breaking Lagrangian (M_{Hu},M_{Hd}) plus radiative electroweak symmetry breaking imply one light Higgs boson and four heavy ones, "decoupling sector"

Calculate ratio M_{higgs}/M_Z – determined by "□" of Higgs potential – write theory at string scale – do "renormalization group running" down to electroweak scale, known through three loops with heavy scalars – use "match and run"

Compactified M-theory (with generic gauge kinetic function and kahler potential) anticipated M_{higgs}=126.4 GeV summer 2011, before data – predicted all decay branching ratios would be within few per cent of Standard Model ones (as observed) – BR not a mystery

Electroweak scale spread of about ±1.2 GeV purely because top quark yukawa and α_s enter RGE running from high scale

Higgs data exactly as expected from compactified M-theory MSSM decoupling sector and electroweak symmetry breaking

Here is where supersymmetry is "hiding" at LHC

LHC

Squark masses ~ gravitino mass ~ few tens of TeV

GAUGINO MASSES ~ TeV

arXiv:1408.1961 [Sebastian Ellis, GK, Bob Zheng]

$M_{gluino} \approx$ 1.5 TeV,

$M_{bino} \approx$ 450 GeV,

$M_{wino} \approx$ 614 GeV

all consistent with current data

Lesson from (compactified M-)theory: should not have expected superpartners at LHC Run 1

$\sigma_{gluino} \approx$ 12 fb (smaller because squarks heavy),

$\sigma_{wino\ pairs} \approx$ 15fb

Any bets?

For 1.5 Tev, 3σ gluino signal probably needs ~ 45 fb^{-1} because of backgrounds (top pairs about 300 times gluino pairs)

3 and only 3 channels at LHC:

$$pp \rightarrow g\,g$$

$$pp \rightarrow w^{+}w^{-}$$

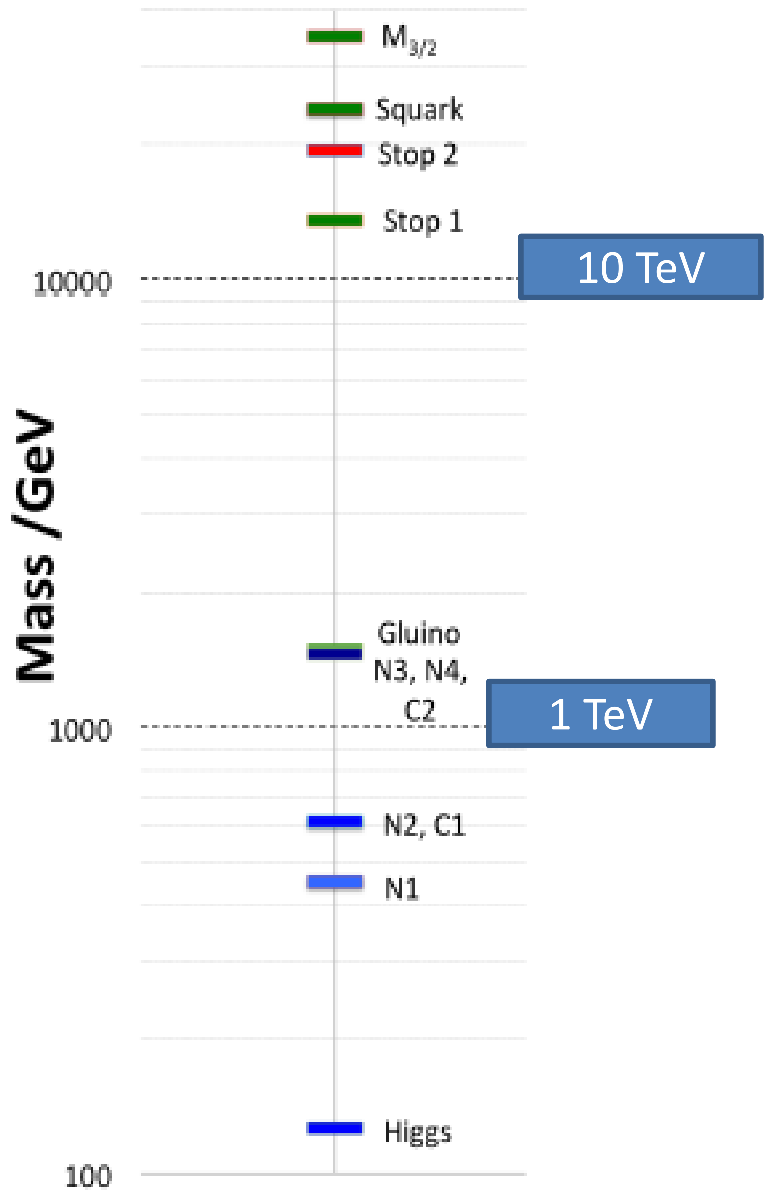
$$pp \rightarrow w^{\pm}w^{o}$$

$$M(W^{+}) = M(W^{0}) = 614GeV$$

$$M(LSP) = 450GeV$$

$$W^{\pm} \rightarrow W^{\pm} + LSP \sim 100\%$$

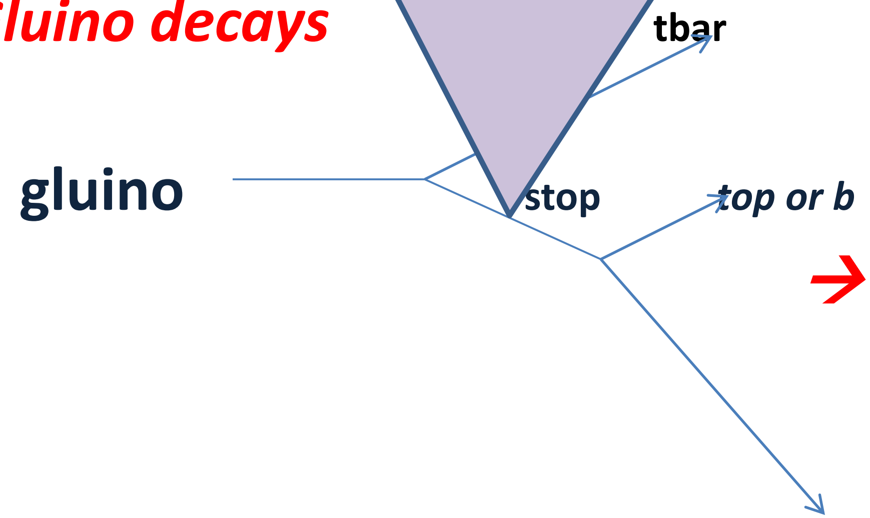
$$W^{0} \rightarrow h + LSP \sim 98\%$$



Particle	Mass (GeV)
m_0	24200
$M_{3/2}$	35000
$\tilde{q}_{L,R}$	24000
$\tilde{t}_2$	19300
$\tilde{t}_1$	13500
$\tilde{b}_2$	23900
$\tilde{b}_1$	19300
$\tilde{g}$	1500
χ_1^0	450
χ_2^0	614
χ_3^0	1460
χ_4^0	1460
$\chi_1^\pm$	614
$\chi_2^\pm$	1460
h	125.2[2]

Virtual stop lighter, enters propagator to 4th power

Gluino decays



[4 tops (or bbbb, or btbt) favored for gluino pair!]

→ enhanced 3rd family decays,

Gluino lifetime ~ 10^{-19} sec, decays in beam pipe

Gluino decays flavor-violating: 3rd family/(1st + 2nd) ≈ 1.2 (naively 0.5)

For heavy squarks, σ(gluinos, 13 TeV)/ σ(gluinos, 8 TeV)≈ 30-45 for 1.5 TeV gluino

Gluino BR

Decay	BR (%)
$\tilde{g} \to \chi_1^{\pm} q_{1,2}\bar{q}_{1,2}$	25
$\tilde{g} \to \chi_1^{\pm} b\bar{t},\ t\bar{b}$	23
$\tilde{g} \to \chi_1^0 t\bar{t}$	20
$\tilde{g} \to \chi_2^0 q_{1,2}\bar{q}_{1,2}$	12
$\tilde{g} \to \chi_1^0 q_{1,2}\bar{q}_{1,2}$	8
$\tilde{g} \to \chi_2^0 b\bar{b}$	7
$\tilde{g} \to \chi_2^0 t\bar{t}$	4
$\tilde{g} \to \chi_1^0 b\bar{b}$	1

1408.1961

Neutralino BR

Decay	BR (%)
$\chi_4^0 \to \chi_1^{\pm} W^{\mp}$	60
$\chi_4^0 \to \chi_2^0 h$	27
$\chi_4^0 \to \chi_1^0 h$	8
$\chi_4^0 \to \chi_2^0 Z$	4
$\chi_4^0 \to \chi_1^0 Z$	2
$\chi_3^0 \to \chi_1^{\pm} W^{\mp}$	60
$\chi_3^0 \to \chi_2^0 Z$	26
$\chi_3^0 \to \chi_1^0 Z$	8
$\chi_3^0 \to \chi_2^0 h$	4
$\chi_3^0 \to \chi_1^0 h$	2
$\chi_2^0 \to \chi_1^0 h$	98
$\chi_2^0 \to \chi_1^0 Z$	2

Chargino BR

Decay	BR (%)
$\chi_2^{\pm} \to \chi_1^{\pm} h$	31
$\chi_2^{\pm} \to \chi_1^{\pm} Z$	30
$\chi_2^{\pm} \to \chi_2^0 W^{\pm}$	30
$\chi_2^{\pm} \to \chi_1^0 W^{\pm}$	9
$\chi_1^{\pm} \to \chi_1^0 W^{\pm}$	100

Future colliders – 100 TeV--gluino + squark associated production

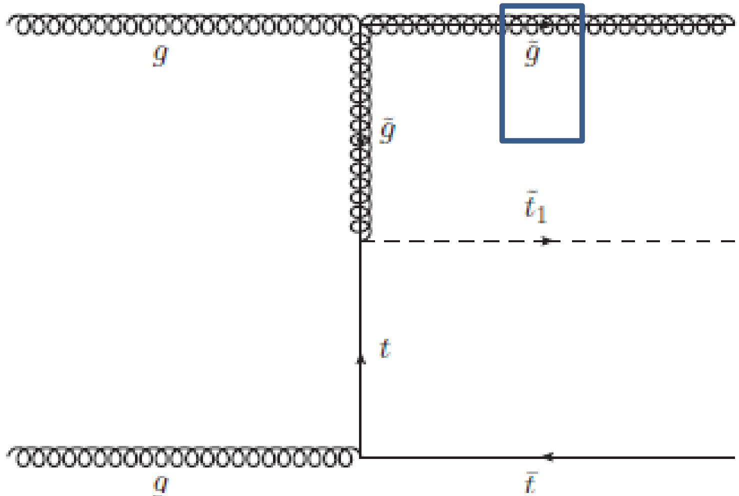


Figure 4: Dominant Feynman graph for stop associated production by gluon splitting.

We computed using MadGraph5 [39] the production cross-sections to leading order for tl
hannels for both $\sqrt{s} = 50\,\text{TeV}$ and 100 TeV. The results are tabulated below, including
umber of events N expected given 3000 fb^{-1} of data.

Channel	$\sigma_{50\ \text{TeV}}$ (fb)	$N_{50\ \text{TeV}}$	$\sigma_{100\ \text{TeV}}$ (fb)	$N_{100\ \text{TeV}}$
$pp \to t\tilde{t}_1\tilde{g}$	7.1×10^{-5}	0	1.6×10^{-2}	47
$pp \to b\tilde{b}_1\tilde{g}$	2.6×10^{-6}	0	3.0×10^{-3}	9
$pp \to \tilde{q}_{1(L,R)}\tilde{g}$	3.2×10^{-4}	1	3.0×10^{-1}	900
$pp \to \chi_3^0\chi_4^0$	9.2×10^{-1}	2800	3.4	10200
$pp \to \chi_3^0\chi_2^\pm$	1.8	5400	6.4	19200
$pp \to \chi_4^0\chi_2^\pm$	1.8	5400	6.4	19200
$pp \to \chi_2^\pm\chi_2^\mp$	1.0	3000	3.7	11100

Gluino, wino, bino mass predictions are generic and robust – not just "a little above current limits" – clear to any knowledgeable person who goes through derivation

Qualitatively:

- Compactification, RGE running down
- F-terms $\neq 0$ from hidden sector gaugino and chiral fermion condensation, so supersymmetry broken – largest gauge groups on 3-cycles run fastest –> scale $\approx 10^{14}$ GeV
  $[\Lambda \approx (M_{pl}/V_7) \exp(-2\pi V_3/3Q) \approx 10^{14} \text{GeV}]$
- Then calculate gravitino mass $\approx$ 40 TeV $[W \sim \Lambda^3/M_{pl}^3,\ M_{3/2} \approx e^{K/2} W/M_{pl}^2]$
- Gaugino masses automatically suppressed to ~ TeV since largest susy-breaking source of mass absent, $V_3/V_7 \sim 1/40$
  → gluino mass ~ 1.5 TeV (±10-15%)
- Gluino cross section ≈ 12 fb - top pair background large – note limits weaker for heavy squarks and for realistic decays

HIDDEN SECTOR DARK MATTER – in progress – predictions and tests

[Acharya, Sebastian Ellis, GK, Brent Nelson, Malcolm Perry, Bob Zheng]

- In M-theory, curled up 7D space has 3D submanifolds (“3-cycles”) that generically have (orbifold) singularities and therefore have particles in gauge groups $\sim$ 100 submanifolds (3rd Betti number) – we live on one, “visible sector”
- Supersymetry breaking due to ones with large gauge groups
- Gravitational interactions, same gravitino and moduli for all
- Other hidden sectors have their own matter, some stable and DM candidates – can calculate spectra, relic densities
- Calculations underway: already published general relic density calculations with a non-thermal cosmological history, arXiv:1502.05406 (Acharya, GK, Nelson, Zheng)
- Now analyzing actual hidden sectors systematically for M-Theory
- Examples of stable relics exist, with relic density of order what is observed – e.g. M-theory case $U(1)^3$, DM mass $\sim$ 10 MeV
- ***Generically, LSP decays to lighter hidden sector states in <u>some</u> hidden sector – LSP “never” dark matter***

  U(1)’s generic explicitly and via larger gauge groups breaking - kinetic mixing portals generic (other portals too) – light gauginos generic – light chiral fermions generic via hierarchical couplings

IT IS NOT GENERIC TO NOT HAVE SIZABLE KINETIC MIXING AND LIGHT HIDDEN SECTOR STATES

LITTLE HIERARCHY ~ 2 TEV, NOT 40 TEV – MAYBE EVEN SOLVED

-- derive tanβ too

Usual EWSB conditions [so higgs potential minimum away from origin]:

$M_Z^2 = -2\mu^2 + 2(M^2_{Hd} - M^2_{Hu}\tan^2\beta)/\tan^2\beta = \mathbf{-2\mu^2 + 2M^2_{Hd}/\tan^2\beta - 2M^2_{Hu}}$

$2B\mu = \sin 2\beta\,(M^2_{Hu} + M^2_{Hd} + 2\mu^2)$

M^2_{Hu} runs to be negative, M^2_{Hd} and B don't run much, μ suppressed, $\sin 2\beta \approx 2/\tan\beta$

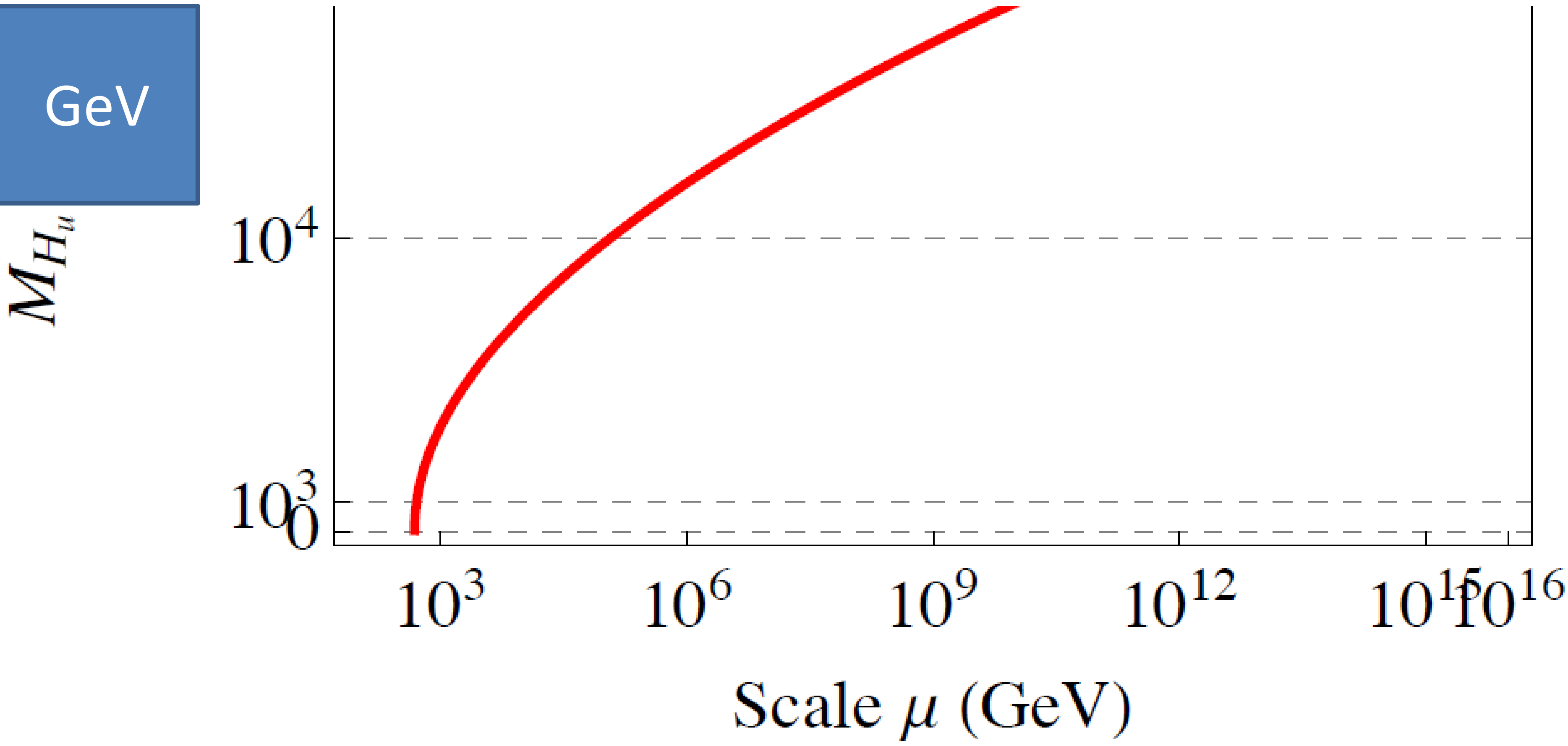
If no μ from superpotential, and visible sector Kahler metric and Higgs bilinear coefficient independent of meson field, and if $F_{mod} \ll F_\phi$ then B (high scale)≈$2M_{3/2}$ – recall $\mu < 0.1M_{3/2}$

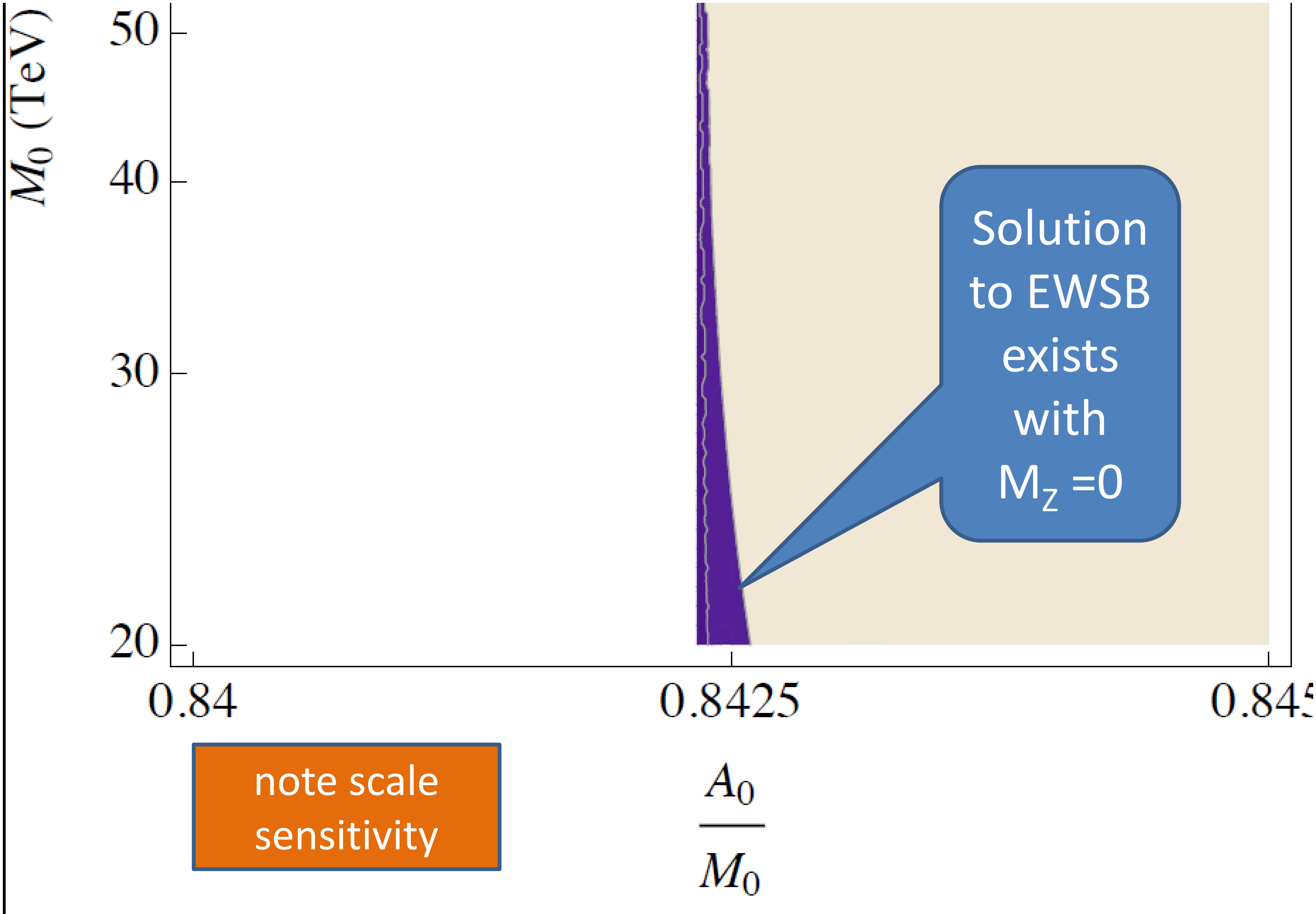
→ $\tan\beta \approx M^2_{Hd}/B\mu \approx M^2_{3/2}/B\mu$ → **$\tan\beta \approx M_{3/2}/2\mu$ (~ 6)**

- **μ, $|M_{Hu}|$ ~ 2 TeV, so little hierarchy ~ 10-20, not ~ $M_{3/2}/M_Z$**
- **Maybe cancellations – have a theory, so meaningful**

- **BUT Calculations of kahler potential, trilinears have corrections**
  - **not yet calculable – so can't calculate running well enough**
- **There are M_0 and A_0 and μ in the range $M_Z \approx 0$**

GeV




M_0 (TeV)
50
40
30
20
0.84
0.8425
0.845
Solution to EWSB exists with M_Z =0
note scale sensitivity
$\frac{A_0}{M_0}$

FINAL REMARKS (1)

- **String/M-theory too important to be left to string theorists**

- **10/11 D String/M-theory with curled up small dimensions may seem complicated – but probably it is the SIMPLEST FRAMEWORK THAT COULD SIMULTANEOUSLY INCORPORATE AND *EXPLAIN* ALL THE PHENOMENA WE WANT TO UNDERSTAND – 10/11D needed → meaningful predictions**

- **Compactified M-theory promising candidate for our vacuum – at least shows not premature to study such compactifications**

FINAL REMARKS (2)

- **Moduli generically present – inevitable in M Theory – implies non-thermal cosmological history – maybe ratio baryons/DM**

- **M_h/M_Z and Higgs decay branching ratios anticipated**

- **LHC: gluino ~ 1.5 TeV, wino, bino ~ 0.5 TeV (± ~ 10%) – good signatures – need ~40 fb^{-1}** because of backgrounds

- **Hidden sector dark matter candidates generic, probably inevitable – LSP generically always decays**

FINAL REMARKS (3)

- **Many results generic, don't depend on manifold**

- gravity mediation;
- moduli stabilized;
- gravitino mass;
- scalars heavy;
- gauginos light (gluino, LSP etc);
- small EDMs
- matter dominated cosmological history
- EWSB, M_h/M_Z, h BR (2 doublets, heavy scalars, EWSB solutions)
- LSP decays to hidden sector matter

FINAL REMARKS (4)

Possible issues:

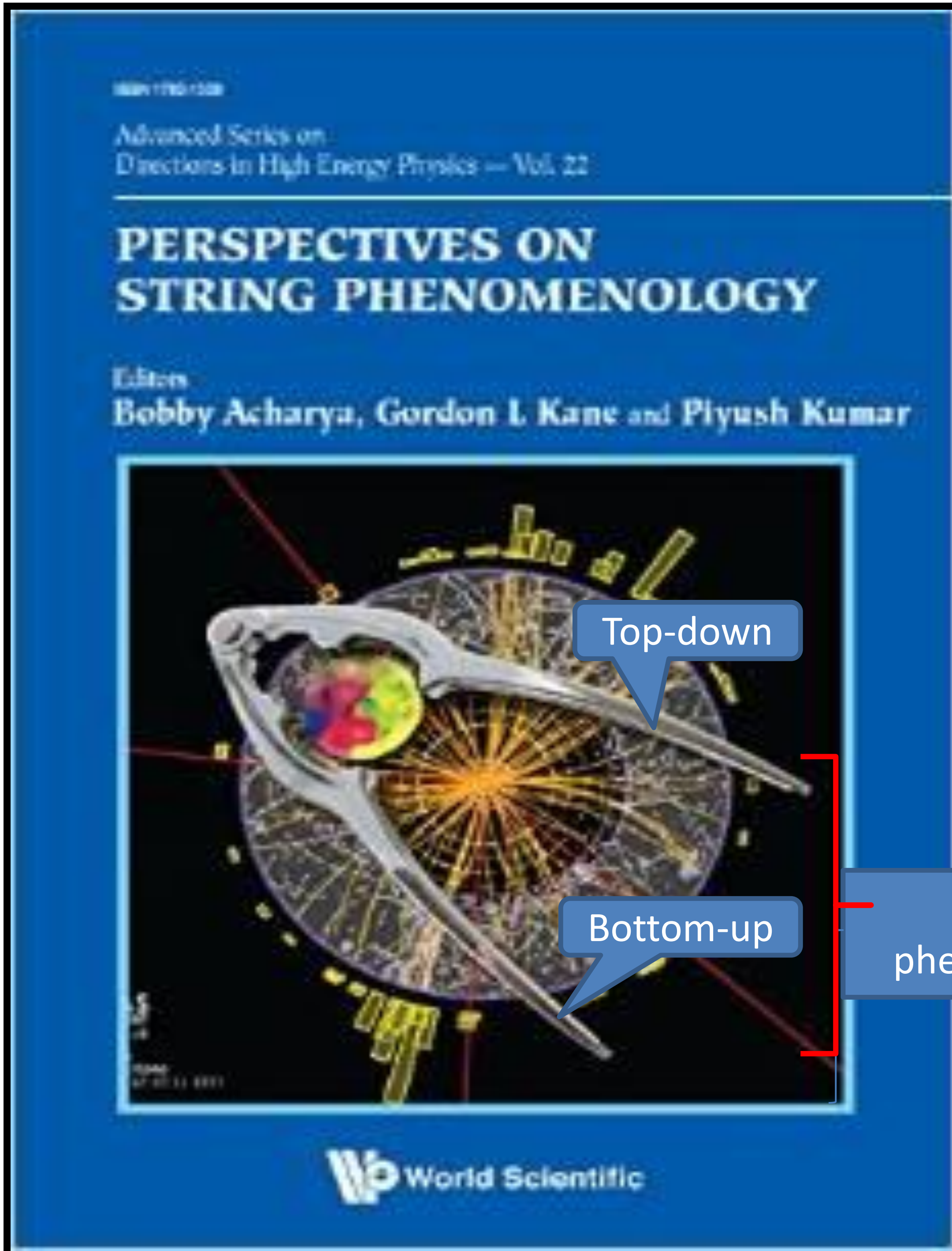
- g_μ-2;
- N_{eff} (Acharya, Chakrit Pong…..1512.07907);
- No clear X(760)→γγ candidate

FINAL REMARKS (5)

- Landscape? – Obviously many solutions
- Examples already show not an obstacle to finding candidate descriptions of our world – then study properties of compactifications to see implications for multiverse populations
- Use phenomenology and theory constraints to find regions of landscape like our world
- Maybe in each vacuum can calculate all major results (?)
- Crucial question - are the many solutions populated? – maybe not [Perry et al; Greene et al; Shiu et al]

“if people don’t want to come to the ballpark nobody’s going to stop them”

Yogi Berra



String phenomenology

Nutcracker!

Compactified M-Theory

- **Derive** solution to large hierarchy problem
- Generic solutions with **EWSB derived**
- main F term drops out of **gaugino masses** so **dynamically suppressed**
- **Trilinears > $M_{3/2}$** necessarily
- **μ incorporated in theory**
- Little hierarchy significantly reduced
- **Scalars = $M_{3/2}$ ~ 50 TeV necessarily** , scalars not very heavy
- Gluino lifetime □ 10^{-19} sec, decay in beam pipe
- **M_h □126 GeV unavoidable** from ratio to Z

SPLIT SUSY (ETC) MODELS

- Assumes **no solution (possible) for large hierarchy problem**
- **EWSB assumed**, not derived
- **Gauginos suppressed by assumed** R-symmetry, suppression arbitrary
- Trilinears small, suppressed compared to scalars
- **μ not in theory** at all; guessed to be $\mu \sim M_{3/2}$
- No solution to little hierarchy
- Scalars **assumed** very heavy, whatever you want, e.g. 10^{10} GeV
- Long lived gluino, perhaps meters or more
- **Any M_h allowed**

M-THEORY – 11D [M-theory, string theory not yet fully defined – standard in physics]

○ Must **"compactify"** to 4D for our world – geometry is $X \times R^{(3,1)}$, R Minkowski, X compact manifold [expected to be near Planck scale size (want natural size, time, energy scale set by G_N , h, c)]

○ X are compact manifolds with G_2 holonomy – admit one covariantly constant spinor → N=1 supersymmetry, a symmetry of the 4D massless modes and interactions and Lagrangian under bosons(integer spin fields) ↔ fermions (spin ½ fields)

○ Metrics with G_2 holonomy are Ricci flat, metric is solution of Einstein's equations in 11D, has finite 4D Newton's constant, spin 2 massless graviton

○ If X smooth no interesting physics – want solutions with singularities

Why N2→ N1 + h dominates:

- N2-N1-h coupling from wino-higgsino-h and bino-higgsino-h couplings in gauge eigenstates
- N1 ~ bino
- N2 ~ wino
- So N2 → N1 h suppressed by one power of gaugino-higgsino mixing, which is $\sim M_Z/\mu \leq 1/10$
- Only higgsinos couple directly to Z, via Z-higgsino-higgsino vertex, so Z-N1-N2 vertex suppressed by two powers, so N2→N1 + Z suppressed by $\sim (M_Z/\mu)^2$

In Witten's M theory approach to $SU(5)$, the combination of the discrete symmetry, the Wilson lines and the fact that GUT multiplets are localised at points, allows one to prevent the MSSM Higgs doublets, H_u and H_d, from having a mass (the μ-term) whilst the colour triplets D and $\overline{D}$ could have large masses. For simplicity we assume that the symmetry is $\mathbf{Z_N}$. We use the following notation: $\overline{\mathbf{5}}^w$ is the multiplet containing H_d and $\overline{D}$ and is localised along the Wilson line (which is a circle in the extra dimensions); $\mathbf{5}^h$ is the multiplet containing H_u; $\overline{\mathbf{5}}^m$ and $\mathbf{10}^m$ are the matter multiplets. Then the transformation rules for these multiplets under $\mathbf{Z_N}$ are:

$$\begin{aligned} \overline{\mathbf{5}}^w &\rightarrow \eta^{\omega}\left(\eta^{\delta} H_d^w \oplus \eta^{\gamma}\overline{D}^w\right), \\ \mathbf{5}^h &\rightarrow \eta^{\chi}\mathbf{5}^h, \\ \overline{\mathbf{5}}^m &\rightarrow \eta^{\tau}\overline{\mathbf{5}}^m, \\ \mathbf{10}^m &\rightarrow \eta^{\sigma}\mathbf{10}^m, \end{aligned} \tag{1}$$

where $\eta \equiv e^{2\pi i/N}$, $2\delta + 3\gamma = 0 \mod N$. By requiring that Yukawa couplings, Majorana neutrino masses, and colour-triplet masses must be present, we obtain constraints on the charges as can be seen in Table I where we chose $\omega = 0$.

TABLE I. Couplings and charges for $SU(5)$ operators.

Coupling	Constraint
$H_u^h \mathbf{10}^m \mathbf{10}^m$	$2\sigma + \chi = 0 \mod N$
$H_d^w \mathbf{10}^m \overline{\mathbf{5}}^m$	$\sigma + \tau + \delta = 0 \mod N$
$H_u^w H_u^w \overline{\mathbf{5}}^m \overline{\mathbf{5}}^m$	$2\chi + 2\tau = 0 \mod N$
$\overline{D}^w D^h$	$\chi + \gamma = 0 \mod N$

One can solve these by writing all angles in terms of, say, σ

$$\begin{aligned} \chi = -\gamma = -2\sigma \quad &\mod N, \\ \delta = -3\sigma + N/2 \quad &\mod N, \\ \tau = 2\sigma + N/2 \quad &\mod N, \end{aligned} \tag{2}$$

which *automatically forbids the μ-term and dimension four and five proton decay operators.*

Generically the vacua of the potential will spontaneously break the $\mathbf{Z_N}$ symmetry. This then generates an effective μ term from, e.g. Kähler potential operators of the form

$$K \supset \frac{s}{m_{pl}} H_u H_d \quad + \quad h.c., \tag{3}$$

à la Giudice-Masiero [20], where s generically denotes a modulus field of the appropriate charge and m_{pl} is the Planck scale. Note that such terms are forbidden in the superpotential due to holomorphy and the axion shift symmetries. From [7–9, 19] we know that the moduli vevs are approximately $\langle s\rangle \sim 0.1 m_{pl}$, $\langle F_s\rangle \sim m_{1/2} m_{pl}$ and from the standard supergravity Lagrangian [21] we get an effective μ-term:

$$\mu = \langle m_{3/2} K_{H_u H_d} - F^k K_{H_u H_d k}\rangle, \tag{4}$$

which leads to

$$\mu \sim \frac{\langle s\rangle}{m_{pl}} m_{3/2} + \frac{\langle F_s\rangle}{m_{pl}}. \tag{5}$$

Since gaugino masses are suppressed [7–9, 19], the F-term vev is subleading and we get

$$\boxed{\mu \sim 0.1 m_{3/2} \sim \mathcal{O}(TeV)}. \tag{6}$$

❑ From Planck scale to 50 TeV "dimensional transmutation"

Scale of gaugino condensation $\Lambda \approx M_{pl} \exp(-8\pi^2/3Qg^2) \approx \exp(2\pi \mathrm{Imf}/3Q)$

where $\mathrm{Imf} = \sum N_i s_i$

Q is rank of condensing gauge group

With Q-P=3, $\mathrm{Imf} = 14Q/\pi \rightarrow \Lambda \approx M_{pl}\, e^{-28/3} \approx 2\times10^{14}$ GeV, so

$\Lambda \approx 10^{-4} M_{pl}$ ≈ *scale at which supersymmetry broken*

Then $W \sim \Lambda^3 \sim 10^{-12} M_{pl} \sim 2\times10^6$ GeV = 2×10^3 TeV. Also expect inverse volume factor $1/V_7$ from $e^{K/2}$ so

$$M_{3/2} \approx e^{K/2}\, W \sim 50 \text{ TeV}$$

Note Imf/Q not explicitly dependent on Q – still dependent because of V_7 and P_{eff}, but weakly – so Λ rather well determined