

String Theory, Our Real World, Higgs Bosons, and LHC

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Particle physics is in a very exciting time, particularly because **data** from **CERN LHC**, and from **dark matter** satellite and laboratory detection experiments, is emerging

There is another, less appreciated reason why we are entering an exciting time!

-- today for the first time there is a coherent, constrained, consistent theoretical framework to address essentially all the basic questions physicists want to ask about the particles that form our world, and the forces, how they fit into a deeper and broader framework, why they are what they are – **“string theory”**

The boundaries of physics are changing!

This is *not* the usual view of string theory, as a quantum theory of gravity

It is unrecognizable to most string theorists – but for me and some others it is the most exciting thing about string theory

Theorists already can make connections of string theories to the real world, and make testable predictions for Higgs physics, LHC, rare decays, cosmological history and more

Outline:

- **Briefly describe Standard Model of particle physics, supersymmetric Standard Model, “string theory”**
- **Compare their goals**
- **Testing string theory (testing any theory?)**
- **Tests obviously of “compactified” (to 4 dimensions) string theories**
- **Examples from compactified M-theory (11D) on 7D manifold of G2 holonomy – Higgs physics – LHC – cosmology - EDMs**
- **Brief comment on cosmological constant, “landscape”**
- **Final remarks**

**FIRST: WHAT DO WE WANT TO UNDERSTAND ABOUT *OUR* UNIVERSE,
AND WHERE ARE WE IN ACHIEVING THAT UNDERSTANDING?**

WHAT MIGHT THE ROLE OF STRING THEORY BE?

Standard Model

- Quarks and electrons interact via strong and electroweak forces to form hadrons, nuclei, atoms, molecules, chocolate, espresso, etc
- Forces are “gauge forces”, i.e. the *form* of the force is determined by an invariance principle
- Combined with ordinary gravity, describes the world we see – since ~ 1973
- Very well tested – a wonderful description of the world we see, the goal of four centuries of physics – full relativistic quantum field theory, no puzzles or contradictions in its domain – predicted W, Z, etc
- Completion with explicit detection of Higgs boson – locked in July 2012

Supersymmetric SM

- Hypothetical extension of SM where the Lagrangian is also invariant under fermions \leftrightarrow bosons
- Considerable indirect evidence
- If indeed a symmetry of nature then should see superpartners of some of the SM particles at LHC
- String/M-theories imply should not have expected to see superpartners so far at LHC, but should see some in next run

Consider how we might describe some result – “Explain”, “Answer”, “Accommodate”, “Address”

- **Consider atomic physics – electrons with spin and orbital motion lead to magnetism – magnetism is not explicitly in the original theory, it emerges and it is *explained* – high-T superconductivity is *addressed*, but not yet explained**
- **Consider Quantum Chromodynamics (QCD), the SM theory of strong interactions – QCD Lagrangian contains quarks interacting via gluons in a gauge theory – not like our world of hadrons (proton, neutron, pions, etc) – QCD **solutions** include proton, pions, etc – **proton an inevitable prediction of QCD, that is, QCD predicts a particle with charge, spin etc of proton (mass now to 3%) – proton emerges and is *explained*****

If proton unknown, QCD would have led us to think of it, look for it

Parity violation in weak interactions is described by the SM theory, but it is put in by hand – it is “*accommodated*”

Supersymmetric SM addresses the problem of **dark matter (and more) – contains good candidate, and relic density can be right – if we did not know about dark matter, supersymmetric SM would make us think of it and look for it**

If we did not know about gravity, or forces like QCD and the electroweak force, or quarks and leptons, or families of particles, or supersymmetry, string theory would make us think of them and look for them – “*addresses*” them

Next look at a table of questions, and status

Some questions beyond the Standard Model	Standard Models	Supersymmetric Standard Models	String Theory
What form is matter (electrons, quarks, ...)?	✓		✓
What is matter?	✓		✓
What is light?	✓✓		
What interactions give our world?	✓		✓
Gravity?			✓✓
Supersymmetry?			✓
How is supersymmetry broken?			✓
Stabilize the quantum hierarchy?		✓✓	
Explain hierarchy (ratio of Planck to weak scales)?			✓
Unify force strengths?		✓✓	
Higgs physics?	~	✓	✓
What is the dark matter?	~	✓	✓
Matter asymmetry?	~	✓	✓
More than one family? <u>3 families?</u>	~	~	✓
<u>Value of quark, lepton masses?</u>	~	~	✓
Origin of CP violation?	~	~	✓
Origin of <u>Parity violation?</u>	~	~	✓
What is the inflaton?		✓	✓
Amount of dark energy?			✓
Cosmological constant too large?		✓	✓
What is an electron? Electric charge?			✓
Space-time?			✓
Rules of quantum theory?			✓

Main point – SM and SSM have limited applicability but string theory may allow answering most (all?) questions

~ Accommodate
 ✓ Address
 ✓✓ answer

CAN “STRING THEORY” REALLY PROVIDE ANSWERS AND TESTABLE UNDERSTANDING?

If one's impression of string theory came from some popular books and articles and blogs, one might be suspicious of taking string theory explanations so seriously

Often claimed that string theory is not testable – untestable explanations would not be helpful

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*)

String theory is too important to be left to string theorists

WHAT IS STRING THEORY?

- **What is any theory? We are trying to write a consistent mathematical theory that describes the natural world.**
- **Must be a quantum theory, must be “relativistic” (consistent with Einstein special relativity)**
- **SM is a consistent relativistic quantum field theory, works well – treats all particles as point-like objects**
- **But a relativistic quantum field theory of gravity based on pointlike particles leads to some meaningless predictions**
- **String theory is an attempt to describe particles not as points but with the equations that would describe the motion of strings – seems to work! – probably any extended objects constrained by special relativity and quantum theory would work – string theory of gravity gives all meaningful results – can describe all particles and forces in mathematically consistent way – if 10/11D!**
- **An electron is still an electron, just described by equations for a string rather than for a point**

10 dimensions?

Can show that a relativistic quantum theory which includes gravity and is mathematically consistent will have 10D.

Actually this is good!

Think about SM – full descriptive theory in 4D. But *only descriptive!* -- Does not explain why quarks exist, why strong force not different, why families of particles, etc.

→ if we want to understand need to go beyond 4D! -- By going beyond 4D we have possible real understanding of many questions!

Higgs mass illustrates this – in SM cannot estimate at all – in Supersymmetric SM can get broad range, e.g. about 50 GeV to about 200 GeV – in string theory can derive and calculate precisely

**Fortunately, increasingly active subfield of “string phenomenologists” -
- focus on formulating a testable string-based description of our
world**

String Vacuum Project, SVP

***12th International Conference on String Phenomenology, Madrid, June
2015***

□ To describe our world can separate 10D into 6 small D (typically they form a “Calabi-Yau manifold” with well studied mathematical properties) and 4 large D that can form the world we are familiar with – jargon “compactification”

□ For 11D (called M-theory) the small 7D manifold is a “ G_2 manifold”
Difference between 10/11 D theories is technical, ignore it here

□ The CY (or G_2) manifold has properties that in part determine the physics that emerges from this compactified string theory, *in particular the particles and forces and moduli*

How large are the compactified regions?

Natural scale for multidimensional world of string theory is Planck scale – form dimensional quantities from **G** (Newton's constant), **c** (speed of light), and **h** (Planck's constant)

-- length $\sim 10^{-33}$ cm

-- time $\sim 10^{-43}$ sec

-- energy $\sim 10^{19}$ GeV

(can formulate theories at smaller energies or larger distances, but no special motivation – today consider only Planck scale case, most difficult to test)



Surprisingly some people have claimed that because string theories are naturally formulated at Planck scale high energies or short distances they cannot be tested! – Obviously collisions will never probe energy scales such as 10^{15} TeV (Planck energy)

Equally obviously you don't have to be somewhere to test something there – always relics

-- big bang – expanding universe, He abundance and nucleosynthesis, CMB radiation

-- no signal faster than speed of light

-- don't have to be present 65 million years ago to test whether asteroid impact was a major cause of dinosaur extinction

Once you have a theory it suggests new tests – e.g. Maxwell's equations → light outside visible spectrum, radio waves

Before we look at details about testing string theory, ask what it means to test theories?

In what sense is $F=ma$ testable?

- claim about actual relation between forces and particle behavior
- might not have been correct
- can test it for any particular force, but *not in general*

Similar for Schrodinger equation!

- Insert particular Hamiltonian, calculate ground state and energy levels, make predictions – without a particular Hamiltonian, no test
- tests are tests of both Schrodinger equation and Hamiltonian

Analogous for string theory!

Currently there is a well defined procedure to “compactify” (procedure for going to 4D)

- Choose manifold of small dimensions
- Determine/write “superpotential”, essentially Lagrangian
- Determine/write “gauge kinetic function”, metric for “gauge fields”
- Determine/write “Kahler potential”, essentially metric for “scalar” fields”
- Calculate potential energy, minimize it → 4D ground state

Eventually theory may determine and allow calculation of all these [“vacuum selection principle”], but not yet

-- now done for some examples – calculations can be hard – some give compactified theories consistent with being good descriptions of what is known, make more testable predictions (examples below)

-- others already give wrong predictions – still testable

There has not been enough thought about what it means to make predictions, explanations from string theory for data – predictions, explanations should be based as much as possible on generic projection of extra dimensional theories into 4D large spacetime, plus small dimensions

Non-generic → less explanatory, maybe risk contradictions, usually add dimensionfull parameters

Crucial to recognize that 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

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

Analogous for string theory – our world corresponds to a stable or metastable ground state – called “vacuum”

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

Simply wrong to say string theory not testable in normal way

**Note, for “philosophers” – one falsifiable prediction is sufficient to
have a theory be testable**

Tests of the string theory are of the compactified theory, but they do *depend on the full 10/11D theory in a number of ways* – there are predicted relations between observables that depend on the full theory, 10 or 11D, the stringy characteristics of the CY or G2 (or even different) space – have to calculate them in each case

Studying such predictions to test theories is how physics has always proceeded

Could there be more general tests of string theory?

Relativistic quantum field theory has some general tests:

- CPT**
- spin and statistics**
- all electrons are identical**
- superposition**

Maybe for string theory?

- 10/11 D theory? Not yet**
- Compactified theories? Yes, gravity, Yang-Mills theories and gauge fields, supersymmetry, moduli, generic chiral fermions**

How *should* we try to relate string/M-theory and *our* real world? Cannot yet calculate everything.

Begin by making assumptions not closely related to observables such as Higgs mass, supersymmetry breaking, etc. Some assumptions are already partially derived.

Then search for solutions of string/M theory framework that could be our world.

**We started M/string compactification fall of 2005,
interested in moduli stabilization, susy breaking, Higgs,
since LHC coming (Bobby Acharya, Piyush Kumar,
Kuflik, Shao, Watson, Vaman – Bob Zheng, Sebastian
Ellis)**

***Give results here in M-theory case since those
calculations done in number of cases – results may
hold in some or all other corners of string theory since
they depend on only a few generic features of resulting
soft-breaking Lagrangian***

PAPERS ABOUT M-THEORY COMPACTIFICATIONS ON G_2 MANIFOLDS

(11 D – 7 small D = our 4D)

Earlier work (stringy, mathematical) ; Witten 1995

- Papadopoulos, Townsend th/9506150, 7D manifold with G_2 holonomy **preserves $N=1$ supersymmetry**
- Acharya, hep-th/9812205, **non-abelian gauge fields localized on singular 3 cycles**
- Atiyah and Witten, hep-th/0107177
- Atiyah, Maldacena, Vafa, hep-th/0011256
- Acharya and Witten, hep-th/0109152, **chiral fermions** supported at points with conical singularities
- Witten, hep-ph/0201018 – shows **embedding MSSM probably ok**
- Beasley and Witten, hep-th/0203061, **Kahler form**
- Friedmann and Witten, th/0211269
- Lukas, Morris hep-th/0305078, **gauge kinetic function**
- Acharya and Gukov, hep-th/0409101 – review – good summary of known results about singularities, holonomy and supersymmetry, etc – **all G_2 moduli geometric** – ***gravity mediated supersymmetry breaking*** because two 3-cycles won't interact directly in 7D manifold



Particles!

ASSUMPTIONS – *note none closely related to results – string phenomenology*

- **Compactify M-theory on G2 manifold (in fluxless sector)**
- **No principle yet to set gauge group and matter at compactification scale – choose MSSM**
- **Assume CC problem orthogonal, and that can tune CC to be small**
- **Assume no mathematical obstacles to ok G2 manifold even though not yet known in detail – some predictions not sensitive to details of manifold**
- **Assume can use generic Kahler potential (Beasley, Witten 2002).**
- **Assume generic gauge kinetic function (Lukas, Morris 2003).**

Need some details about compactified string theories:

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 the theory, for all superpartners, for some dark matter

Also:

MODULI – new, from string/M theory

- to describe sizes and shapes and metrics of small manifolds the theory provides a number of fields, called “moduli” fields**
- supersymmetry breaking generates a potential for all moduli**
- moduli fields have definite values in the ground state (vacuum) – jargon is “stabilized” – then measurable quantities such as masses, coupling strengths, etc, are determined in that ground state**
- moduli fields like all fields have quanta (also called moduli), with masses fixed by fluctuations around minimum of moduli potential**

Amazing generic connection of moduli to *cosmological history*

- Moduli quanta unstable to decay to particles and superpartners since couple universally via gravity
- Lifetime $\sim 1/\text{width}(\Gamma)$, $\Gamma \sim M_{\text{mod}}^3/M_{\text{Pl}}^2$
- As universe cools after big bang, nucleosynthesis begins after few seconds
- If moduli decay then they produce particles that break up nuclei and ruin nucleosynthesis!
- So lower limit on $M_{\text{mod}} (\geq 30 \text{ TeV})$ (can also calculate this theoretically)

- All properties of cooling universe before then are washed out by decaying moduli \rightarrow “non-thermal” cosmological history!

[Thermal = after BB universe just expands and cools, no new entropy sources, etc]

- Then Dark Matter, baryonic matter all from moduli decay! \rightarrow may solve problem of ratio of baryonic matter to Dark Matter!

Surprise!

**NEXT CALCULATE GRAVITINO MASS – all superpartner masses
proportional to $M_{3/2}$**

$$M_{3/2} = e^{K/2M_{PL}^2} |W| / M_{PL}^2$$

Numerically, basically,

$$W \approx \Lambda^3 / M_{PL}^2$$

And

$$\Lambda \approx M_{PL} e^{-2\pi V_3/3Q} / V_7^{1/2} \approx \frac{1}{2} 10^{14} \text{ GeV}$$

$$e^{K/2} \approx 1 / V_7^{3/2}$$

→ $M_{3/2} \sim 50 \text{ TeV}$ (~ factor 2)!

Surprise!

→ **LARGE HIERARCHY PROBLEM SOLVED DYNAMICALLY!**

And supergravity → scalars (e.g. squarks) $\sim M_{3/2} \sim 50 \text{ TeV}$, not observable at LHC!! – [prediction]

Surprise!

Hierarchy problem solved IF number of moduli large enough!

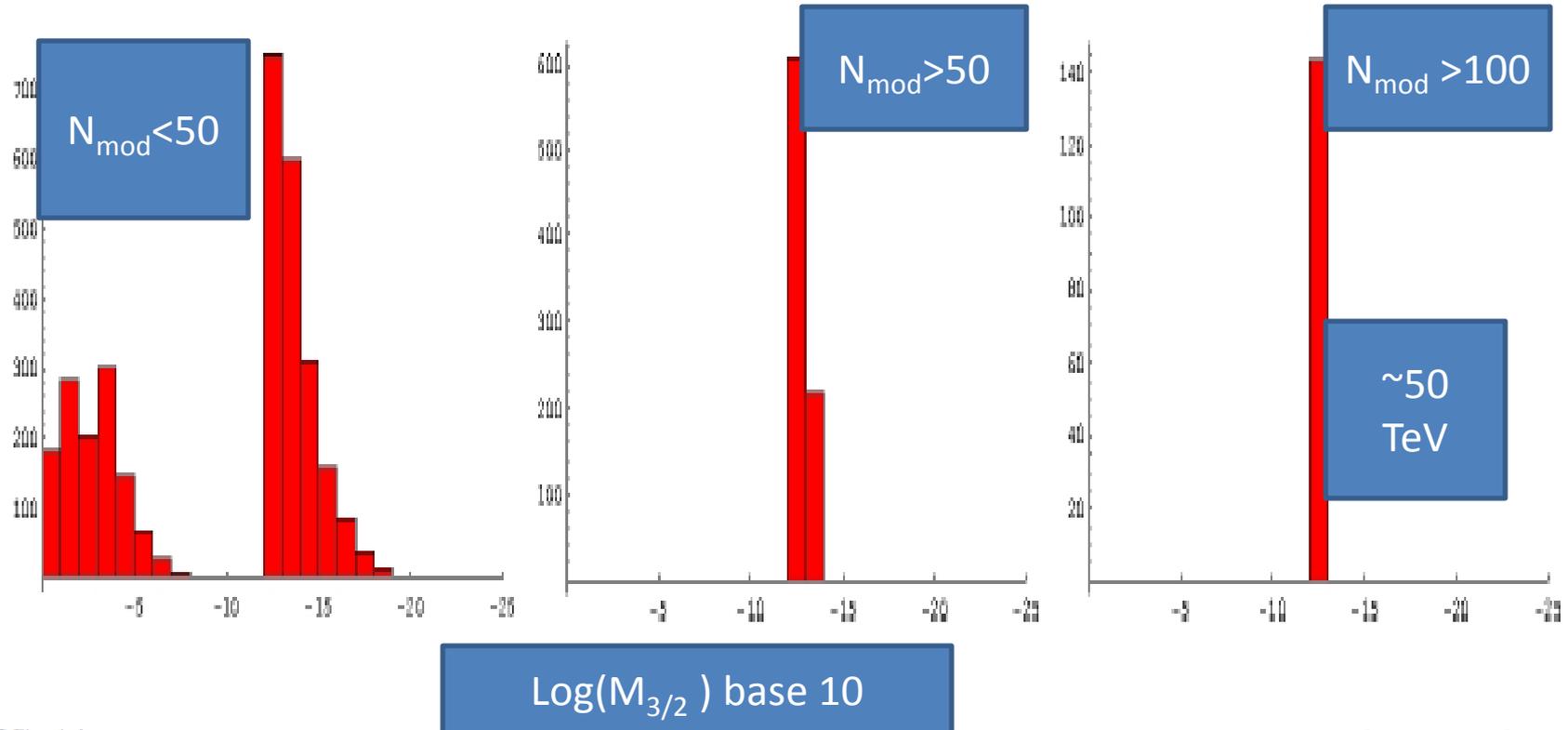
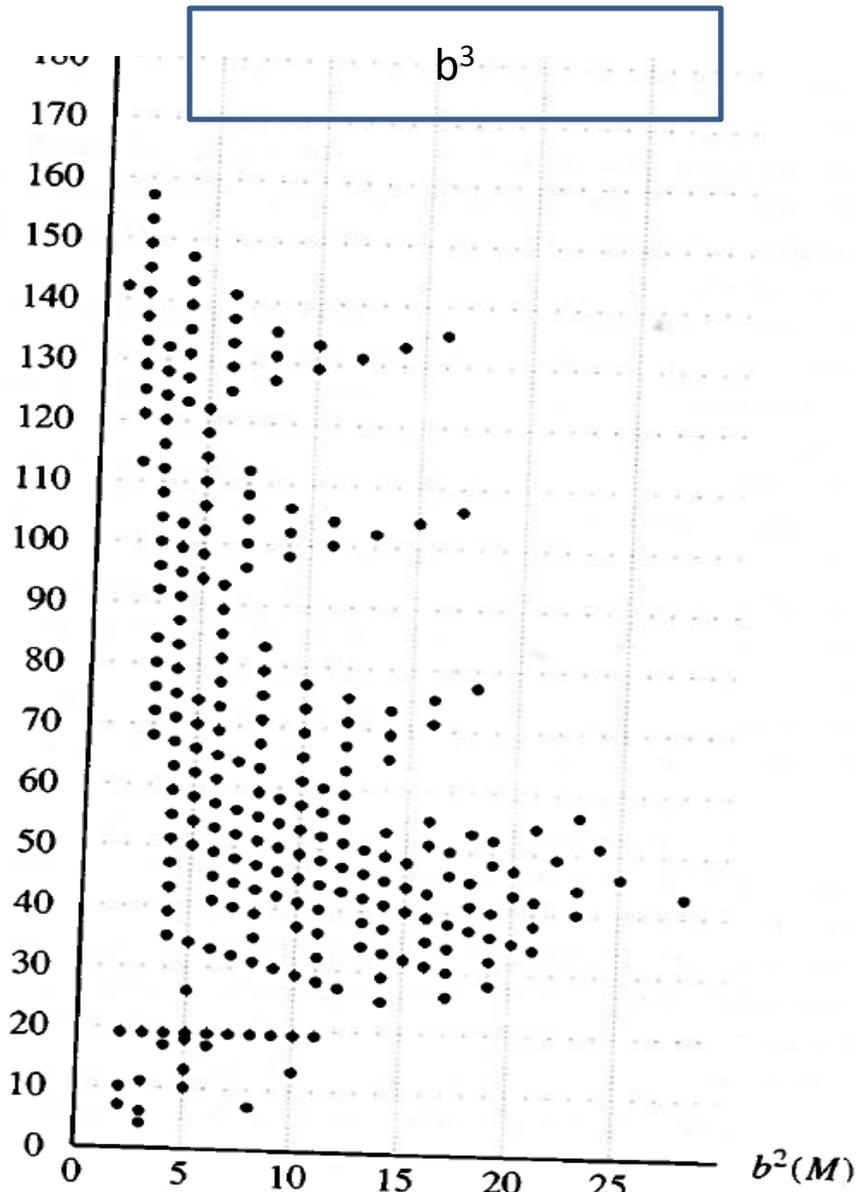


FIG. 14: The gravitino mass distribution with the x-axis denoting the logarithm of the gravitino mass (to base 10). Left: Distribution corresponding to scan four in (203). Middle: Distribution corresponding to scan five in (204) for which manifolds with the number of moduli $N < 50$ were excluded from the scan. Right: Distribution corresponding to scan six in (205) for which manifolds with the number of moduli $N < 100$ were excluded from the scan.



Dominic Joyce,
 "Compact Manifold
 with Special
 Holonomy"

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

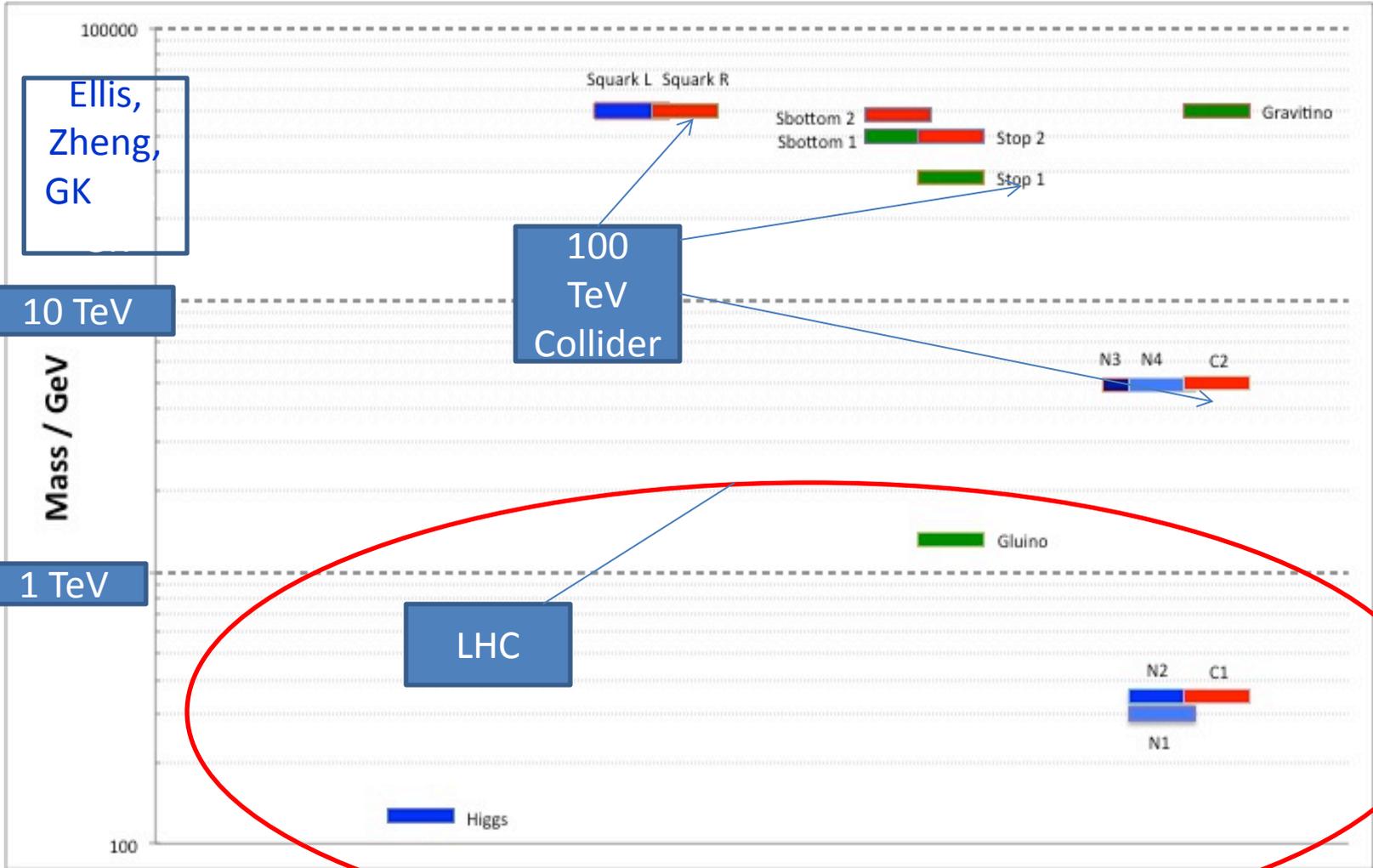
➤ DE SITTER VACUUM, GAUGINO MASSES SUPRESSED

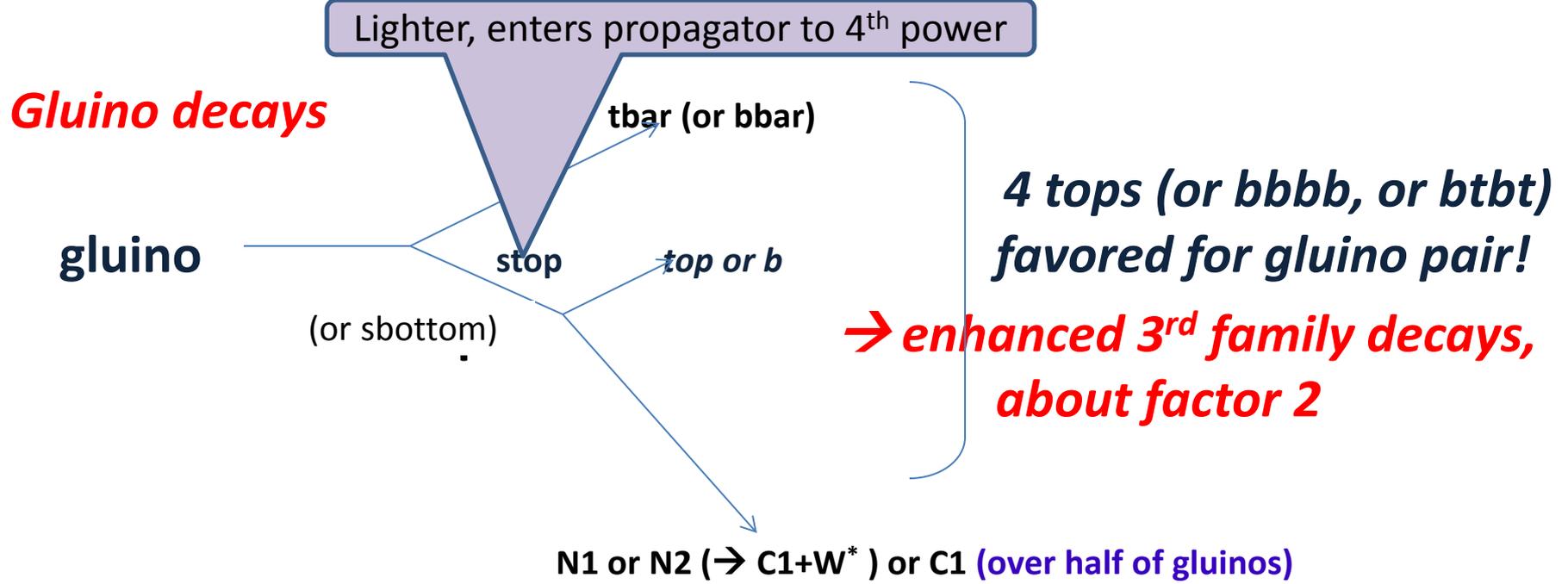
Gaugino masses suppressed

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

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

-- can't calculate suppression precisely, estimate \sim scalars/40
(gauginos also suppressed in heterotic, IIB?)





Glino lifetime $\sim 10^{-19}$ sec, decays in beam pipe

Glino decays flavor-violating

Papers LHC14,0901.3367; LHC7, 1106.1963

prediction

- **Predicted gluino mass about 1.5 TeV**
- **Cross section about 20 fb so about 4000 events in 200 fb⁻¹ integrated luminosity (~2 years?)**
- **Signatures good**
 $\text{BR}(N_2 \rightarrow N_1 h) \approx 98\%$

WHAT ABOUT HIGGS SECTOR? (Kumar, Zheng, GK, Lu)

Philosophy to compute Higgs mass, properties:

Divide all compactified string/M theories into two classes

- Some generically have TeV scale physics, *Electroweak Symmetry Breaking*, no contradictions with cosmology, etc – study all these – compute Higgs mass, etc
- If our world is described by a compactified string/M theory it will look like these – turns out it's easy to find them
- The rest

Find many

Higgs sector

In supersymmetric theory two higgs doublets present for anomaly cancellation – by “Higgs mass” mean mass of lightest CP-even neutral scalar in Higgs sector

Precise value depends on all the soft-breaking parameters -- theory at high scale, then run down

$\tan\beta$ does not exist until higgs fields H_u and H_d get vevs, well below high scale

Why 126 GeV? – no simple formula, must do RGE running, relate terms, smallest eigenvalue of matrix

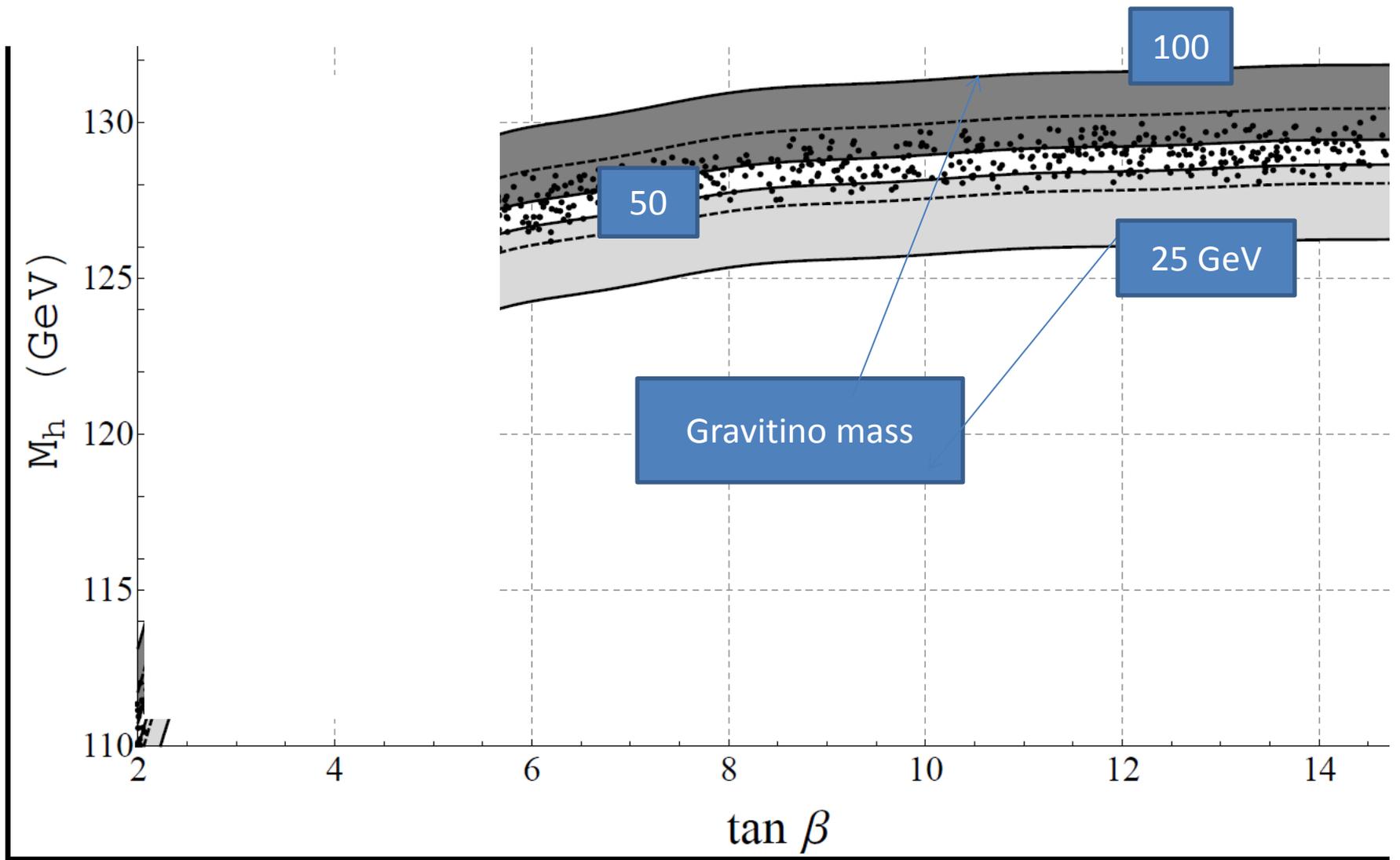
Ask for all solutions with EWSB

- Then calculate λ (of λh^4) – large soft masses M_{H_u} and M_{H_d} imply in “decoupling” sector of two doublet susy higgs sector
- Use Witten argument for no μ in superpotential, and supergravity, and EWSB conditions $\rightarrow \tan\beta \approx M_{3/2} / 1.7\mu$ (EW scale)
- Stabilization breaks Witten symmetry so $\mu \neq 0$ but $\mu \sim$ moduli vev $\times M_{3/2}$ so $\mu \sim$ few TeV, so $\tan\beta \square 6$
- Calculate M_h for all solutions with EWSB – study them
- Turns out all solutions satisfying above have $M_h = 126 \pm 2$!!

Could think of this as derivation of Higgs mass

OR

Could think of this as a correlation between vacua with our assumptions and Higgs mass



ELECTRIC DIPOLE MOMENTS (Ellis, GK)

- **Generically masses of superpartners complex numbers, so time reversal and CP conservation are violated**
 - **Then quantum corrections induce an EDM, e.g. for electron**
 - **So far experiments have not observed such an EDM – limit ~ 1000 times below naïve estimates (similar estimates in other extensions of SM)**
 - **In compactified M-theory all superpartner masses have same phase, so it can be rotated away - μ and associated breaking term have same phase so it can be rotated away by PQ rotation**
 - **So at compactification scale Lagrangian is real and EDMs are zero**
 - **RGE running to low scale rotate phases from Yukawa couplings into masses and induce EDMs – Yukawas not fully known, but can calculate an upper limit on EDMs**
- Explanation of smallness of EDMs!**

Electron EDM

M-theory:

$$< 0.05 \times 10^{-28} \text{ e-cm}$$

Current experiment

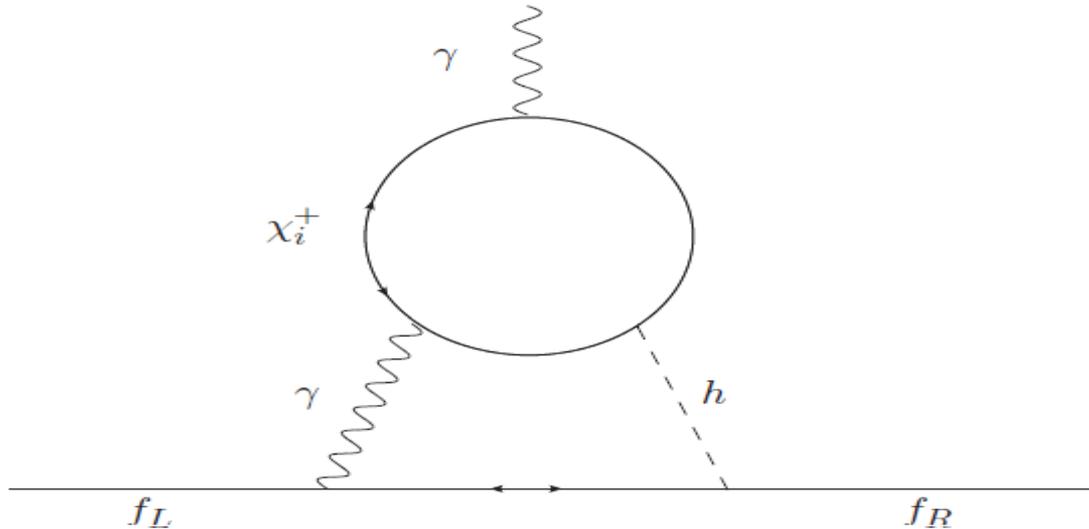
$$< 1 \times 10^{-28}$$

Generic supersymmetry

$$\sim 100\text{-}1000 \times 10^{-28}$$

Standard Model

$$10^{-10} \times 10^{-28}$$



COMPACTIFIED (STRING) M THEORY

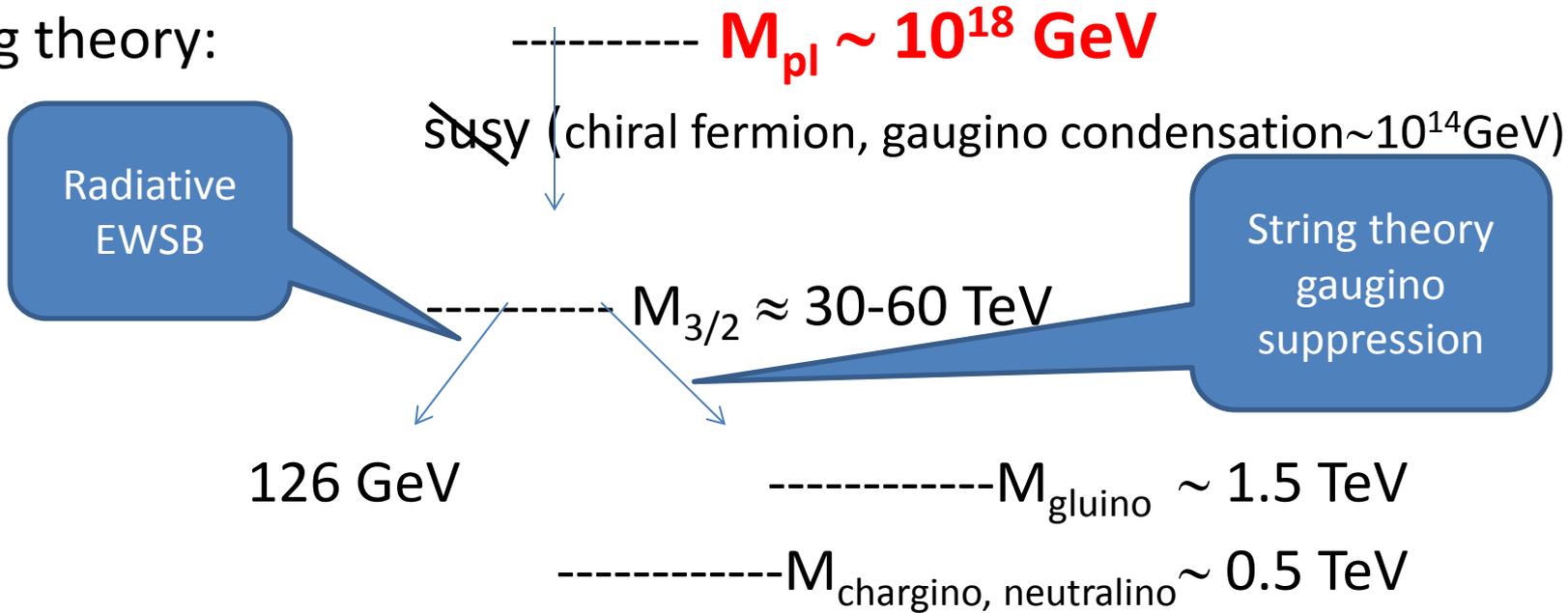
- **Derive** solution to large hierarchy problem
- Generic solutions with **EWSB derived**
- main F term drops out of **gaugino masses** so **dynamically suppressed**
- **Trilinears** $> M_{3/2}$ necessarily
- **μ incorporated in theory (M-theory)**
- Little hierarchy significantly reduced
- **Scalars**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

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**

Naturalness? Fine-tuning? Little hierarchy? Of course compactified string theory is “natural”

M/String theory:



Cosmological constant problems?

-- *naively* too large – explain actual value? – why now?

- **Does present inability to solve this cause a problem for understanding our string vacuum?**
 - **Probably not – basically an orthogonal issue in most ways of thinking about it, particularly if true CC (rather than a scalar field)**
 - **In M-theory case (and other approaches) we calculate all observables before and after tuning CC to be small, and find no large effects – standard method**
 - **Note analogous issue with strong CP problem – many predictions for QCD would be different if strong CP effects ~ 1 , but we successfully ignore it**
- **CC problem(s) – interesting – but probably not most important problem(s) in physics – solving them not likely to help with all the rest we want to understand – not solving them not likely to hinder us**

String theory framework (plus inflation) has many solutions (“landscape”)

- If many of them can have compactified solutions with stabilized moduli need to understand how, and implications
- Suppose there are many
- Some have argued that if there are many, then it is unlikely we can find one (or more) describing *our* vacuum
- But it is not like throwing darts and choosing vacua and testing them – we already know so much about what to look for and are addressing so many questions whose answers are related that it is reasonable to be optimistic about finding very good candidates for our string vacuum, and soon – examples like the G_2 one show major progress possible

(of course, unlikely to find correct vacuum from top-down string theory!)

TO DO:

- Finish derivation of top yukawa ~ 1 – probably done
- Construct theory or model of full up, down, L,R yukawas – model probably emerges from top yukawa derivation
- **Dark matter! – axions plus wimps – hidden sector matter!**
- **Incorporate inflation**
- **Better understanding of how gauge and matter group emerges from G2 manifold**

FINAL REMARKS

- String theory too important to leave to string theorists
 - string/M-Theory maturing into useful predictive framework that relates many explanations and tests
- Testing string/M-Theory means testing compactified theories and is underway – some tests already, lots of predictions to test
- The opposite of “natural” is having a theory
- Higgs mass and decays predicted
 - Higgs looks like what is expected from compactified M-theory with stabilized moduli – 126 GeV *NOT* unnatural or weird – not metastable vacuum
- μ , $\tan\beta$ included in theory, correlated with M_h
- LHC – gluinos but not squarks
 - gluinos have enhanced 3rd family decays
 - gluino cross section tests spin $\frac{1}{2}$, expected for superpartner
 - two light neutralinos and light chargino also observable
- $B_s \rightarrow \mu\mu$ and $(g_\mu - 2)$ should deviate only a few % from SM values

SUCSESSES – toward “Compactified Stringy Supersymmetric SM”

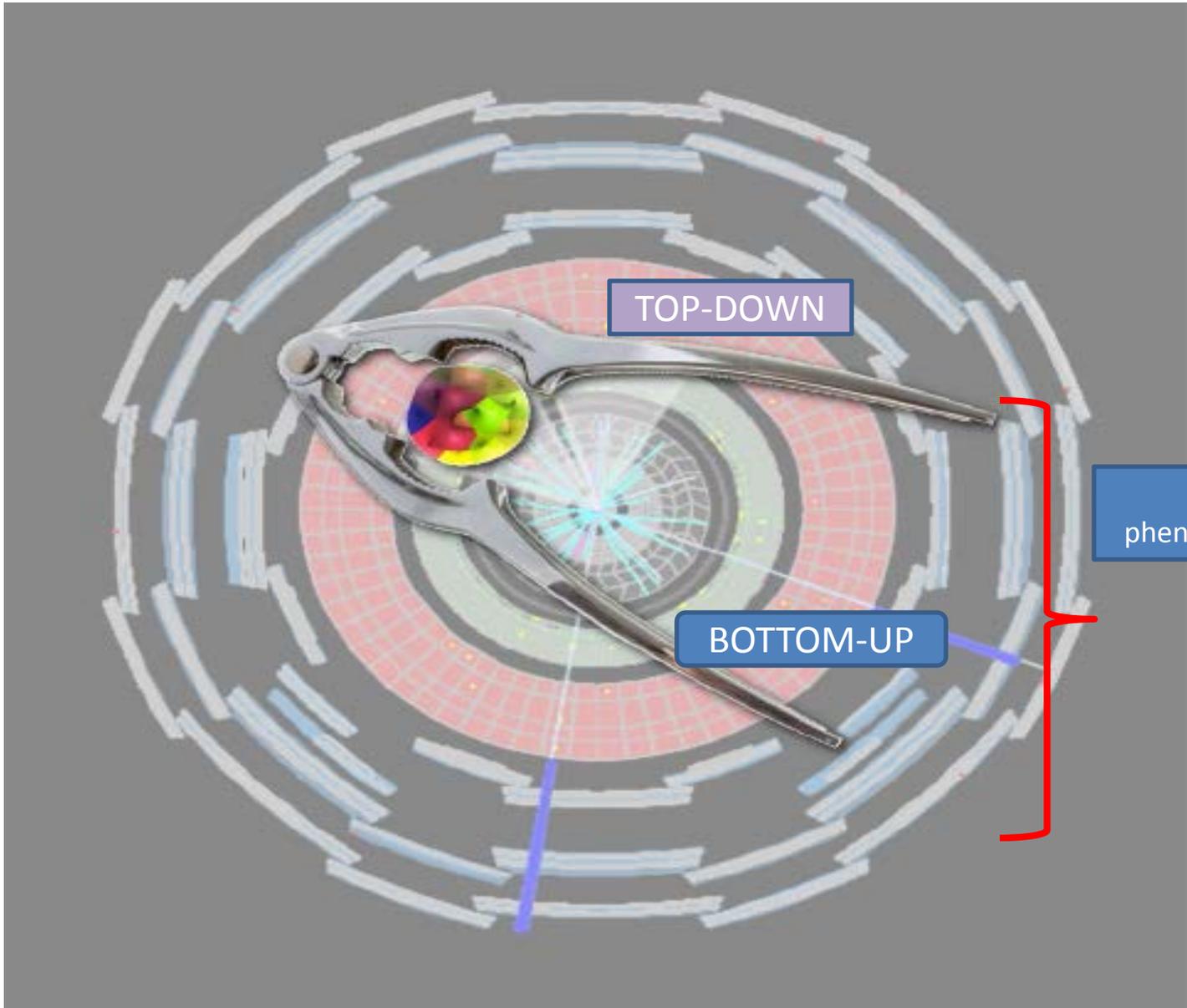
- **N= 1 supersymmetry**
- **Supersymmetry broken by gaugino *and* chiral fermion condensation**
- **Moduli stabilized by supersymmetry breaking**
- **Standard Model q, l charges, and Yang-Mills forces, accomodated**
- **De Sitter vacuum**
- **Hierarchy problem solved – TeV scale emerges from Planck scale!**
- **Electroweak symmetry breaking allowed (Higgs mechanism)**
- **Anticipated Higgs boson mass and decay properties**
- **Can incorporate μ in theory**
- **Solves strong CP problem**
- **Solves weak CP and flavor and EDM problems**
- **No moduli and gravitino problems**

PREDICTIONS

- Gravitino mass
- Scalar masses (squarks, sleptons, higgs sector) heavy
- Gaugino masses light
- $\mu \sim M_{3/2}/10$
- Non-thermal cosmological history \rightarrow dark matter and baryons both arise from moduli decay, explain ratio
- Gluino mass and decay branching ratios
- Neutralino and chargino masses and BR
- g_μ -2 current 3 standard deviation effect goes away

FAILURES and CHALLENGES?

- **CC problem**
- **Muon anomalous magnetic moment 3 standard deviations, not compelling**
- **Top yukawa ~ 1 in M-theory**
- **Only one yukawa coupling ~ 1 , hierarchy of quark masses**
- **Compact singular G2 manifolds!**
- **Funding string phenomenology**



TOP-DOWN

BOTTOM-UP

String phenomenology

➤ From Planck scale to 50 TeV “dimensional transmutation”

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

where $\text{Im}f = \sum N_i s_i$

Q is rank of condensing gauge group

With $Q-P=3$, $\text{Im}f=14Q/\pi \rightarrow \Lambda \approx M_{\text{pl}} e^{-28/3} \approx 2 \times 10^{14}$ GeV, so

$\Lambda \approx 10^{-4} M_{\text{pl}} \approx \text{scale at which supersymmetry broken (F's} \neq 0)$

Then $W \sim \Lambda^3 \sim 10^{-12} M_{\text{pl}} \sim 2 \times 10^6$ 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 $\text{Im}f/Q$ not explicitly dependent on Q – still dependent because of V_7 and P_{eff} , but weakly – so Λ rather well determined]

➤ ***Can look at the full moduli mass matrix -- show it generically has at least one eigenvalue of order the gravitino mass or less -- new***

[first noticed by Denef and Douglas, independently by Louis and Scrucca and collaborators, for different reasons – both 2005 – we generalized and connected to cosmology arxiv:1006.3272]

General for compactified string theories with broken supersymmetry

Ties moduli masses to gravitino masses! Moduli masses are strongly constrained by cosmology → gravitino mass constrained!

And gravitino mass sets scale for supersymmetry breaking, superpartner masses, LSP dark matter

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

- Normally μ and $\tan\beta$ 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 $\mu=0$**
- Witten, hep-ph/0201018 – found discrete symmetry for G_2 compactification, closely connected to doublet-triplet splitting problem, proton lifetime, R-parity
- **Unbroken discrete symmetry so $\mu \equiv 0$** – 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 $\mu \rightarrow 0$ if susy unbroken
- **Also μ proportional to moduli vev** since $\mu \rightarrow 0$ if moduli not stabilized
- **Stabilization led to moduli vev/ $M_{pl} \simeq 0.1$**
- **So finally expect $\mu < 0.1 M_{3/2}$**
- discrete symmetry anomalous, Z_9 ok – sub group unbroken \rightarrow Rparity

arXiv:1102.0556, Acharya, Kane,
Kuflik, Lu

EWSB, μ , $\tan\beta$, naturalness

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

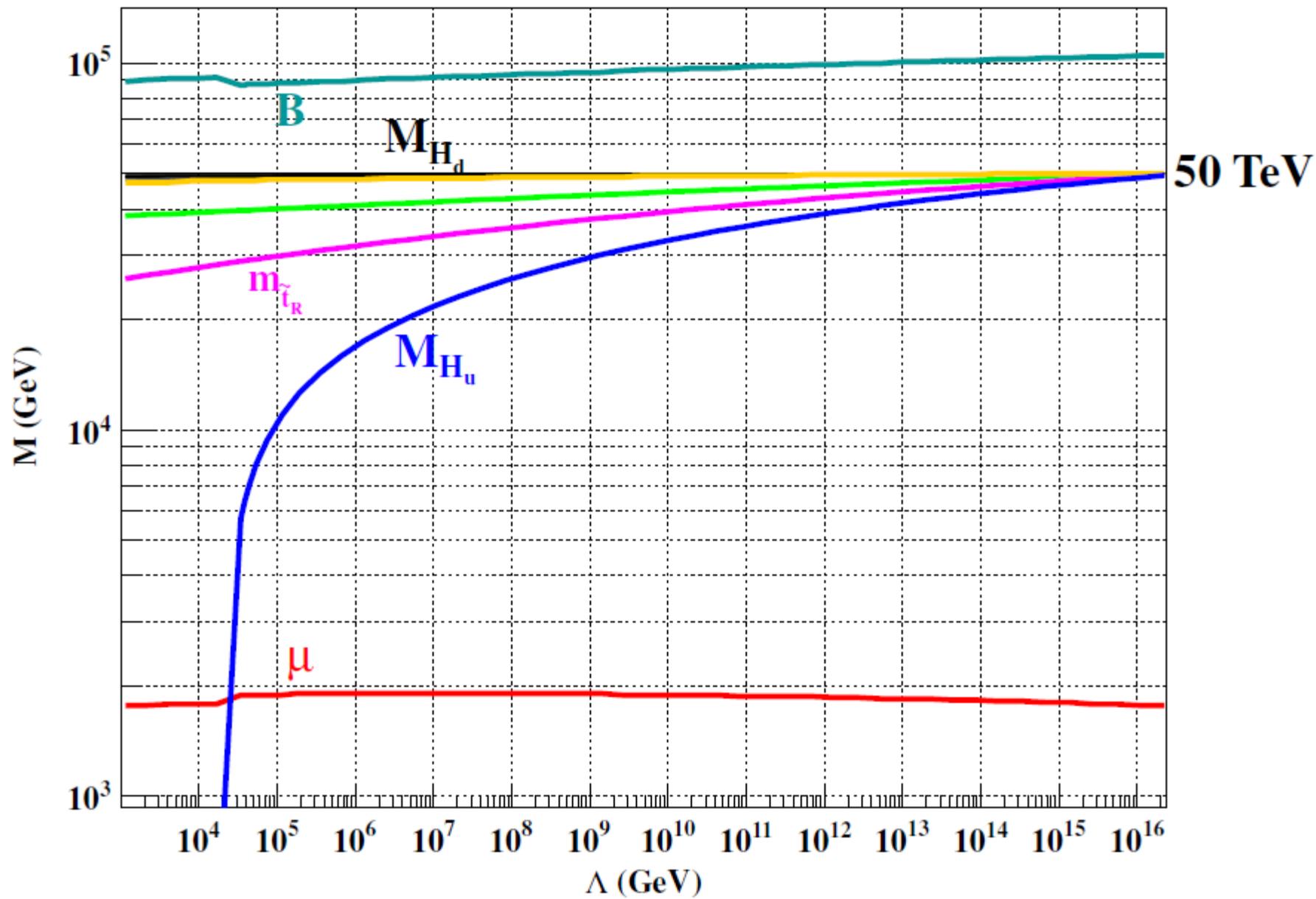
$$M_Z^2 = -2\mu^2 + 2(M_{Hd}^2 - M_{Hu}^2 \tan^2\beta) / \tan^2\beta = -2\mu^2 + 2M_{Hd}^2 / \tan^2\beta - 2M_{Hu}^2$$

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

M_{Hu}^2 runs to be small, M_{Hd}^2 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 $F_{\text{mod}} \ll F_\phi$ then B (high scale) $\approx 2M_{3/2}$ – recall $\mu < 0.1M_{3/2}$

$$\rightarrow \tan\beta \approx M_{Hd}^2 / B\mu \approx M_{3/2}^2 / B\mu \rightarrow \tan\beta \approx M_{3/2} / 2\mu (\sim 15)$$



THEORY AT HIGH SCALE, TECHNICAL DETAILS OF COMPUTING M_H

- Write theory at scale $\sim 10^{16}$ GeV, fix soft-breaking Lagrangian parameters by theory – no free parameters
- Run down, maintain REWSB
- Use “match-and-run” and also SOFTSUSY and Spheno, compare – match at $(M_{\text{stop1}}M_{\text{stop2}})^{1/2}$ – two-loop RGEs – expect public software to work since scalars not too large
- Main sources of imprecision for given $M_{3/2}$ are M_{top} (1 GeV uncertainty in M_{top} gives 0.8 GeV in M_h), α_{strong} , theoretical gluino mass (allow 600 GeV to 1.2 TeV), trilinear couplings (allow $0.8-1.5M_0$)

Is h SM-like?

Theory -- all scalar terms in the soft-breaking Lagrangian predicted to be of order gravitino mass, ≈ 30 TeV so “decoupling” limit

Still supersymmetric Higgs sector of course, but H, A, H^\pm also about equal to the gravitino mass ≈ 30 TeV, h light and SM-like

h is the lightest eigenvalue of the supersymmetric higgs mass matrix, in the decoupling limit \rightarrow BR are SM-like

Typically chargino and neutralino loops give few per cent deviations

Realistic Branching Fraction

$$\left. \begin{array}{l} m_{3/2} = 50 \text{ TeV} \\ M_{\text{gluino}} = 900 \text{ GeV} \\ M_{\text{LSP}} = 145 \text{ GeV} \end{array} \right\} \begin{array}{l} BR(\tilde{g} \rightarrow t \bar{t} \tilde{\chi}^0) \approx 0.15 \\ BR(\tilde{g} \rightarrow t \bar{b} \tilde{\chi}^- + h.c.) \approx 0.28 \\ BR(\tilde{g} \rightarrow b \bar{b} \tilde{\chi}^0) \approx 0.08 \end{array}$$

So **BR (third family)** $\square \frac{1}{2}$,
BR (1st + 2nd families $\square \frac{1}{2}$) per gluino

➤ String/M theory crucial for *deriving Higgs results!*

- Must have theory with **stabilized moduli and spontaneous supersymmetry breaking** – compactified string theories
- Must derive soft terms, otherwise could choose anything – e.g. large trilinears important, but people in past guessed they were small – string theory gave prediction of large trilinears
- Must have μ embedded in string theory
- Must exhibit string solutions with REWSB
- Must have effectively no parameters
- No R symmetry, since trilinears heavy and gauginos light

LITTLE HIERARCHY PROBLEM – NEW APPROACH

Running of M^2_{Hu} in string/M theory [\[arXiv:1105.3765 Feldman, GK, Kuflik, Lu\]](#)

**Compactified M
theory $\rightarrow A_0 > M_0$**

$$M^2_{Hu}(t) \approx f_M(t) M^2_0 - f_A(t) A^2_0$$

$$A_0 > M_0 = M_{3/2} \approx 50 \text{ TeV}$$

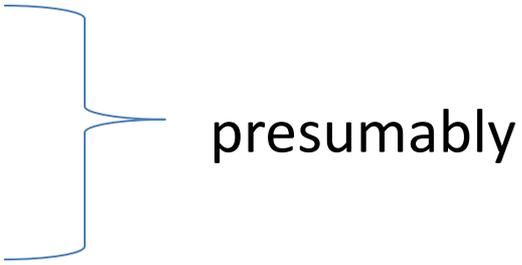
f_M, f_A calculated
 from SM inputs,
 both about 0.12-
 0.13

So stringy prediction is a decrease ≈ 50 in M^2_{Hu} – **if trilinears not large get order of magnitude less decrease in M^2_{Hu}**

Greatly reduces “little hierarchy problem” – covers gap from $M_{3/2}$ to TeV

- Historically physics progressed by interplay of experiment and theory – String “theory” is fitting nicely into that tradition
- If a compactified string theory ground state is indeed found that explains what is in “Question Table” in a unified way, it will be a very strong candidate for the SSSM, a theory that explains an extraordinary amount and leave little unanswered
- People are working on such constructions, finding good candidates
- Some people who talk about testing string theory are taking a pure formal approach – is 10D string theory falsifiable? – probably meaningless question, certainly not the relevant question
- The 10D nature of the compactified theory *is* tested by *relations among the answers* to the Questions Table
- If no good candidates for compactified string theories emerge, most physicists will lose interest
- If one or more turns up it will be a powerful success for science, and bring us close to (or even at) an ultimate theory

Tests will be for “string theories” that can describe our world

- 4D
 - TeV scale emerges from Planck scale
 - De Sitter vacuum – positive vacuum energy
 - Allows cosmological constant (minimum of potential energy) consistent with observation
 - Nucleosynthesis
 - Supersymmetry (N=1)
 - Broken supersymmetry
 - Supergravity framework valid
 - Electroweak symmetry breaking (Higgs mechanism)
 - Etc
- 
- presumably

Many solutions – expect many can describe our world, many cannot – don’t care about latter

THEN – with no parameters:

- **N=1 supersymmetry derived, and generically gauge matter and chiral fermions**
 - Stabilize moduli and simultaneously break supersymmetry from gaugino and meson condensation, F-terms non-zero at $\sim 10^{14}$ GeV
 - **Have 4D supergravity relativistic quantum field theory below compactification**
 - Calculate full soft-breaking supersymmetric Lagrangian
 - **Calculate stabilized moduli vevs, 1-2 orders of magnitude below M_{pl}**
 - Can calculate moduli mass matrix – only need some properties
 - **Have proved gravitino mass \approx lightest eigenvalue of moduli mass matrix**
 - Top-down “dimensional transmutation” calculation gives $M_{3/2} \sim 50$ TeV (\sim factor 2)
[solves hierarchy problem ($M_{\text{grav}} = e^K W$, $W \sim \Lambda^3$, $\Lambda \sim 10^{-4}$, $e^K \sim 1/V$)]
 - **Moduli only interact gravitationally so can calculate lifetimes, decay early, so no moduli problem, BBN ok**
 - Supergravity $\rightarrow M_{\text{scalars}} = M_{3/2}$ so squarks too heavy for LHC; $B_s \rightarrow \mu\mu$ has SM value
 - **Include μ in theory via Witten method – discrete symmetry sets $\mu=0$ – then moduli stabilization breaks symmetry so $\mu \neq 0$ but suppressed by moduli vev**
- \rightarrow Lots of testable predictions!**

Our M-theory papers --[Review arXiv:1204.2795](#) , Acharya, Kane, Kumar [Acharya, Kane, Vaman, Piyush Kumar, Bobkov, Kuflik, Shao, Lu, Watson, Zheng]

- M-Theory Solution to Hierarchy Problem [th/0606262](#), PhysRevLett 97(2006)
- **Stabilized Moduli, TeV scale, *squark masses = gravitino mass, heavy; gaugino masses suppressed*** [0701034](#)
- **Spectrum, scalars heavy, wino-like LSP, large trilinears (no R-symmetry)** [0801.0478](#)
- Study moduli, **Nonthermal** cosmological history– **generically moduli \square 30 TeV so gravitino \square 30 TeV, squarks \square gravitino so squarks \square 30 TeV** [0804.0863](#)
- CP Phases in M-theory (weak CPV OK) and EDMs [0905.2986](#)
- **Lightest moduli masses \square gravitino mass** [1006.3272](#) (Douglas Denef 2004; Gomez-Reino, Scrucca 2006)
- **Axions** stabilized, strong CP OK, string axions OK [1004.5138](#)
- Gluino, Multi-top searches at **LHC** (also Suruliz, Wang) [0901.336](#)
- No flavor problems, (also Velasco-Sevilla Kersten, Kadota)
- Theory, phenomenology of μ in M-theory [1102.0566](#) via Witten
- Baryogenesis, ratio of DM to baryons (also Watson, Yu) [1108.5178](#)
- String-motivated approach to little hierarchy problem, (also Feldman) [1105.3765](#)
- **Higgs Mass Prediction** [1112.1059](#) (Kumar, Lu, Zheng)
- R-parity conservation

To take Higgs results fully seriously good to know other major physics questions addressed OK in same theory

More details on gravitino mass – semi-analytic example

$$m_{3/2} \equiv m_p^{-2} e^{\frac{K}{2m_p^2}} |W|$$

Q,P ranks of typical gauge groups from 3-cycle singularities, Q=6,7,8,9 –
moduli vevs $\sim 3Q \sim 1/\alpha_{\text{GUT}}$ -- put CC=0 to solve for $\text{PIn}(\) = P_{\text{eff}}$

$$m_{3/2} = m_{\text{pl}} \frac{\alpha_{\text{GUT}}^{7/2}}{\sqrt{\pi}} \frac{|Q-P|}{Q} e^{-\frac{P_{\text{eff}}}{Q-P}}$$

→ $m_{3/2} \approx 50 \text{ TeV}$

$$(e^{-20} \approx 10^{-9}, P_{\text{eff}} = \frac{14(3(Q-P)-2)}{3(3(Q-P)-2)\sqrt{6(Q-P)}} \sim 60 \text{ when } Q - P = 3)$$

$$M_{\text{GUT}} = M_{11} \alpha_{\text{Gut}}^{1/3})$$

➤ DE SITTER VACUUM, GAUGINO MASSES SUPRESSED

- For M theory, positive F terms from chiral fermion condensates automatically present, cancel for CC and give deS minima – “uplift”
- also, in M theory case the deS minima come from susy preserving extremum if ignore meson F terms, so the minima is near a susy preserving point in field space where gaugino masses would vanish
- so gaugino masses are doubly suppressed – vanish at susy preserving point, and get no contribution from large F terms of mesons

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

- can't calculate suppression precisely, estimate \sim scalars/40
- gauginos probably also suppressed in heterotic, IIB?