String Theory, Our Real World, and Higgs Bosons

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Particle physics entering a very exciting time, particularly because data from **CERN LHC**, and from **dark matter** satellite and laboratory detection experiments, is beginning to emerge

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:

Long introduction

- Briefly describe Standard Model of particle physics, supersymmetric Standard Model, "string theory"
- Compare their goals
- Testing string theory – testing any theory?
- Tests are of "compactified" (to 4 dimensions) string theories

More technical

- Examples – Higgs physics – LHC – cosmology
- 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 leptons 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, …

- Final check was 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
- Lightest superpartner can be stable, can give the right relic density to be a good candidate for the dark matter of the universe (could be partner of W boson, or Higgs boson, or photon or hidden sector particle or …)

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 the 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 – the SSM "***addresses***" the problem of dark matter

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, or axions, 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? 3 families?	~	~	√
Value of quark, lepton masses?	~	~	√
Origin of CP violation?	~	~	√
Origin of Parity violation?	~	~	√
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
Ö Address
Ö 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")

String theory is too important to be left to string theorists

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

String Vacuum Project, SVP -

11th International Conference on String Phenomenology, International Center for Theoretical Physics, Trieste, July 2014

- String theory formulated in 10 or 11 space-time dimensions, in order to have a mathematically consistent theory (no anomalies)

- 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*

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 ~ 10^{-33} cm

-- time ~ 10^{-43} sec

-- energy ~ 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 several 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 <u>*generic*</u> *projection of extra dimensional theories into 4D large spacetime, plus small dimensions*

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

What would you agree is a prediction?

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

The 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?

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

Do the derivations here in M-theory case since those calculations effectively complete – 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 (but μ, $\tan\beta$?)

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**
- Acharya, hep-th/0011289
- 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* *because two 3-cycles won't interact directly in 7D manifold***

Particles!

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

- 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 G_2 manifold even though not yet known in detail – some predictions not sensitive to details of manifold
- Keep approach fully generic, don't fix any parameters or parameter space regions, don't introduce any parameters
- 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

-- 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

THEN – with no adjustable 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 □ 10^{14} GeV
- Have 4D supergravity relativistic quantum field theory below compactification
- Calculate full soft-breaking supersymmetric Lagrangian, values of superpartner masses, etc
- Calculate stabilized moduli vevs, 1-2 orders of magnitude below M_{PL}
- Can calculate moduli mass matrix – only need some properties
- Prove gravitino mass □ lightest eigenvalue of moduli mass matrix
- Top-down “dimensional transmutation” calculation gives $M_{3/2}$ □ 50 TeV (□factor 2)

  [solves hierarchy problem ($M_{grav} = e^K W$, W□ □^{3}, □□10^{-4} , e^K □1/V)]
- Moduli only interact gravitationally so can calculate lifetimes, decay early, so no moduli problem, BBN ok
- Supergravity → $M_{scalars} = M_{3/2}$ so squarks too heavy for LHC; B_s →μμ and $g_{□}$ -2 have SM value
- Include □ in theory via Witten method – discrete symmetry sets □=0 – then moduli stabilization breaks symmetry so □□0 but suppressed by moduli vev

WHAT ABOUT HIGGS SECTOR?

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 – "Compactified Constrained string/M Theories"

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 including B, μ -- theory at high scale, then run down

tan[illegible] 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

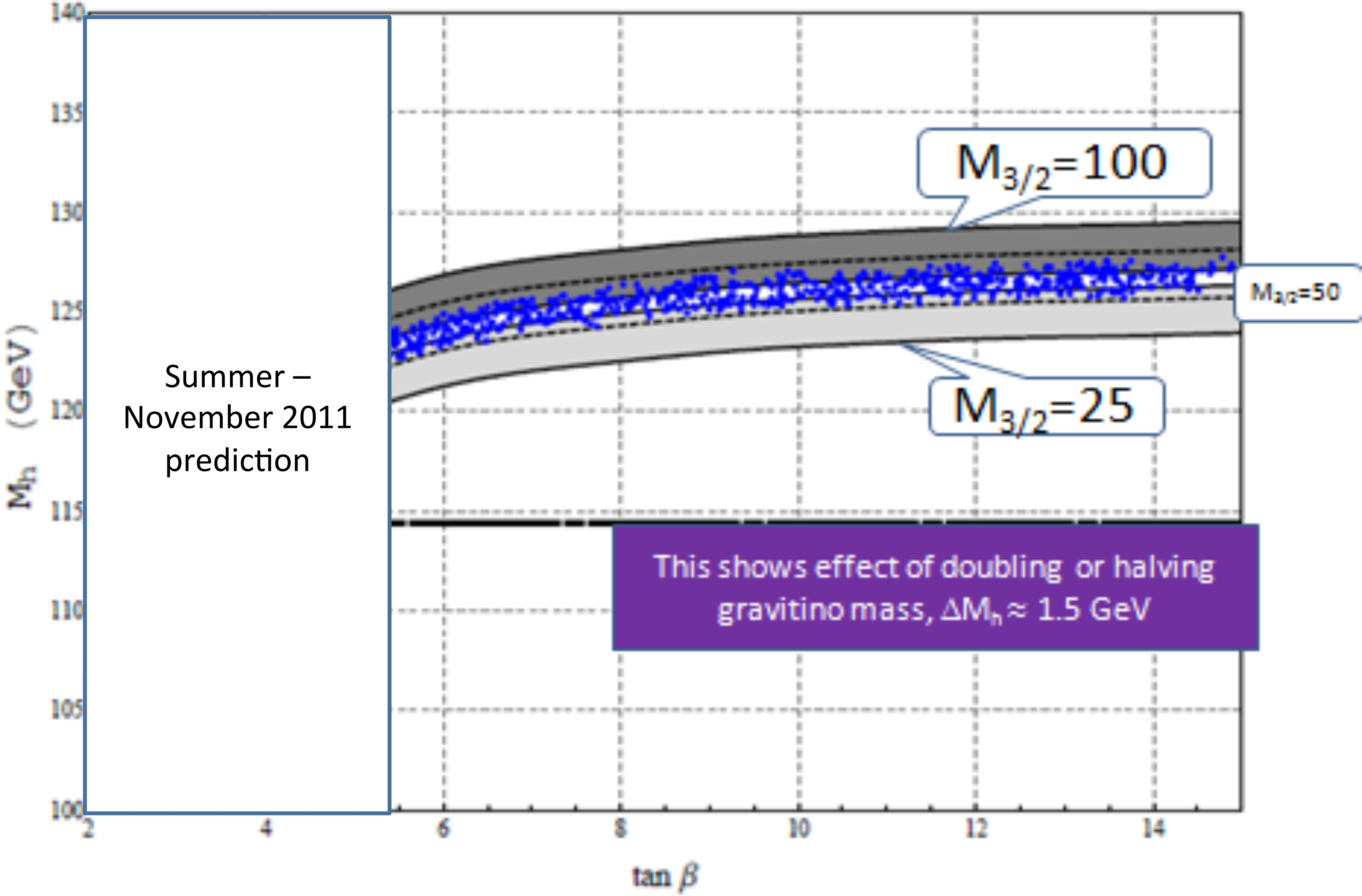
- Then calculate λ (of λh^4) – large soft masses M_{Hu} and M_{Hd} imply theory is in "decoupling" sector of two doublet susy higgs sector
- Use Witten argument for no μ in superpotential, and supergravity, and EWSB conditions → $\tan\beta \sim M_{3/2}/1.7\mu$ (EW scale)
- Stabilization breaks Witten symmetry so $\mu \neq 0$ but $\mu \sim$ moduli vev x $M_{3/2}$ so $\mu \sim$ few TeV, so $\tan\beta \gtrsim 5$
- Calculate M_h for all solutions with EWSB – study them
- Turns out all solutions satisfying above have M_h=126±2 !!

Could think of this as derivation of Higgs mass

OR

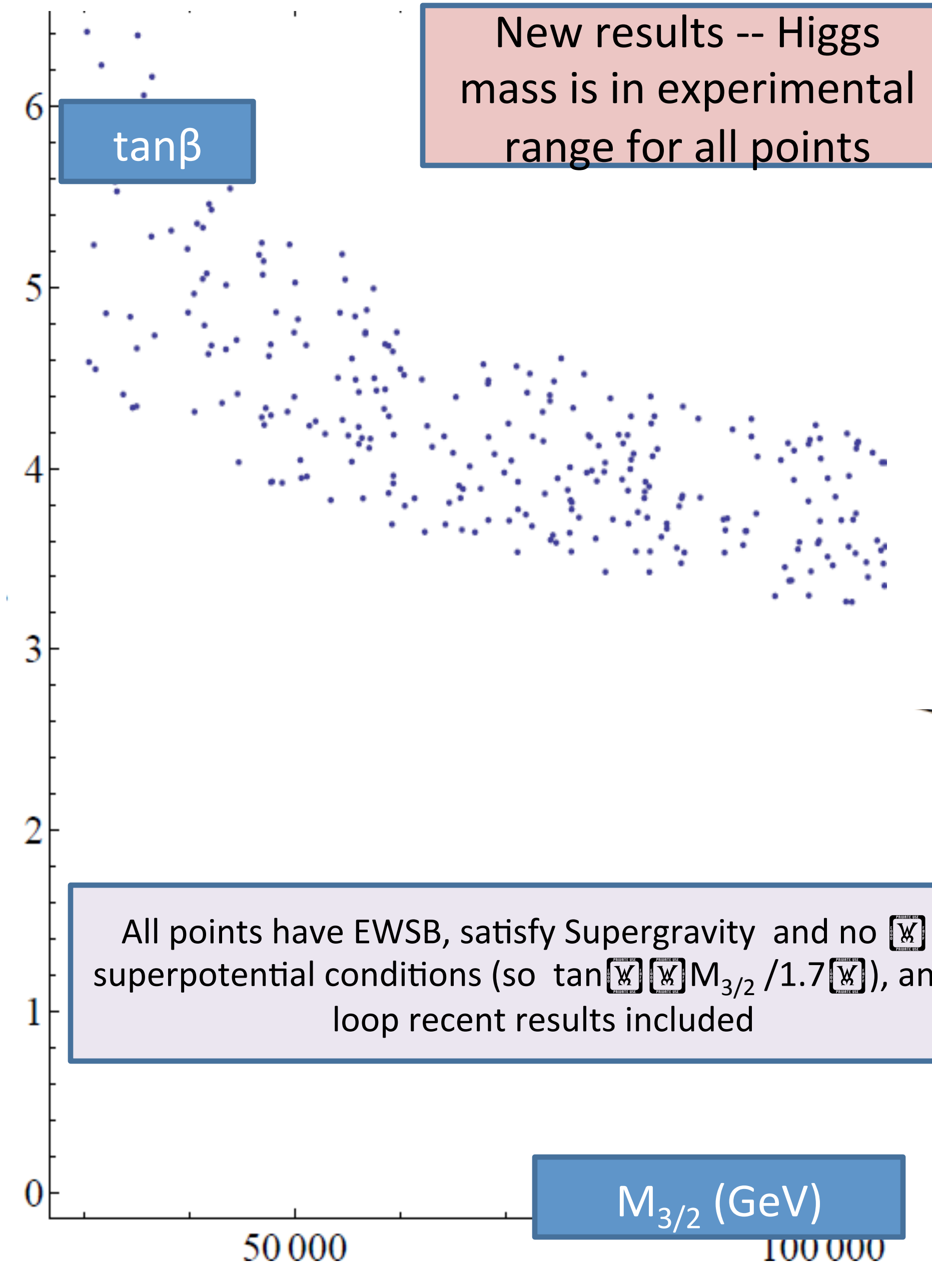
Could think of this as a correlation between vacua with our assumptions and Higgs mass

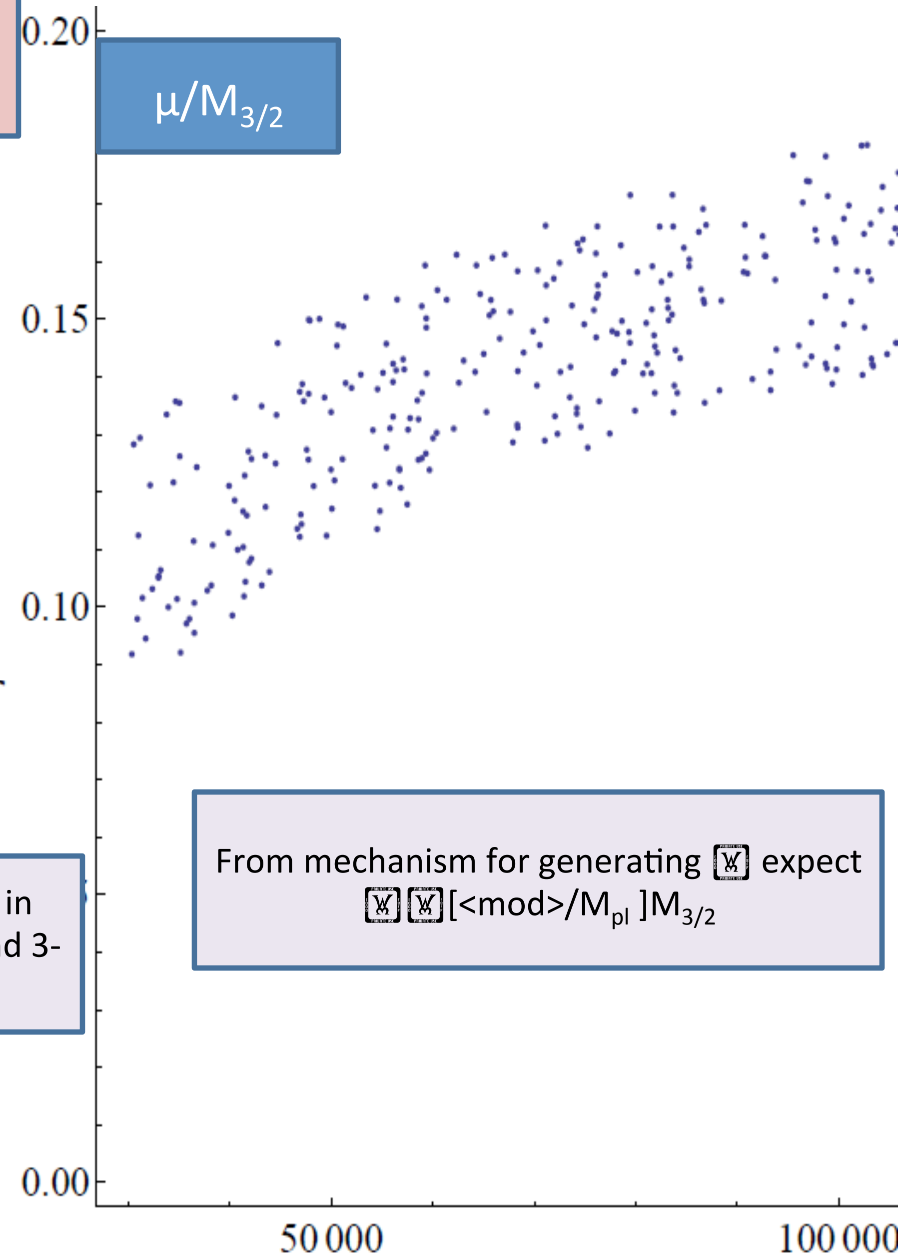
- Procedure – match higgs quartic coupling to effective theory at stop1-stop2 geometric mean (minimizes threshold corrections), so heavier scalar scales "integrated out" – run from there to M_{top} – compute M_h = [illegible]([illegible](M_t)+[illegible][illegible]$_{light}$) v – originally used one loop threshold corrections for heavy and light, and two-loop beta functions to run from stop scale to top scale
- Now use two loop threshold corrections for heavy and light, and three loop beta functions
- Two loop gluino threshold corrections leading log [illegible] ln(gluino/stop) decreases M_h by [illegible] 0.3 GeV, and two loop higgsino threshold corrections increases M_h [illegible] 0.3 GeV – going from two loop to 3 loop decreases M_h [illegible]0.06 GeV – other effects smaller
- Typos/errors in Giudice/Strumia et al that we only caught after original paper shift M_h by about 2 GeV



140
135
130
125
120
115
110
105
100
2
4
6
8
10
12
14
M_h (GeV)
tan β
Summer – November 2011 prediction
M_{3/2}=100
M_{3/2}=50
M_{3/2}=25
This shows effect of doubling or halving gravitino mass, ΔM_h ≈ 1.5 GeV

New results -- Higgs mass is in experimental range for all points





All points have EWSB, satisfy Supergravity and no [illegible] in superpotential conditions (so tan[illegible][illegible]$M_{3/2}$ /1.7[illegible]), and 3-loop recent results included

From mechanism for generating [illegible] expect [illegible][illegible][<mod>/M_{pl}]$M_{3/2}$

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 $\gtrsim$ 30 TeV so gravitino $\gtrsim$ 30 TeV,** squarks gravitino so squarks 30 TeV 0804.0863
- CP Phases in M-theory (weak CPV OK) and EDMs 0905.2986
- **Lightest moduli masses $\lesssim$ 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 (A, L, K, K, Z)
- calculate EDMs, prove one and only one yukawa unity (Perry)

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

- ALSO:

- Gluinos get no mass contribution from meson condensate F term since includes only derivative of gauge kinetic function with respect to gauginos – gaugino condensate F term [illegible] V_3 while meson F term [illegible] V_7 so suppression factor [illegible] 30 – very general in M-theory

- Derive that all terms in soft-breaking Lagrangian have same phase at tree level, so no “susy CP problem” – predict e, q EDMs

- Get axion spectrum, strong CP problem solved, no problem with upper bound on axion decay constant

- Next briefly compare M-**theory** derivation with **models** assuming heavy scalars – first James Wells hep-th/0302127, Nelson et al
  - Very different
  - History very distorted, even recently

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 = $M_{3/2}$ □ 50 TeV necessarily** , scalars not very heavy
- Gluino lifetime $\lesssim 10^{-19}$ sec, decay in beam pipe
- **M_h □ 126 GeV unavoidable**, predicted

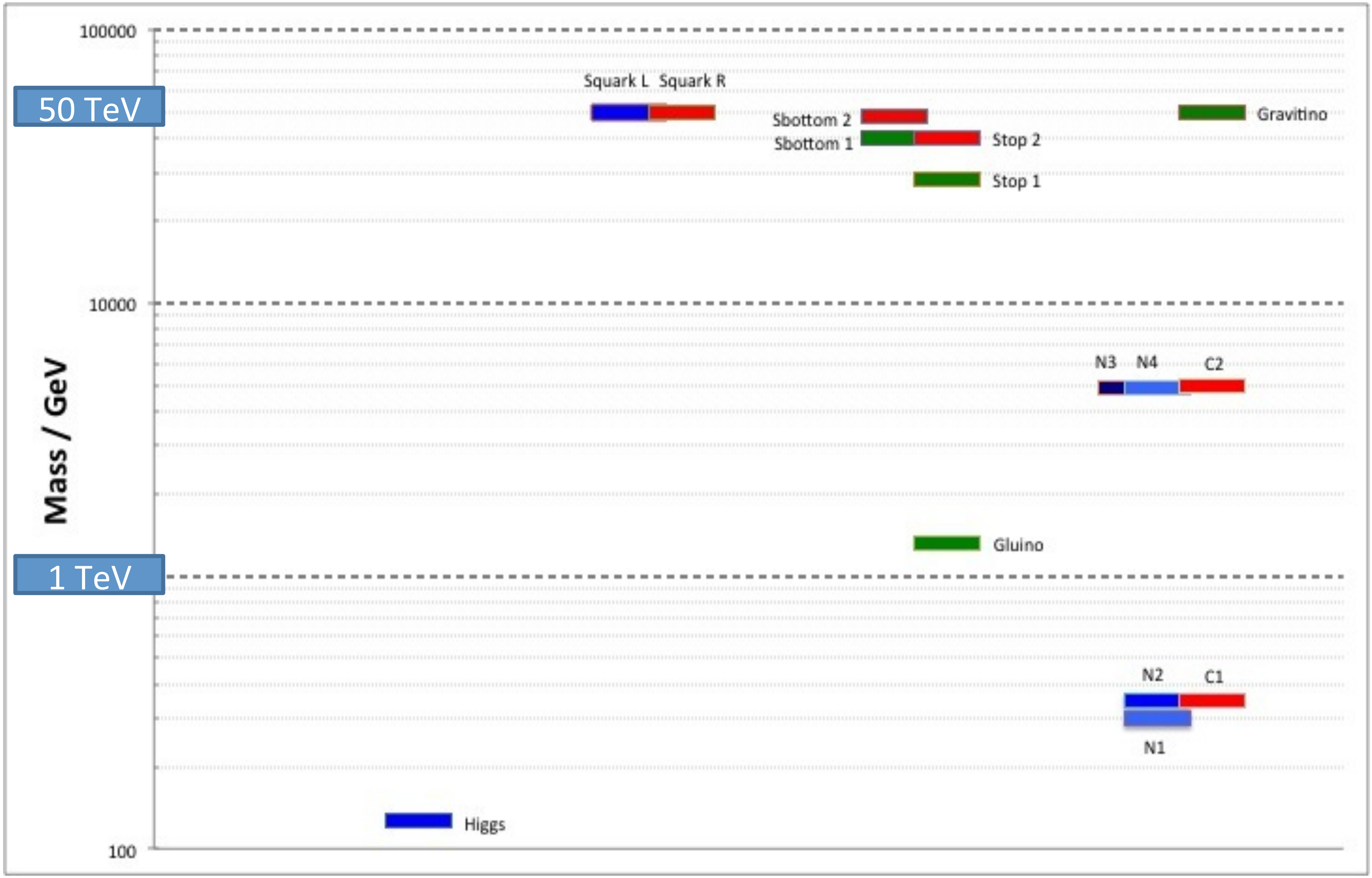
SPLIT SUSY (ETC) MODELS

- 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 μ □ $M_{3/2}$
- 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**

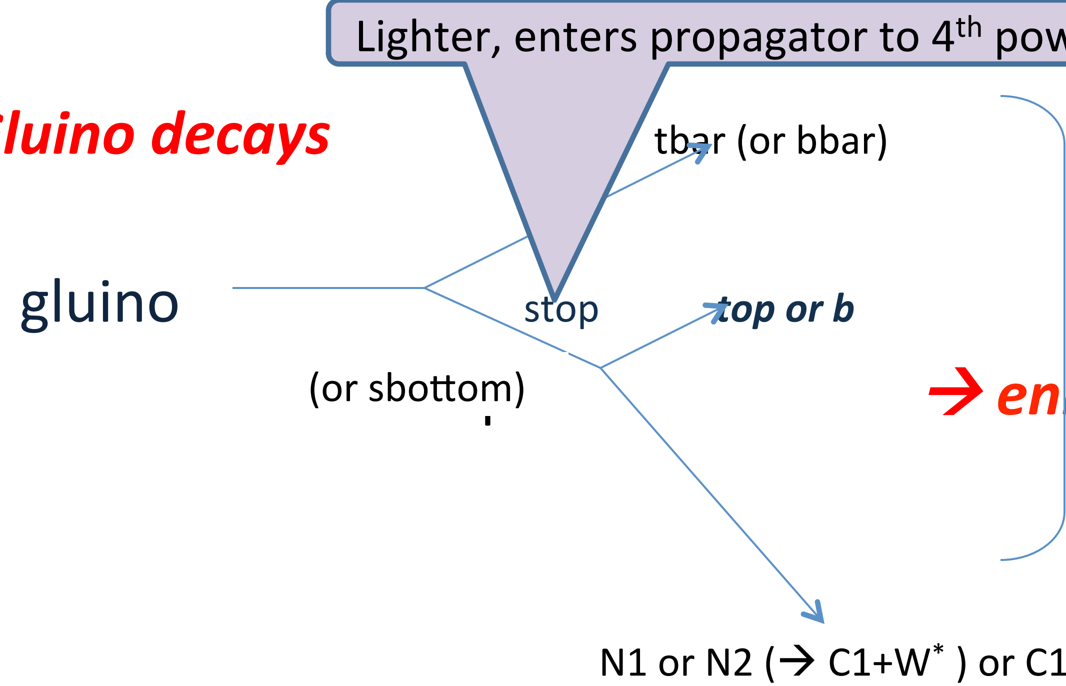
➢ *LHC*

Generic implications of moduli – gravitino – scalars connection for LHC

- ❑ ***Gravitino mass*** $\gtrsim$ **30 TeV**
- ❑ **Supergravity equations → scalar superpartner masses [illegible] gravitino mass [illegible] 30 TeV!**
- ❑ **Effectively one Higgs doublet, like SM but NOT same as SM**
- ❑ **Gaugino masses (gluino etc) generically suppressed [illegible] TeV**
- ❑ **Do renormalization group running down to TeV scale, 3rd family runs fastest because running proportional to masses of quarks →because of virtual propagators stops, sbottoms lightest, dominate gluino decay → final states bbbb, bbtt, btbt, tttt plus two of N1 N2, C1 for gluino pairs**


100000
10000
100
50 TeV
1 TeV
Mass / GeV
Squark L
Squark R
Sbottom 2
Sbottom 1
Stop 2
Stop 1
Gravitino
N3
N4
C2
Gluino
N2
C1
N1
Higgs

Gluino decays



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

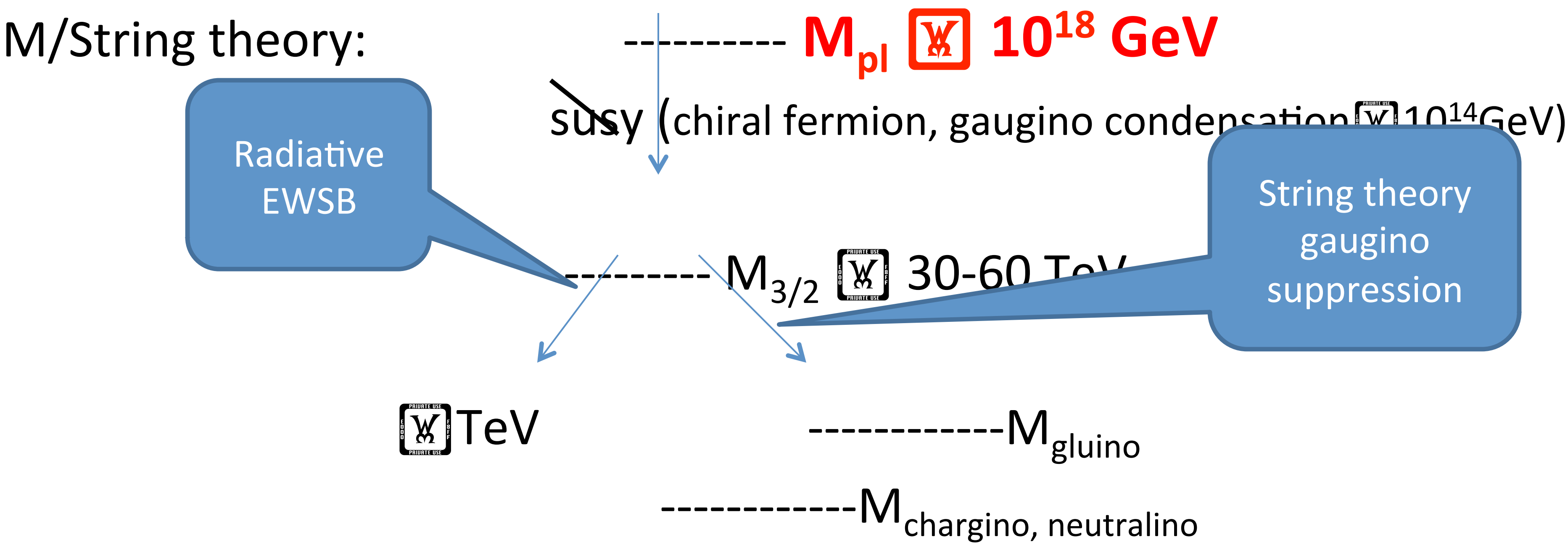
→ enhanced 3rd family decays, about factor 2

Gluino lifetime [illegible] 10^{-19} sec, decays in beam pipe

Gluino decays flavor-violating

Papers LHC14,0901.3367; LHC7, 1106.1963

Naturalness? Fine-tuning? Little hierarchy? Natural?



Mention two issues:

- Cosmological constant problem(s)
- Multiverse, landscape

Do these cause problems for understanding our string vacuum?

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 [illegible] 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 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 [illegible] 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!
- Accurate calculation of gluino mass
- Incorporate inflation
- G_2 manifolds

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 as expected from compactified M-theory, stabilized moduli – 126 GeV *NOT* unnatural or weird (115, 140) – not metastable vacuum

- **[illegible], tan[illegible] included in theory, correlated with M_h**
- **LHC – gluinos but not squarks**

  -- gluinos have enhanced 3rd family decays

  -- gluino cross section tests spin ½, expected for superpartner

  -- two light neutralinos and light chargino also probably observable

- **B_s → [illegible][illegible] and ($g_{[illegible]}$ -2) should deviate only a few % from SM values**