STRING THEORY AND OUR REAL WORLD

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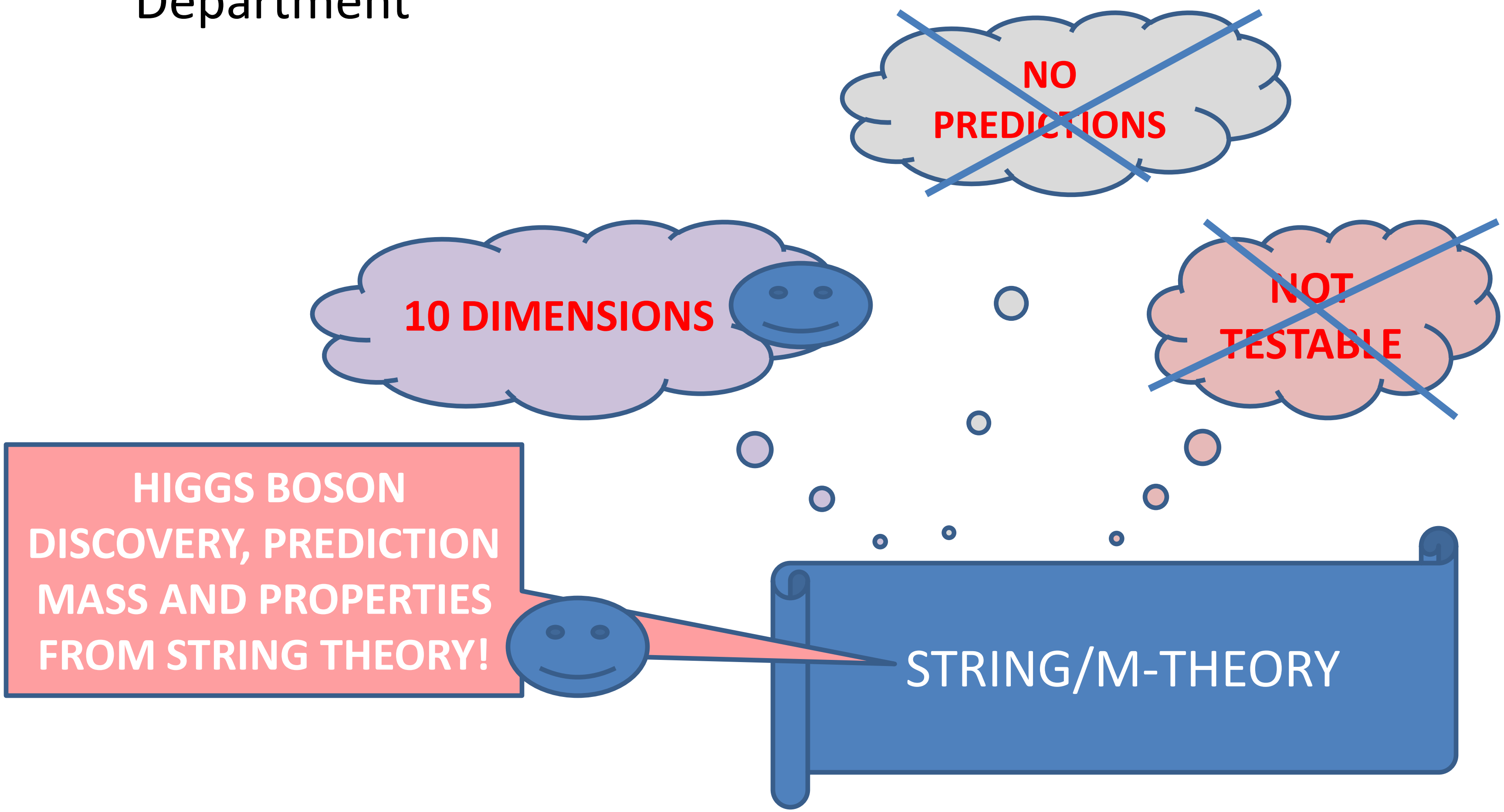


OUTLINE

- **Brief introduction**
- **What do we know about the physical universe? What do we want to know?**
- **Is string theory likely to provide new answers? (yes)**
- **Is string theory testable? (yes)**
- **A string theory cosmological testable prediction**
- **Higgs boson – recent data from CERN LHC**

  -- string theory prediction of mass, properties
- **Brief topics – multiverse? – why 10 D? – what is string theory?**
- **Final remarks**

PERSPECTIVE

To understand the physical universe and its underlying laws need at least three things:

- **Rules** – quantum theory + Einstein relativity – hold for any force, any particles – tell how to calculate any prediction – relativistic quantum field theory in place by about 1930, no change since then (but increasingly better understanding) – no change anticipated
- **Forces** – what forces act on particles to form our world?
  – strong, electromagnetic, weak, gravity
- **Particles** – underlying final constituents? – quarks, leptons

Standard Model, proposed 1972, 1973, confirmed by mid 1980s

E.g. Newton's law F=ma is a rule, for any force, particle
– put in force and calculate motion for any object

Particle physics is entering a very exciting era – **data** from **CERN LHC**, (and from **dark matter** satellite and laboratory detection experiments), is beginning to emerge – took 3 decades since Standard Model (**SM**) stage

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

Today finally a consistent theoretical framework to address essentially all the 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

– essentially all basic questions being addressed

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

This is not the usual view of string theory (as a quantum theory of gravity) – but for me and some others it is the most exciting thing about string theory

What *are* the main issues we want to address?

Very informative to compare what physics questions are "addressed" or "answered" or "explained" in (define these below)

A. Standard Model (SM)
B. Supersymmetric Standard Model
C. String /M-theory (mostly don't separate these)

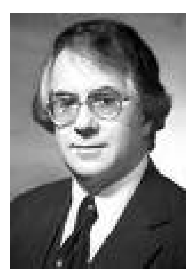
Ways to describe results – **"Address"**, **"Explain"**, **"Answer"**

Newton's laws of motion and gravity ***address*** and ***answer*** sending a rocket to the moon, but do not address why the universe is made of matter but not antimatter

Consider atomic physics – we know that electrons with spin and orbital motion **address** question of magnetism, and lead to magnetism – magnetism is not explicitly in the original theory, it emerges and it is ***explained*** – but high-temperature superconductivity is ***addressed***, not yet explained

Standard Model of particle physics
[formulated in 1972-73, AB]

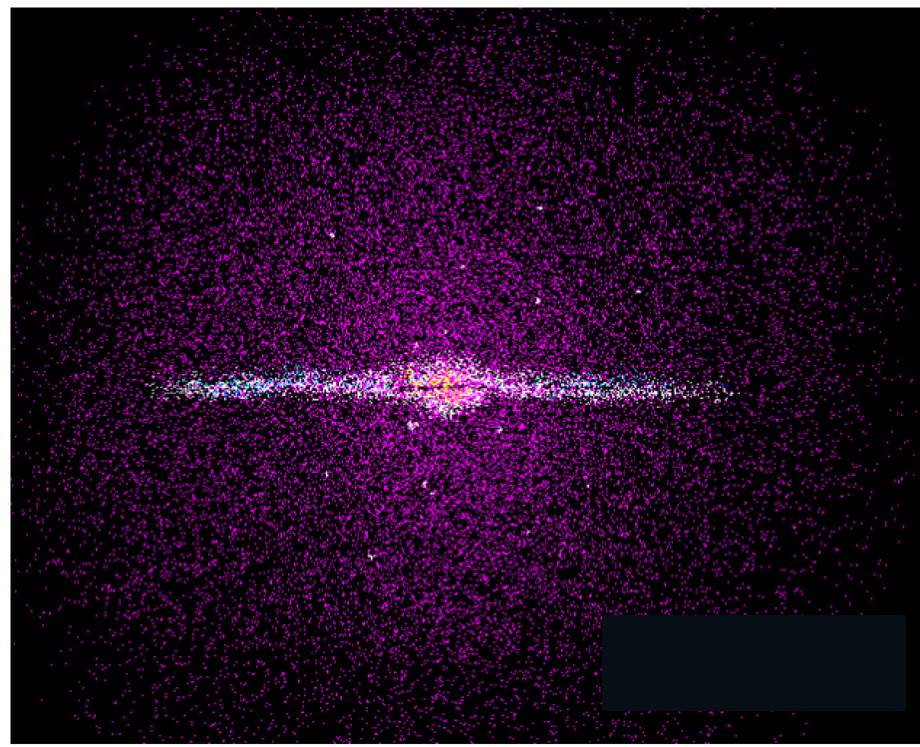
- Quarks and leptons interact via strong, electromagnetic, weak forces to form protons, nuclei, atoms, molecules, donuts, espresso, etc
- Forces are not arbitrary – the ***form*** of the force is determined by an invariance principle ("gauge forces")
- Combined with gravity, **describes the world we see!**
- **Very well tested** – a wonderful description of the world we see, the goal of four centuries of physics – full relativistic quantum field **theory (not model)**, no puzzles in its domain – **here to stay**
- Final ingredient – need explicit detection of **Higgs boson** – probably observed at LHC!!


Universe contains **dark matter** – about a quarter of the mass-energy of the universe – dark matter has gravitational interactions and probably weak force interactions, but does not have significant electromagnetic or strong interactions

The SM has no candidate for dark matter – not just that we don't know one, **can prove SM cannot provide dark matter**

Sherri Smith "Great Cosmic Census"



Supersymmetric SM (1973)

- Hypothetical **extension of SM** where the theory is also invariant under interchange of fermions (spin ½) $\leftrightarrow$ bosons (spin 0)
- Considerable indirect evidence for supersymmetry in nature
- If indeed a symmetry of nature then **should see superpartners** of some of the SM particles (electron, photon, gluon etc) **at LHC – not expected yet, but probably during 2012**
- **Superpartners: electron→selectron, quark→squark, photon→photino, etc**
- Don't focus on supersymmetry today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Supersymmetric SM *does* address the problem of dark matter (and more) – lightest superpartner typically stable particle and good candidate for dark matter

If we did not know about dark matter, supersymmetric SM would actually make us think of it and look for it – historically both theory and data at about same time

String theory addresses much more -- If we did not know about gravity, or forces like strong force and the electroweak force, or quarks, 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 compare SM, supersymmetric SM, string theory

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?			√
What is dark matter?		√	√
Origin of matter asymmetry?		√	√
Dark Energy?			√
Number of dimensions?			√

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

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, you 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 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)

Fortunately, increasingly active subfield of "**string phenomenology**" -- focuses on formulating testable string-based description of **our world (formal string theorists study string theory for its own sake)**

NSF has funded the "**String Vacuum Project**", SVP, consortium of 8-10 universities – support for PHD students in string phenomenology http://www.northeastern.edu/svp

Vacuum is ground state, lowest energy state, of universe

2010 international string phenomenology meeting, Paris, http://stringpheno.cpht.polytechnique.fr/

2011 Madison

http://conferencing.uwex.edu/conferences/stringpheno2011/index.cfm

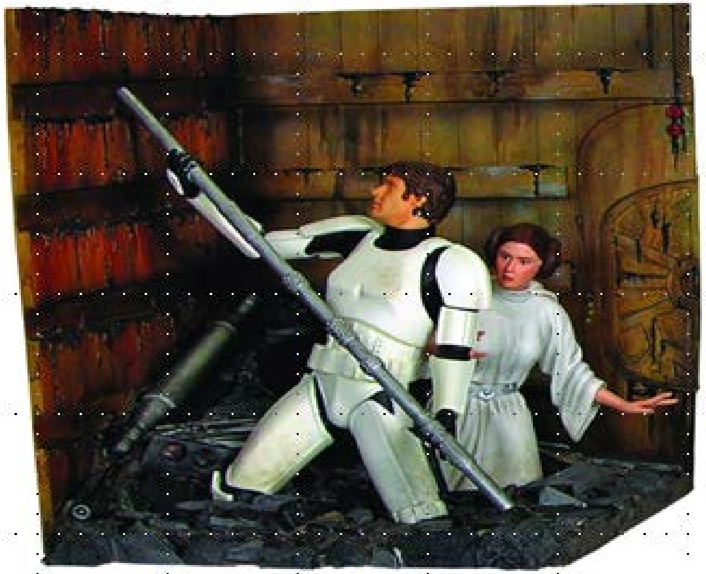
2012 University of Cambridge (England), June,

http://www.newton.ac.uk/programmes/BSM/bsmw05.html

String theory is too important to be left to string THEORISTS

String theory formulated in 10 or 11 space-time dimensions, in order to have a mathematically consistent theory – for our purposes ignore 10 vs 11

To describe our world can separate 10D into 4 large dimensions that form our world, and 6 small D we don't experience (typically they form a "Calabi-Yau manifold" with well studied mathematical properties) and – jargon "**compactification**" – for 11D (called M-theory) the small 7D manifold is called a "G_2 manifold"



How large should the curled up universe be?

There is a natural size, **Planck scale size**…

(could be larger than Planck size, but no motivation and no successes)

PLANCK SIZE

From Newton's $\mathbf{G_N}$; Einstein's **c** (speed of light) ; Planck's constant **h** (the unit for quantum theory) can form quantities of length, time, energy, etc

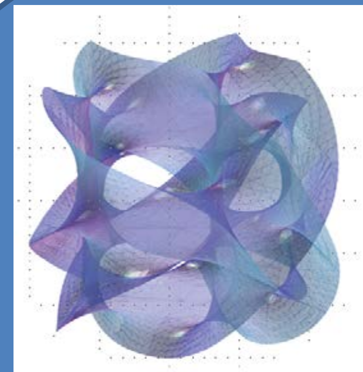
Expect the laws to be simple expressions when the associated lengths are the Planck ones

"These necessarily retain their meaning for all times and all civilizations, even extraterrestrial and non-human ones, and can therefore be designated as "natural units"" – Max Planck, about 1905

→ Planck length ~ 10^{-33} cm [$L = (hG_N/c^3)^{1/2}$]

→ Planck time ~ 10^{-43} sec

→ Planck energy ~ 10^{19} GeV (about 10^{15} larger than LHC energy)



The Calabi-Yau (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* – there is a known procedure for calculating predictions of a compactified string theory

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 (atom about 10^{-8}cm)

Equally 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

What does it mean to test theories?

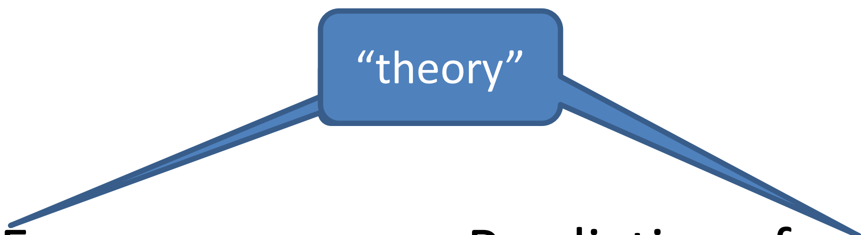
In what sense is F=ma testable?

-- 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?



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

COMPACTIFIED STRING THEORIES GIVE 4D TESTABLE RELATIVISTIC QUANTUM FIELD THEORIES, CALCULABLE PREDICTIONS

Simply wrong to say string theory not testable in normal way

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

So it is possible to make some specific tests of compactified string theories – more and more being made now

Can we do better?

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

Very important concept

“**generic**” – what you get if you just carry out the calculations naturally

– don’t adjust quantities or assumptions to get some particular result

– most results, solutions generic

– usually non-generic results lead to inconsistencies with some data or theory constraint, but may be hard to prove that

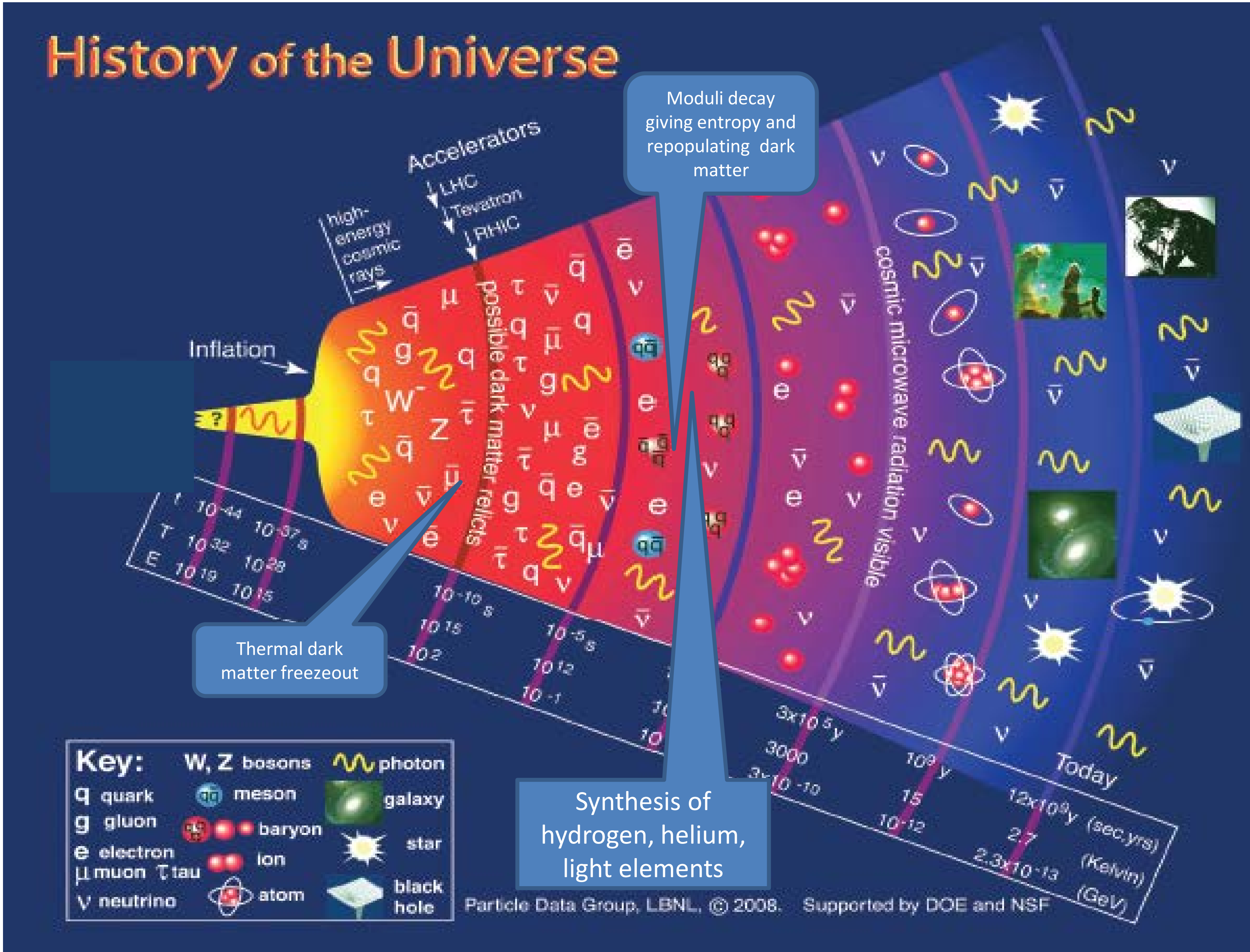
“**generic**” always arises for **solutions** (which describe actual systems)

One generic string theory prediction (derivation long)**:**

The universe has a *non-thermal* cosmological history

Usual *assumption* is a "thermal cosmological history" – at the big bang about 10^{80} particles emitted – then the universe expands and cools – particles collide, annihilate, decay – some emerge from other particle collisions – eventually amount of dark matter stays about constant when other particles have too little energy to make dark matter particles in collisions

String theory generic prediction – **not assumption!** – additional particles are present (called moduli) – their decay produces many particles, which dilutes thermal dark matter relic density a lot – and new dark matter particles emerge in moduli decay → **"non-thermal"**

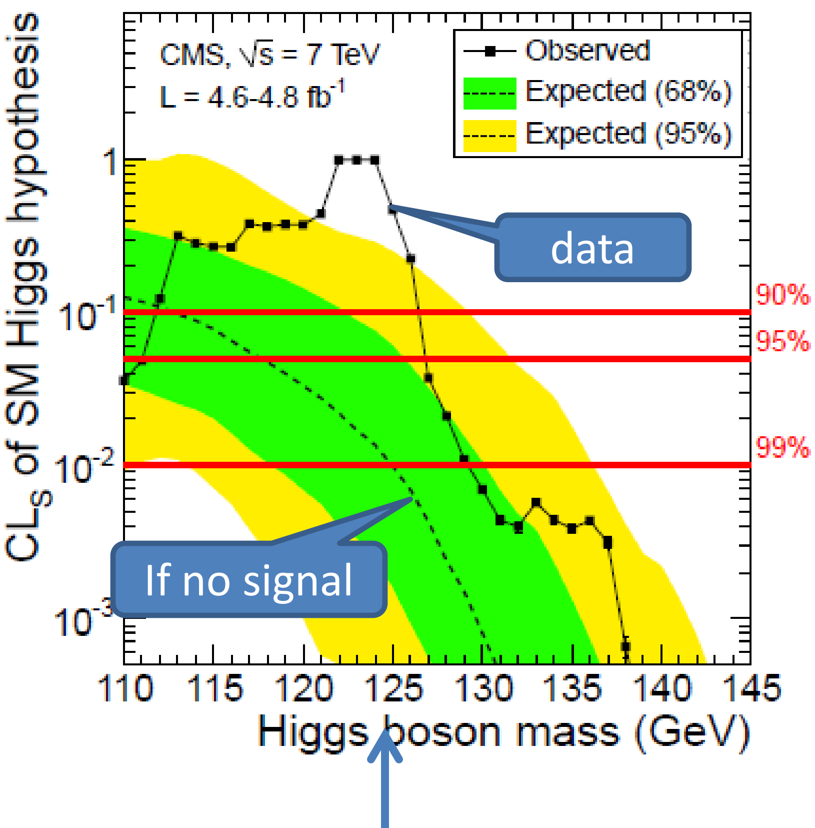

History of the Universe
Moduli decay giving entropy and repopulating dark matter
Thermal dark matter freezeout
Synthesis of hydrogen, helium, light elements
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
possible dark matter relicts
cosmic microwave radiation visible
Today
(sec,yrs)
(Kelvin)
(GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

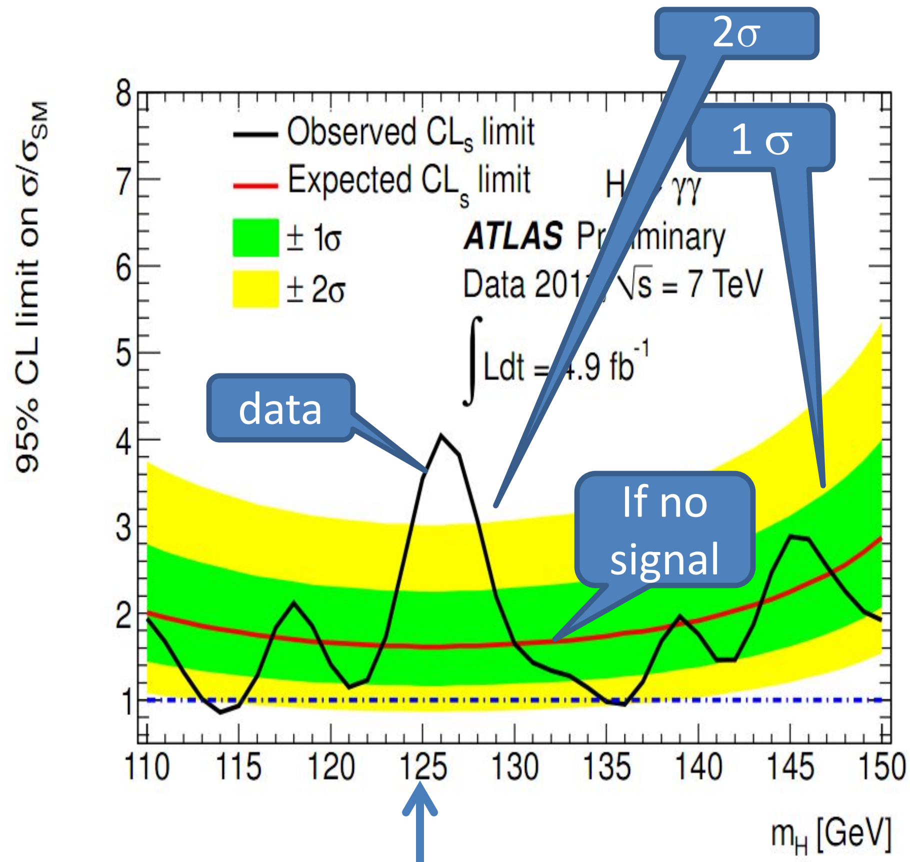
Next consider **Higgs boson** – recent report of "**evidence**" from LHC

I and many others view results as "**discovery**" – two detectors see same result – but conventional evidence rules not quite satisfied – neither detector individually can claim discovery – detectors can combine data – either few weeks or early summer

Basic idea of Higgs physics – lowest energy state of universe (vacuum) has a "Higgs" **field** throughout space-time – other particles interact with the Higgs field and behave as if they have mass – Higgs **boson** is quantum of Higgs field

Huge step in our understanding of the universe, **huge success for humans in figuring out how to detect it and in building and making work a facility that could do it** – took about 35 years after serious quest began


CMS, √s = 7 TeV
L = 4.6-4.8 fb-1
Observed
Expected (68%)
Expected (95%)
data
90%
95%
99%
If no signal
CLs of SM Higgs hypothesis
Higgs boson mass (GeV)
110 115 120 125 130 135 140 145


2σ
1 σ
Observed CLs limit
Expected CLs limit
± 1σ
± 2σ
H→γγ
ATLAS Preliminary
Data 2011 √s = 7 TeV
∫Ldt = 4.9 fb-1
data
If no signal
95% CL limit on σ/σSM
mH [GeV]
110 115 120 125 130 135 140 145 150

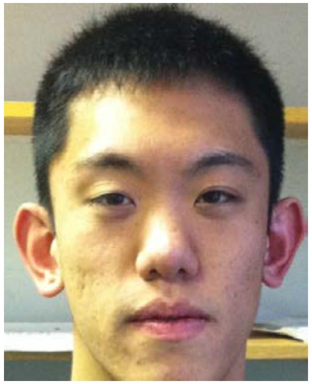
Discovery of Higgs boson → completes the Standard Model!

Also the properties of the observed Higgs boson imply we're on the right track to look for supersymmetry next at LHC

And I and my former and present students were able to do a successful generic ***string/M-theory prediction (last summer) of the mass and properties of the Higgs boson!*** – major test and validation of string theory as framework to understand our world

Piyush Kumar, Columbia

Ran Lu



Bob Zheng

Derivation of Higgs boson mass, properties in string/M-theories!

Look for string/M-theories compactified to 4D, and solutions that:

- Do not violate cosmology constraints, e.g. nucleosynthesis OK
- Have supersymmetric extension of SM, superpartners
- Have Higgs field in vacuum (ground state)

Such solutions generically predict that scalar superpartner masses needed to calculate Higgs mass are very large, which allows calculation of Higgs mass to be carried out

- In such solutions can generically calculate M(Higgs boson)/M(Z)

Prediction has no parameters, but some quantities only approximately known

- **→predicted Higgs boson mass $\approx$ 125 GeV**
- **Theory accuracy about 2%, experimental accuracy similar**
- **AND (surprising)** – SM has one Higgs boson – supersymmetric extension has several, perhaps with different properties – theory predicts the one that can be detected will behave very much like the SM one – also confirmed by LHC

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

More predictions for LHC underway

Consider some topics briefly:

- Multiverse, landscape?
- Why 10 dimensions?
- What is string theory?

String theory framework has *many* solutions ("landscape", multiverses)

- There *are* many solutions – also, once inflation occurs more universes grow and inflate off of earlier ones
- Some have argued that if there are many, then it is unlikely we can find one describing *our* vacuum
- Probably true if do it purely theoretically
- But it is not like 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
- "if you are looking for golf balls, first find golf courses" [Stuart Raby]
- 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)

Why 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 140 GeV – in string theory can derive and calculate precisely

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! – theory of gravity gives all meaningful results – can describe all particles and forces in mathematically consistent way – if 10D!
- An electron is still an electron, just described by equations for a string rather than for a point

String/M-theory addresses our questions about the physical universe, has testable answers, makes predictions for the Higgs boson and more including LHC and dark matter predictions, got the Higgs boson right! – people finding good candidates for *our* string vacuum

Backup slides

Cosmological constant problems (accelerated expansion of universe)?

-- ***naively*** far too large when calculated – explain actual value?

- 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 zero, and find no large effects – standard method

→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

Origin of universe? Why is there something rather than nothing? Being *addressed* too…

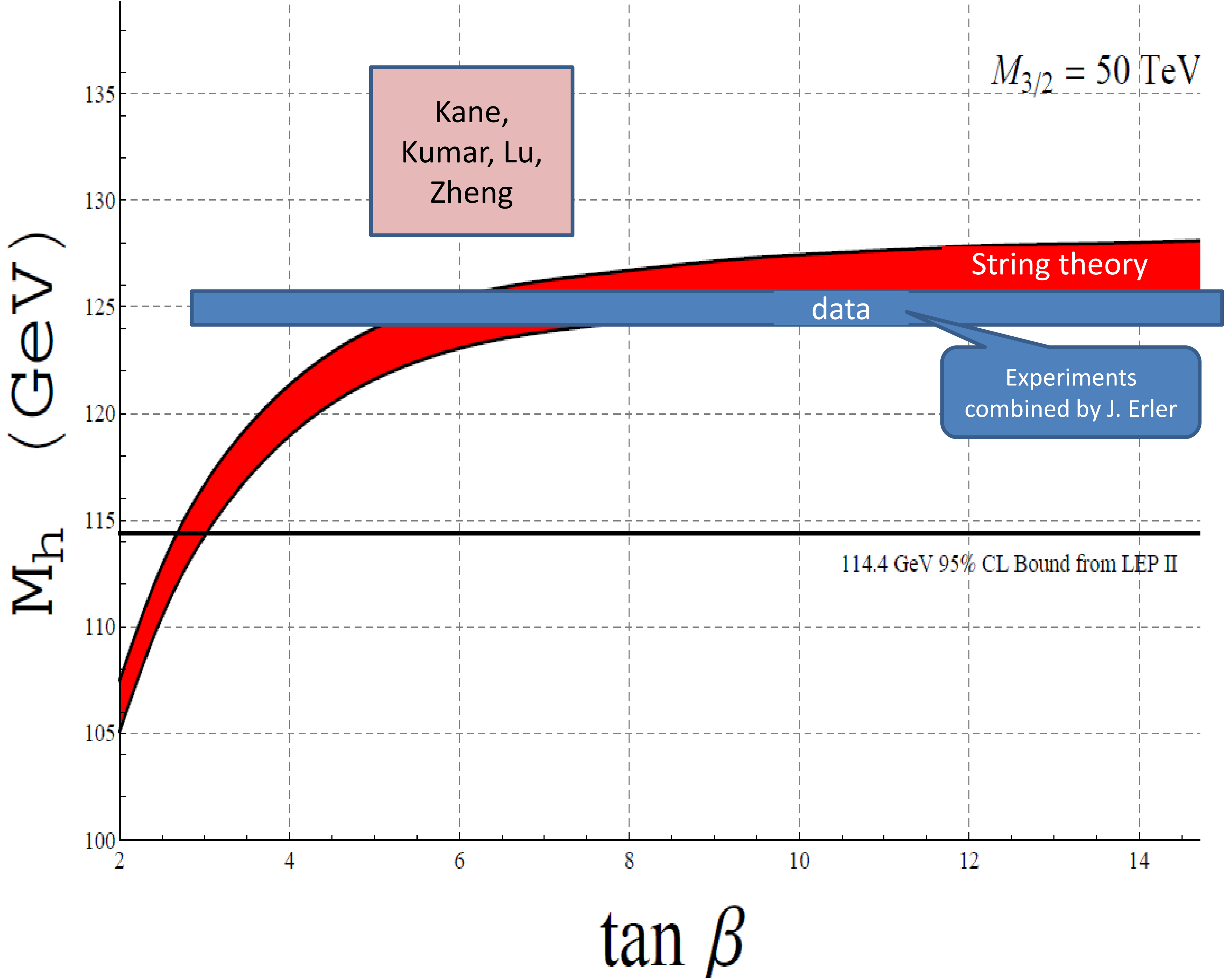
ALL WE KNOW IS CONSISTENT WITH SPONTANEOUS CREATION OF UNIVERSES
-- need mechanism without a cause, but expect that from quantum theory

- **IS THE UNIVERSE A VACUUM FLUCTUATION.** E.P. Tryon, 1973. 2pp.
- **IS IT POSSIBLE TO CREATE A UNIVERSE IN THE LABORATORY BY QUANTUM TUNNELING?** E. Farhi, A. Guth, J. Guven 1989, 67pp
- **CREATION OF A COMPACT TOPOLOGICALLY NONTRIVIAL INFLATIONARY UNIVERSE.** By A. Linde 2004

For example – Quantum fluctuations create particle-antiparticle pairs and fields temporarily from nothing – events without causes standard in quantum theory – creation of pairs may occur in varying gravitational field so particles move, can't find each other to annihilate – energy density – inflates – energy released in big bang, etc – total energy zero including gravitational field energy

From time to time universes begin, all the time – total energy zero, only truly free thing – *lots* of universes

R.I.P.



$M_{3/2}$ = 50 TeV
Kane, Kumar, Lu, Zheng
String theory
data
Experiments combined by J. Erler
114.4 GeV 95% CL Bound from LEP II
M_h (GeV)
tan β
135
130
125
120
115
110
105
100
2
4
6
8
10
12
14

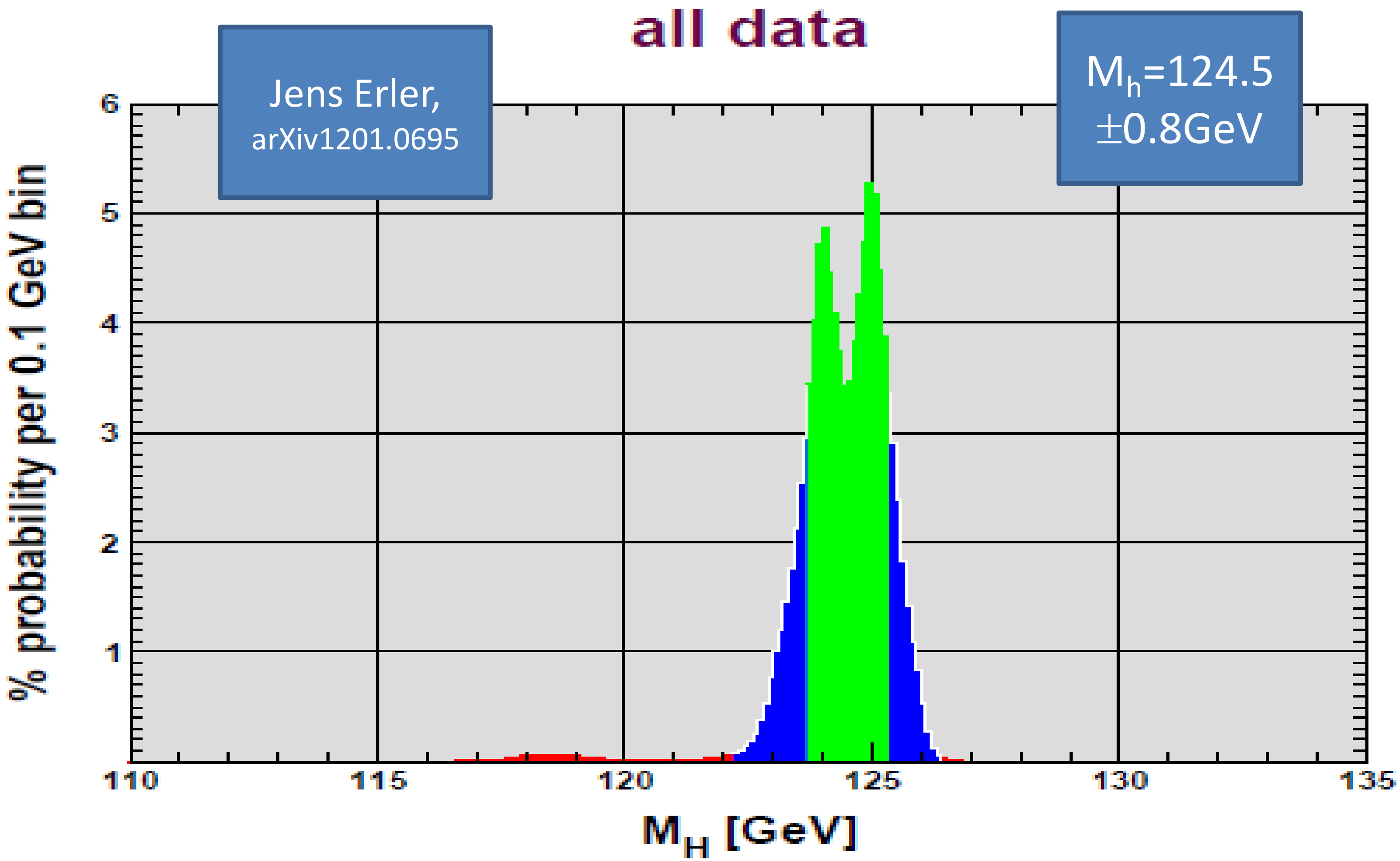


FIG. 3. The normalized probability distribution of M_H in the low mass region based on all data. Shown in green (blue) is the 68% (98.2%) CL highest probability density region.

More technically

– compactifications generically have moduli fields that describe sizes and shapes of curled up manifold

– moduli quanta have to be heavy to avoid inconsistencies with cosmology

– gravitino mass generically connected to moduli mass

– scalars (squarks, Higgs “soft-breaking masses”) connected to gravitino mass

– from scalars can calculate Higgs boson mass and properties

Martinus Veltman, Universities of Michigan and Utrecht.
"You are mistaken about the Higgs search at Cern. The machine runs at half energy so far, and no one expects relevant (for the Higgs particle) results. After the shutdown [in 2013] the machine will gradually go up in energy, and if all goes well (this is non-trivial) then in about half a year the machine energy might reach design value and there might be Higgs-relevant results. So if you are thinking next week then you are mistaken. Of course, we never know what surprises nature has in store for us … **It is my opinion that there is no Higgs.“**

December 6, 2011, Manchester Guardian