STRING THEORY AND OUR REAL WORLD

-- greatly improved understanding

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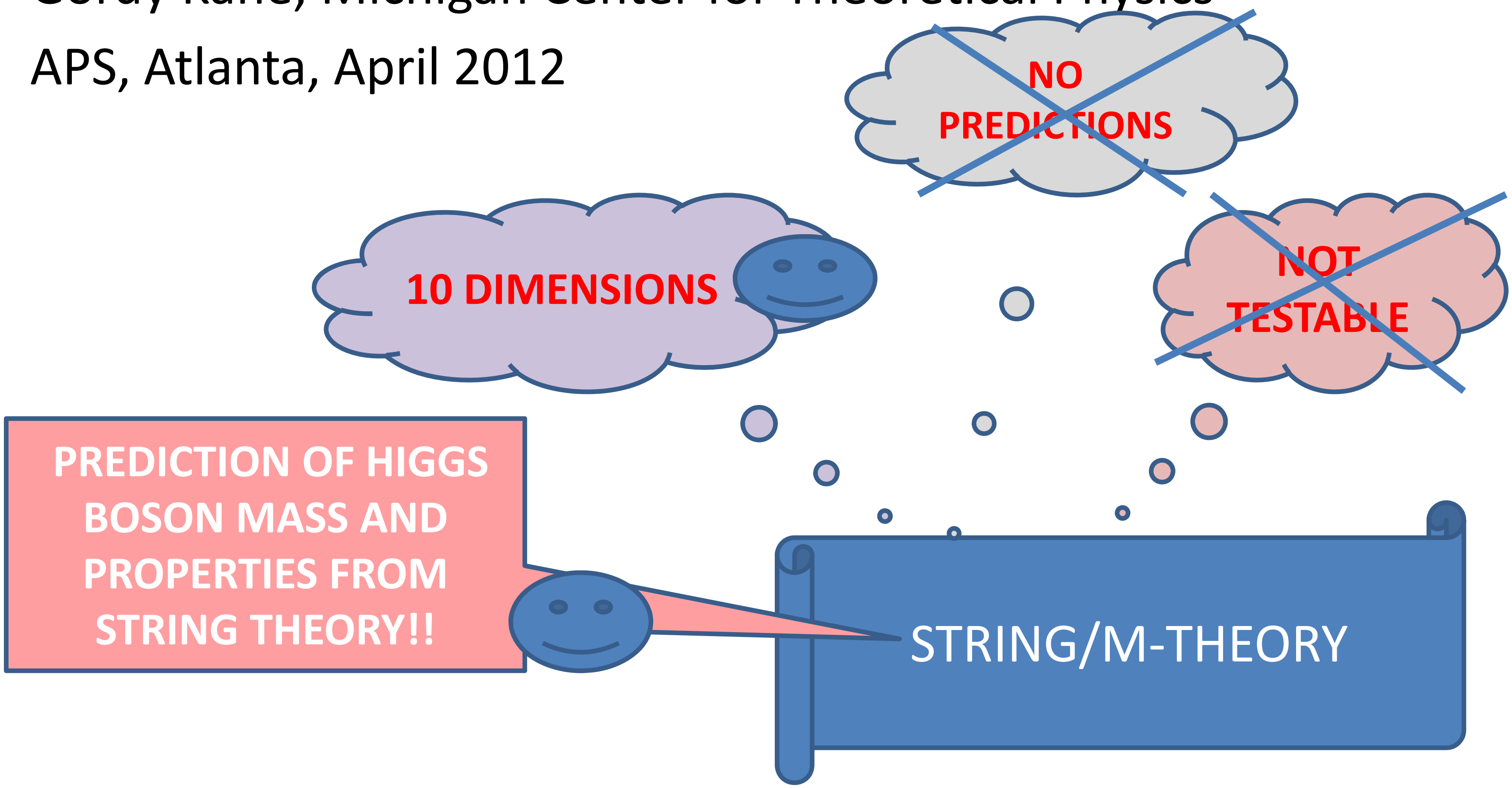


Particle physics has entered a very exciting era – **data** from **CERN LHC**, (and from **dark matter** satellite and laboratory detection experiments), is beginning to emerge

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

Today finally a consistent theoretical framework to address basic questions physicists want to ask

– about **particles** – about **forces** – how they fit into a deeper and broader framework – **why** they are what they are

-- about dark matter, matter asymmetry, much more

"**string theory**" – started mid 1980s, now getting well understood

OUTLINE

- Brief introduction
- What can we already or hope to explain about the physical universe?
- Is string theory likely to provide new interconnected answers? (yes)
- Is string theory testable? (yes)
- An LHC prediction for squark masses
- A cosmological history testable prediction
- Higgs boson – string/M theory prediction of mass, properties

  FIRST STRING/M-THEORY TESTED PREDICTION FOR NEW PHYSICS -- predicted 125 GeV (August)
- Very brief topics – LHC superpartners – M-theory and our string vacuum – CC? – multiverse, landscape? – 10 dimensions?
- Final remarks

Shadowed topics more technical – but you wouldn't believe me without technical details

String theory not easy – we try to find ways to make contact with experiment by using general arguments and properties, and work around some difficult issues – can do this in certain areas!

String theorists – study theory for its own sake

String phenomenologists – traditional physics, find our string vacuum – growing subfield for decade – 11th international conference at Newton Institute, Cambridge June 2012; NSF-funded String Vacuum Project (network, 3 years)

String theory is exciting because it allows us to address many questions we want to understand

Questions for Standard Model and beyond	Standard Model	Supersymmetric Standard Model	String Theory
What form is matter (electrons, quarks, etc)?	√ **(addresses)**		√
What *is* matter?			√
What is light?	√√ (answers)		
Which interactions give our world?	√		√
Gravity?		√	√√
Is supersymmetry valid?			√
Origin of matter asymmetry? Dark matter?		√ √	√ √
Gauge coupling unification		√	√
Dark Energy?			√
Number of dimensions?			√

SM and Supersymmetric SM limited, but **string theory addresses all (?) questions**

”**GENERIC**” $\approx$ perhaps not theorem, but holds very generally – just calculate naturally without special assumptions – have to work hard to find or construct (non-generic) exceptions (if possible), and to show possible exceptions don’t have problems that exclude them

“**COMPACTIFY**” – string theory must be formulated in 10 dimensions (or 11 for M-theory) – must separate into 4 large space-time dimensions and 6 (7) small, curled up ones to test it

“**MODULI**” – the small dimensions are described (parameterized) by scalar fields that specify sizes, relative orientations, etc – called “moduli fields” – their quanta are scalar bosons, “moduli” – no familiar analogy, but properties calculable – moduli *c*ouple gravitationally to all matter

COMPACTIFY *(small extra dimensions)*

We focus here, try to work around issues that are problems

EMBED MSSM, study spectrum, masses of quarks and leptons, gauge group of forces – now many examples of successful embeddings

Stabilize moduli, generate TeV scale from Planck scale, calculate supersymmetry breaking Lagrangian, study Higgs and LHC and DM predictions

STRING THEORY USUALLY VIEWED AS QUANTUM THEORY OF GRAVITY, OR MATHEMATICAL FRAMEWORK – STRING PHENOMENOLOGISTS VIEW IT INSTEAD AS ADDRESSING QUESTIONS ABOUT OUR WORLD, AND PROVIDING POSSIBLE SOLUTIONS, RELATED SOLUTIONS

Want to know **our string vacuum**

EXCITING THAT STRING THEORY ADDRESSES THE QUESTIONS -- but

CAN "STRING THEORY" PROVIDE ANSWERS AND *TESTABLE* UNDERSTANDING?

If your impression of string theory came from some popular books and articles and blogs (or from formal string theorists) you might be suspicious of taking string theory explanations seriously

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

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

Surprisingly some people have claimed that because string theories are naturally formulated at Planck scale high energies or small distances they cannot be tested!

Obviously collisions will never probe energy scales such as the Planck energy 10^{16} TeV (about 10^{15} times LHC), or see distances as small as 10^{-33} cm

Equally or more obviously don't have to be somewhere to test something there

– always relics

-- stars elsewhere are made of same chemical elements as ours

-- big bang – evidence includes [1] expanding universe, [2] Helium abundance and nucleosynthesis, [3] Cosmic microwave background radiation

-- 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

More fundamentally, what does it mean to test theories?

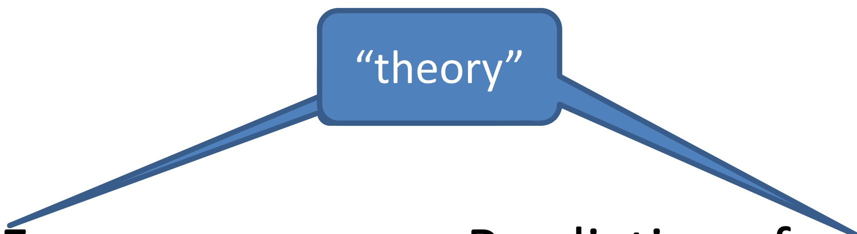
In what sense is F=ma testable?

-- 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*

In what sense is string theory testable? Same!!!



Predictions from F=ma

-- pick F, pick m

-- ***find solutions***

-- calculate acceleration a

Predictions from string theory

--**compactify** to 4D, choose manifold

-- ***find solutions***

-- calculate Higgs boson mass, etc

Theories are Lagrangians, Hamiltonians – they have many solutions – the world, physical systems, are described by the ***solutions***

Normally the system relaxes to the lowest energy state, where we study its properties

String theory like having Lagrangian, many solutions – physical systems described by compactified string theories, in vacuum state

We want to describe *our string vacuum*

SO COMPACTIFIED STRING THEORIES GIVE TESTABLE 4D RELATIVISTIC QUANTUM FIELD THEORY CALCULABLE PREDICTIONS – for masses of superpartners (LHC), dark matter (direct, indirect detection, LHC), axions, cosmology, CP violation, etc)

Simply wrong to say string theory not testable in normal way

(Note – one falsifiable prediction is sufficient for a theory to be testable)

Can we do better than tests in particular compactifications?

Yes, can find some tests that hold for *generic* compactifications of the 10/11D theory to many manifolds!

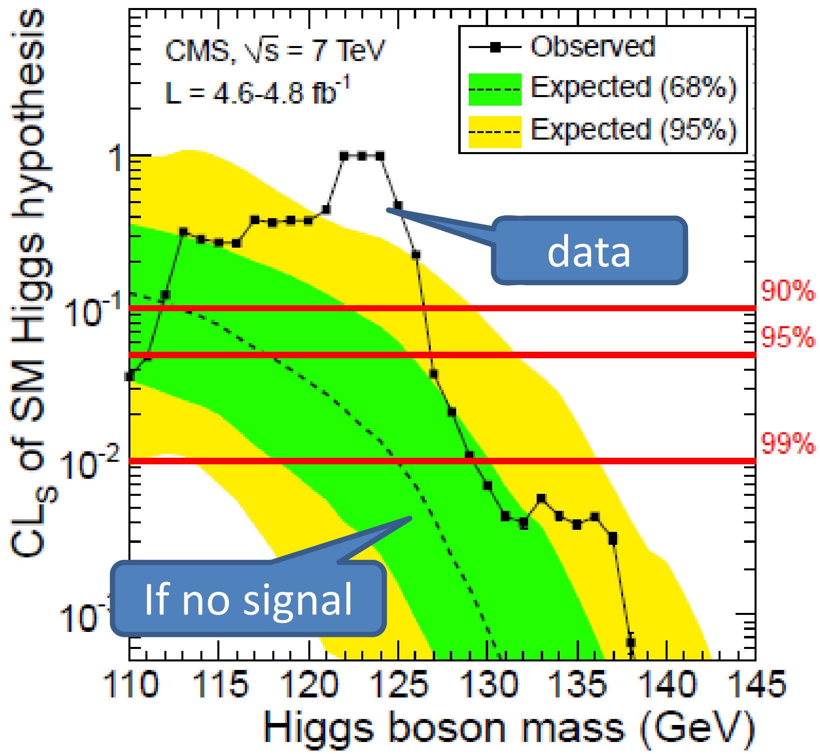
→ Predictions for squark masses, cosmological history, Higgs boson mass and properties

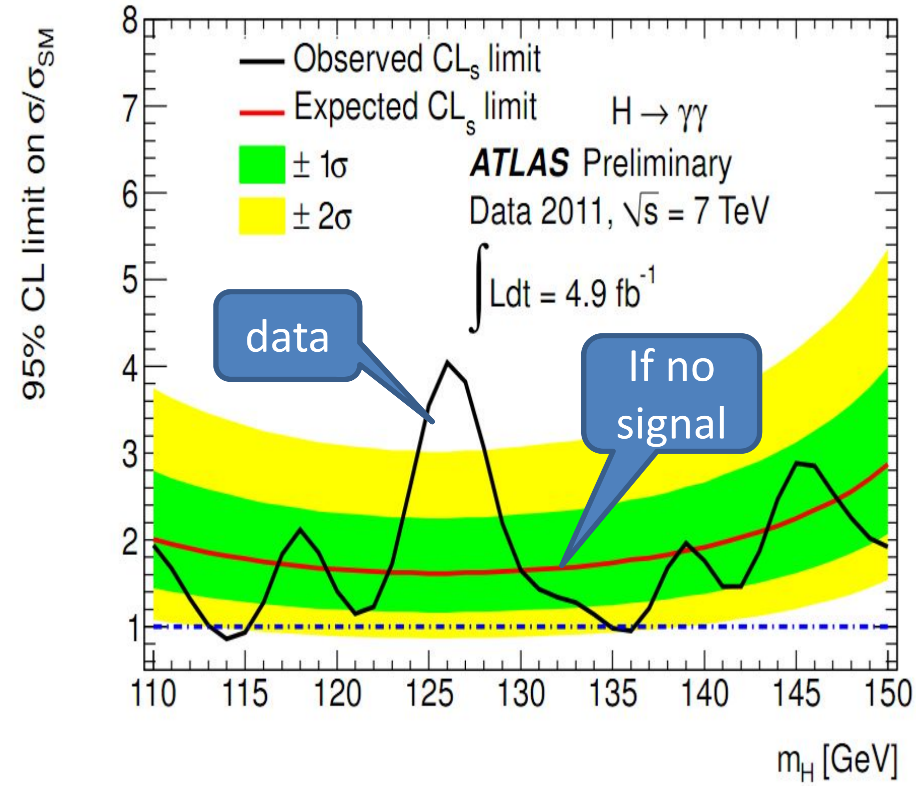
Discovery of Higgs boson, quantum of Higgs field!!

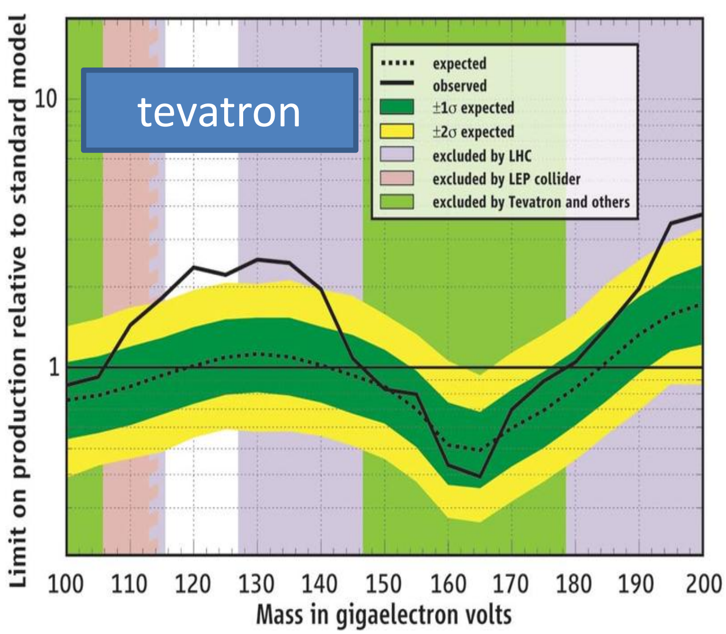
- **Completes the Standard Model of particle physics as full relativistic quantum field theory that describes the world we see**

- **Form it takes points to extending the SM to broader underlying theory**

- **The lowest energy state of the universe, "vacuum", contains the Higgs field – non-zero quantum numbers (electroweak charge, hypercharge) – not just quantum fluctuations but permanently – Lorentz invariant – huge conceptual leap**







Seen by 3 independent detectors – add significances – LHC mainly $\gamma\gamma$

--Note Tevatron sees hWW coupling, essential for proving EWSB, and hbb

NEXT DESCRIBE HIGGS MASS PREDICTION – somewhat technical

- Overview – 2 slides
- More detailed physics summary – 3 slides
- Details of crucial part, string-based connection of moduli, gravitino masses – 2 slides
- Connect high scale theory to TeV scale prediction – 1 slide
- Results – 2 slides
- Note "μ" included

HIGGS MASS PREDICTION – overview – two slides

arXiv:1112.1059 GK, Piyush Kumar, Ran Lu, Bob Zheng (Acharya)

Assume world described by compactified string/M-theory – no relevant free parameters (some quantities not yet fully calculable)

Look for, find, generic solutions of compactified string/M-theories having certain properties like our world **– moduli can be "stabilized"** i.e. get definite vacuum values **, (softly) broken supersymmetry, supergravity field theory limit, supersymmetric Standard Model spectrum below compactification scale, non-zero Higgs field in lowest energy state of universe via "radiative electroweak symmetry breaking", be consistent with all cosmology and particle data**

In such solutions can calculate M_h/M_Z → $M_h \approx 125$ GeV (for $\tan\beta \gtrsim 6$)

- **And h predicted to be closely SM-like, so h production and decays must not deviate significantly from h looking like a SM Higgs boson – consistent with current data**

- Results depend strongly on existence and properties of moduli, and on stringy relation of moduli and gravitino masses (below)

- Results depend a little on gravitino mass value, on gauge group and spectrum below compactification scale, on how μ problem solved

HIGGS MASS PREDICTION – more detailed physics argument – 3 slides

- **Compactify to 4D** – generically have **moduli** fields that parameterize curled up space – all corners of string/M-theory
- Moduli generically **stabilized** (get a potential energy, settle at minimum) by non-perturbative contributions to superpotential – any moduli interactions ok, don't need to be able to calculate them – supersymmetry generically broken
- Moduli quanta couple universally via gravity to everything – can write operators for widths, $\Gamma \sim M^3_{mod}/M^2_{pl}$ with coefficient ~ unity – can check coefficient in model, **calculate moduli lifetime**
- Generically, to **avoid** cosmology problems such as **destroying good nucleosynthesis results**, or overclosing universe, **moduli must decay before nucleosynthesis** – [any possible ways out less likely as more studied, non-generic – no workable example – for late inflation see Fan Reece Wang]→ **$M_{mod} \gtrsim$ 30 TeV**

- Note supersymmetry breaking (stringy origin) generates **gravitino** mass ($M_{3/2}$), splitting from its superpartner the graviton
- **Gravitino has spin 3/2**, so projections 3/2, 1/2, -1/2, -3/2 – it has absorbed **spin ½ Goldstino** – Goldstino has **scalar partner sGoldstino** – generically all have $M_{3/2}$
- sGoldstino complex scalar, mixes with moduli – part of moduli mass matrix
- Next **consider moduli mass matrix** – don't need to calculate it
- Theorem: lightest eigenvalue of mass matrix < eigenvalue of any diagonal 2x2 submatrix

→ $\mathbf{M_{mod} \lesssim M_{3/2}}$ from string/M theory, not just field theory

→ $\mathbf{M_{3/2} \gtrsim 30\ TeV}$

- Supergravity → scalars from supersymmetry breaking Lagrangian all have $\mathbf{M_{scalars}} \approx \mathbf{M_{3/2}}$
- **So squarks $\gtrsim$ 30 TeV, not observable at LHC!**
- **Scalars include Higgs sector soft terms M^2_{Hu} , M^2_{Hd}**
- Ask for solutions that have a **higgs mechanism** (higgs field nonzero in vacuum) – occurs by radiative EWSB, so **higgs field zero in vacuum at compactification, but RGE running down to TeV scale shifts minimum of Higgs potential away from origin** – find many solutions
- Study supersymmetric higgs sector → mass eigenstates H, A, $H^{\pm}$ also $\gtrsim$ 30 TeV , h light – **can calculate M_h /M_Z** – h like SM higgs, few per cent deviations from chargino loops, etc
- **tanβ (ratio of two Higgs vevs) not yet accurately calculable so show it as parameter**

RELATE MODULI, GRAVITINO MASSES – 2 slides

- Can write 4D scalar potential V in terms of function

  G= $K + m_{pl}^2 ln(W\bar{W}/m_{pl}^6)$ $\quad V = m_{pl}^2 e^{G/m_{pl}^2}\left(G^i G_i - 3m_{pl}^2\right)$

- Then calculate scalar mass matrix (CC=0)

Scrucca et al, 2006

Douglas and Denef, 2006

Acharya, Kane, Kuflik

1006.3272

$$\begin{pmatrix} M_{i\bar{j}}^2 & M_{ij}^2 \\ M_{\bar{i}\bar{j}}^2 & M_{\bar{i}j}^2 \end{pmatrix}$$

$$M_{i\bar{j}}^2 = e^{G/m_{pl}^2}\left(\nabla_i G_k \nabla_{\bar{j}} G^k - R_{i\bar{j}k\bar{l}} G^k G^{\bar{l}} + G_{i\bar{j}}\right)$$
$$M_{ij}^2 = e^{G/m_{pl}^2}\left(2\nabla_i G_j + G^k \nabla_i \nabla_j G_k\right)$$

- Look near minima of V, mass matrix positive definite – use theorem smallest eigenvalue of mass matrix is less than $\xi^\dagger M \xi$ for any unit vector ξ. (1006.3272 appendix c)
- Take $\xi = (G^{\bar{j}} \quad cG^j)/\sqrt{3(1+|c|^2)}$ with c any complex number
- Get a one complex parameter set of constraints on upper bound of lowest mass moduli eigenvalue

$$
\begin{aligned}
m^2_{\min} &\le \frac{1}{3(1+|c|^2)} \left(G^i \;\; c^\dagger G^{\bar{i}} \right) \begin{pmatrix} M^2_{i\bar{j}} & M^2_{ij} \\ M^2_{\bar{i}\bar{j}} & M^2_{\bar{i}j} \end{pmatrix} \begin{pmatrix} G^{\bar{j}} \\ c G^j \end{pmatrix} \\
&\le m^2_{3/2} \left(2\frac{|1-c|^2}{1+|c|^2} + \mathrm{Re}\{\frac{2c}{1+|c|^2}\frac{u}{m^2_{pl}}\} - \frac{r}{m^2_{pl}} \right)
\end{aligned}
$$

Where $u \equiv \frac{1}{3} G^i G^j G^k \nabla_i \nabla_j G_k$, $r \equiv \frac{1}{3} R_{i\bar{j}k\bar{l}} G^i G^{\bar{j}} G^k G^{\bar{l}}$, $m^2_{3/2} = m^2_{pl} e^{\bar{G}/m^2_{pl}}$

- r is the holomorphic sectional curvature of the scalar field space, projected in the sgoldstino directions
- So

$$
m^2_{\min} < m^2_{3/2} \left(2 - \frac{r}{m^2_{pl}} \right)
$$

This bound is very general – what about r?

- Simple case, $r/m^2_{pl} = 14/N_{mod}$, $N_{mod} \sim 50$?
- Kumar, to be published, sharpen stabilization assumptions, get similar bound with no r dependence – covers all known cases

Supersymmetric "μ problem" – affects M_h , affects EWSB

- Need a symmetry to set μ small, but broken symmetry so μ not zero
- recent work on including μ in string theory
- Probably 2 possibilities

  (a) $\mu \approx M_{3/2}$, should vanish if no supersymmetry breaking [IIB?]

  (b) $\mu \approx (\langle moduli \rangle / M_{pl})\, M_{3/2} \lesssim 1/10\, M_{3/2}$ [M-theory?]

Value of μ also important for direct detection experiments predictions (Xenon100, LUX, CDMS, PandaX…)

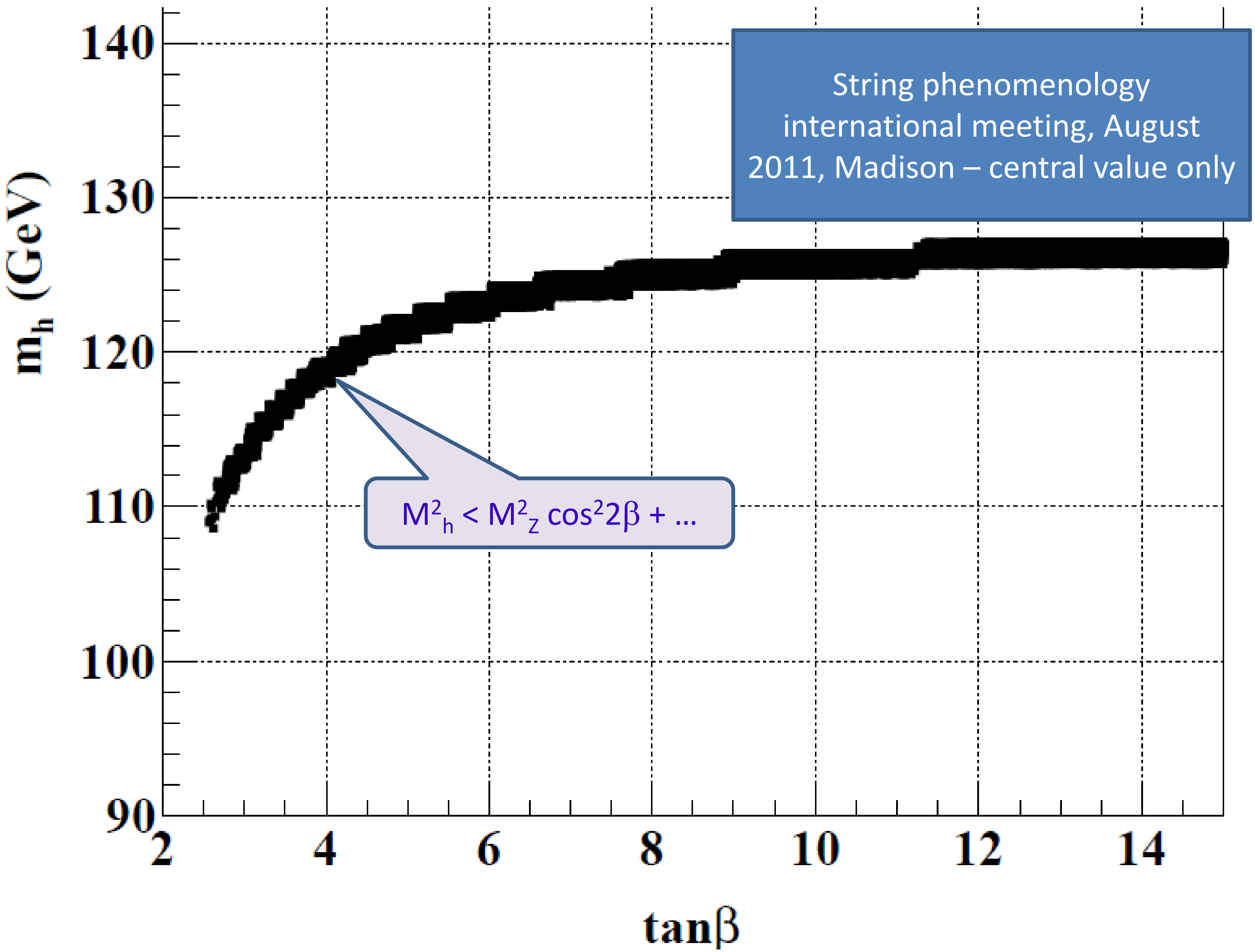
THEORY AT HIGH SCALE (10^{16} GeV), COMPUTE PHYSICAL M_h

- Write theory at scale $\sim 10^{16}$ GeV, fix soft-breaking Lagrangian parameters
- RGE run down, maintain REWSB
- $\tan\beta$ calculable in principle but not yet in practice, but constrained since related to B,μ
- **Use "match-and-run" and also SOFTSUSY and Spheno, compare** – match at $(M_{stop1}M_{stop2})^{1/2}$ – two-loop RGEs
- Main sources of imprecision

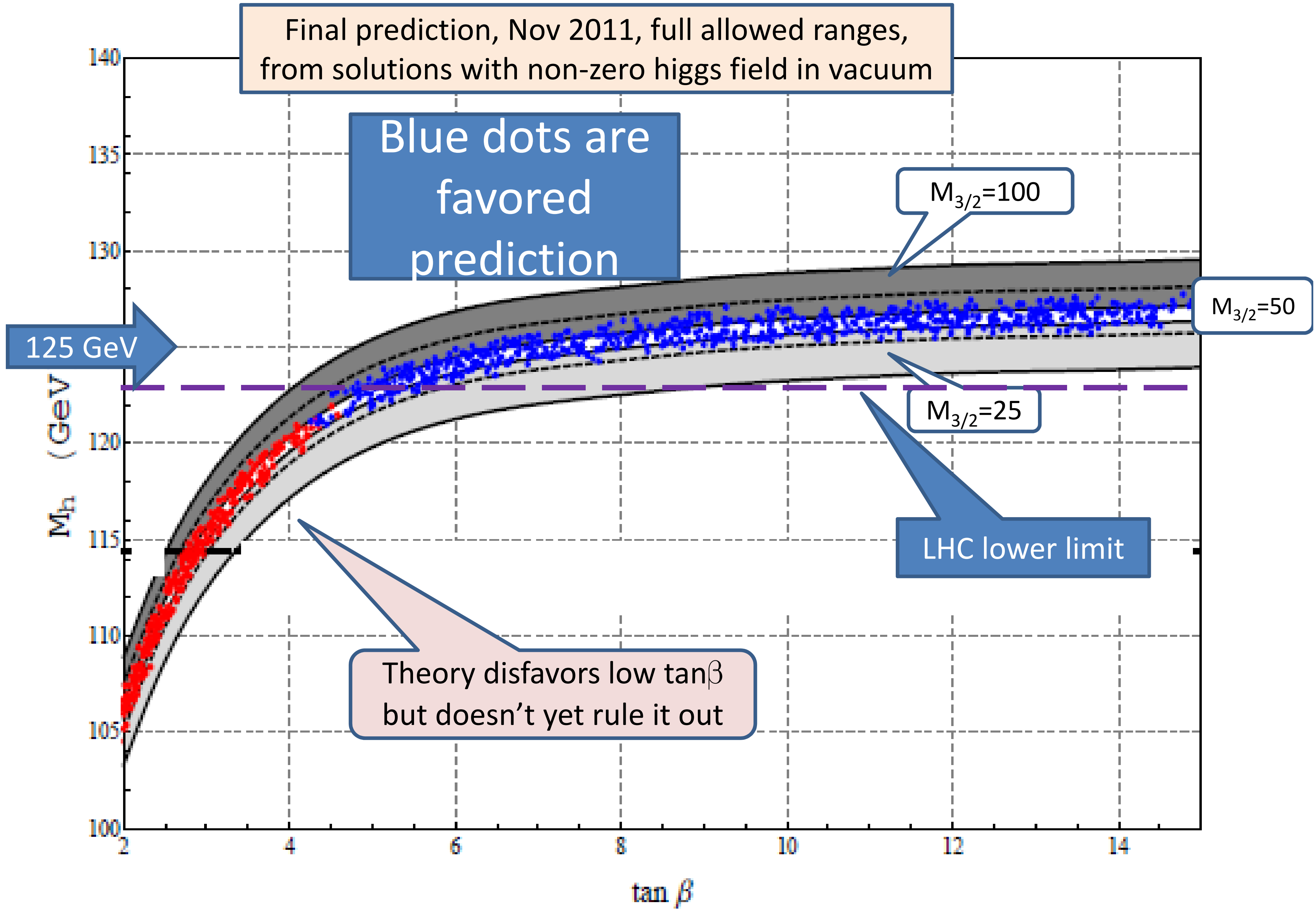
  -- gravitino mass

  – experimental M_{top} , α_{strong}

  – theoretical gluino mass (allow 600 GeV to 1.2 TeV), trilinear couplings (allow 0.8-1.5M_0)

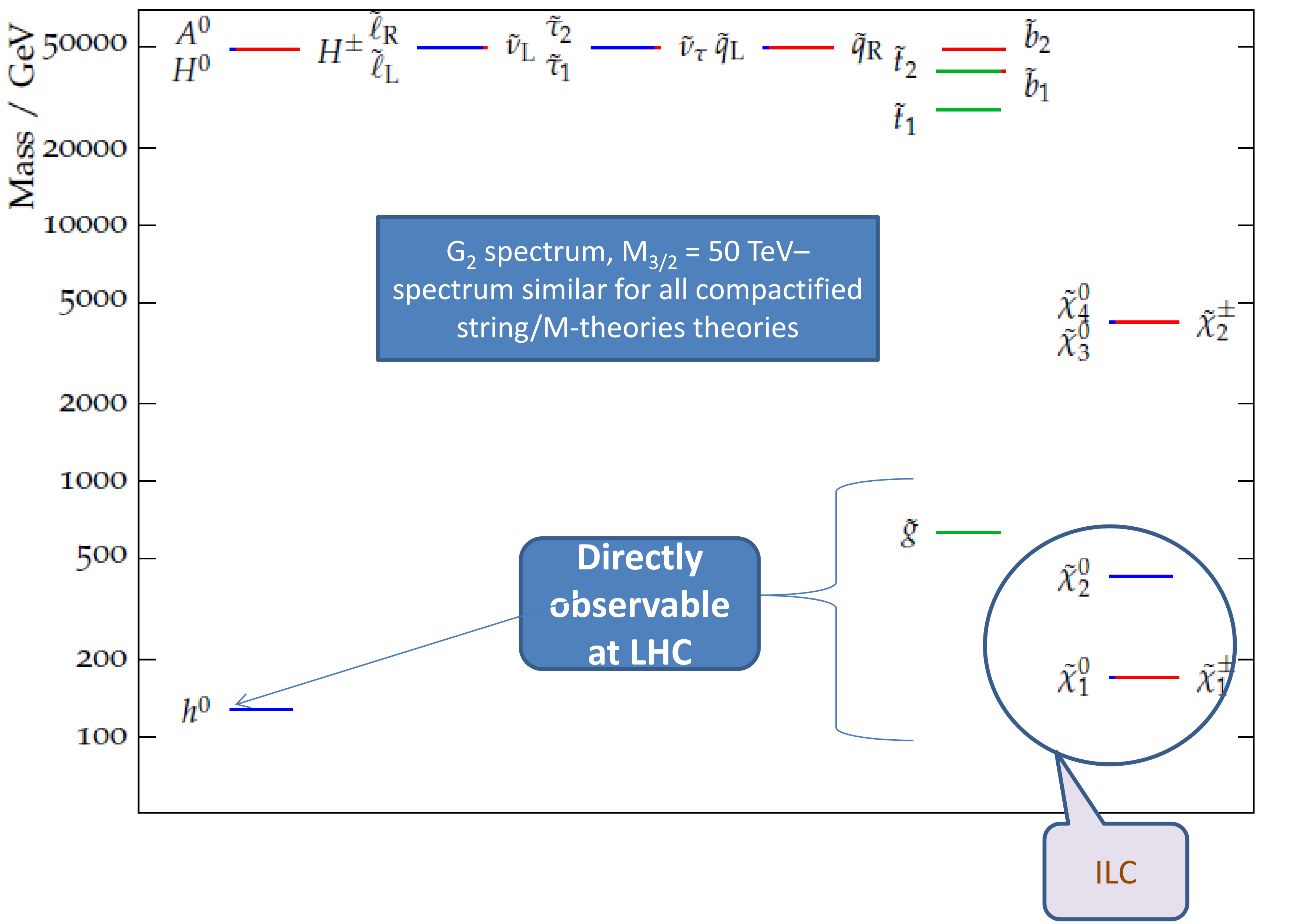


String phenomenology international meeting, August 2011, Madison – central value only
$M^2_h < M^2_Z \cos^2 2\beta + \ldots$
m_h (GeV)
140
130
120
110
100
90
2
4
6
8
10
12
14
$\tan\beta$

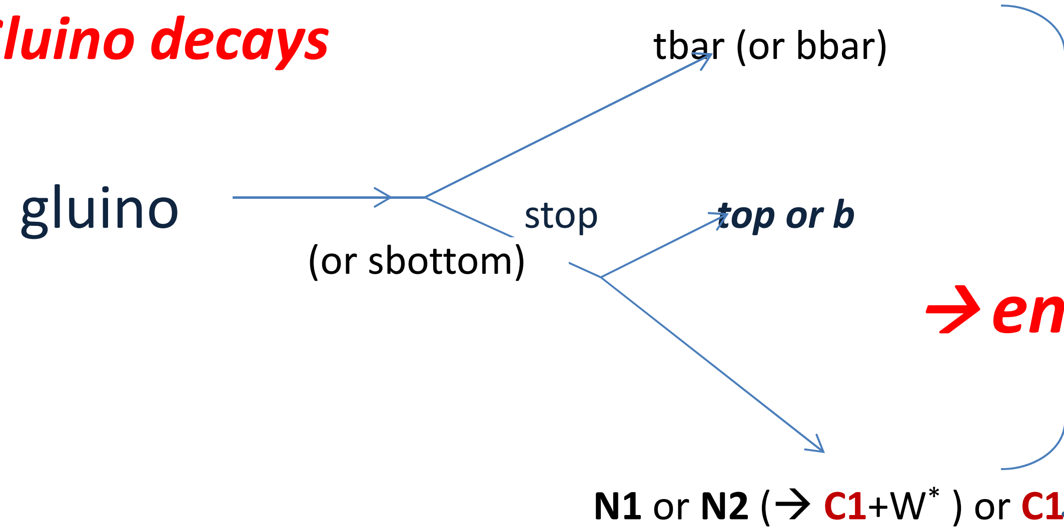

Final prediction, Nov 2011, full allowed ranges,
from solutions with non-zero higgs field in vacuum
Blue dots are favored prediction
$M_{3/2}$=100
$M_{3/2}$=50
$M_{3/2}$=25
125 GeV
LHC lower limit
Theory disfavors low tanβ but doesn't yet rule it out
M_h (GeV
tan β
100
105
110
115
120
130
135
140
2
4
6
8
10
12
14

Briefly describe LHC predictions

Generic LHC predictions – same physics as Higgs mass prediction



Gluino decays



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

→ enhanced 3rd family decays

$\gamma c\tau \approx 10$ cm for wino-like LSP

Gluino lifetime ~ 10^{-19} sec

Current limit for gluinos from string/M theory about 700 GeV

LHC14, arXiv:0901.3367; LHC7, arXiv:1106.1963

Briefly describe our work on M-theory fluxless compactification – good start toward **a candidate for *our string vacuum*** – gaugino masses

STRINGY

- 7 dimensions form a space with G_2 holonomy, preserves N=1 supersymmetry in 4D

- In these vacua, non-Abelian gauge fields localized along 3D submanifolds at which there is an orbifold singularity [Acharya, th/9812205;th/0011089; Achaya-Gukov th/0409191]

- Chiral fermions localized at points at which there are conical singularities [Acharya and Witten, th/0109152, Acharya and Gukov, th/0409191; Atiyah and Witten, th/0107177]

- Generically two 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 → **susy breaking generically gravity mediated in these vacua**

DE SITTER VACUUM, GAUGINO MASSES

-- With only compactification moduli one gets AdS extrema – minima, maxima, saddle points (no go theorems, Maldacena and Nunez…) – some break susy, some preserve it -- so some other contribution is crucial to get deS minima – see explicitly in M theory

-- For M theory positive F terms from chiral fermion condensates cancel the $3W^2$ and give deS minima

-- also, in M theory case the deS minima come from promoting susy preserving saddle point, so the minima is near a susy preserving point in field space

-- so SM 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 $\sim$ 1/60

-- KKLT puts in anti D brane by hand to uplift in type IIB

-- general situation not known – gauginos suppressed in heterotic?

Other results for M-theory compactification

- Compute full soft breaking Lagrangian
- All terms relatively real! → **no susy CP problem** (GK, Kumar, Shao)

Potential stabilizes real parts of moduli, only a few axions – generically one axion combination t stabilized at cost=-1 – then terms in W align with same phase – overall phase of W can be rotated away – remaining axions stabilized exponentially smaller giving contributions that work to also ***solve strong CP problem*** (Acharya, Bobkov, Kumar)

- **Universe moduli dominated after inflation** so axion limit larger, string axion problem almost solved(Acharya, Bobkov, Kumar)
- **Include μ** (Witten; Acharya, Kane, Kuflik, Lu)
- **Flavor OK** (GK, Kadota, Kirsten, Valesco-Sevilla)
- **Gauge Coupling Unification**
- **Baryogenesis *and* ratio of baryons to DM from moduli decay after Affleck-Dine baryogenesis** (GK, Shao, Watson, Yu)
- **Higgs physics, EWSB, fine tuning alleviated** (GK, Feldman, Kuflik, Lu)

Mention two final topics:

Cosmological constant/dark energy?

“Landscape”?

COSMOLOGICAL CONSTANT/DARK ENERGY

- No solution expected in particular string vacuum
- **Expect solution decoupled from all the particle physics issues – this holds in all known approaches**
- **Solving CC/DE unlikely to help answer particle physics questions**
- **Not solving CC/DE unlikely to prevent answering questions**

- In practice, set CC to zero for calculations, and ensure can do that and have deSitter minimum for vacuum – requires two contributions to breaking supersymmetry

STRING THEORY FRAMEWORK HAS *MANY* SOLUTIONS ("LANDSCAPE")

- There *are* many solutions – if the theory implies they exist, and the theory is well tested …
- Some have argued that if there are many, then it is unlikely we can find one describing *our* vacuum
- Indeed, probably unlikely if do it purely theoretically
- But not choosing vacua one by one and testing them

- Already have candidates for our string vacuum in which can calculate Higgs boson mass and properties and solve several problems (dark matter candidate, weak and strong CP problems etc) – also many with MSSM quark and leptons embedded, no extra matter – not yet one with everything

CONCLUDING REMARKS

- ***Generic predictions now possible from compactified string/M-theories***
- **First prediction from string theory for new physics: $M_h \approx$ 125 GeV (for tan$\beta \gtrsim 6$) !! And h must be SM-like!!**
- **Squarks heavy, gluinos probably at LHC in 2012** – enhanced 3rd family decays, disappearing charginos
- In M-theory case get TeV scale etc – **compactified M-theory on G_2 manifold a good candidate for our string vacuum!**
- **probably the compactified string theory is as simple as any theory could be and explain our world**
- **To understand (not just describe) probably necessary to embed the theory in extra dimensions**