STRING THEORY AND THE REAL WORLD

-- string phenomenology, amazing opportunity

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“String theorists have temporarily given up trying to make contact with experiment”

String phenomenology? – don’t know what string theory is, how can it have a phenomenology?

- Theory/phenomenology distinction not present in most fields

“The Trouble with Physics – the rise of string theory, the fall of a science, and what comes next”

Introduction – from the Standard Model(s) to extra dimensions

Unanswered questions beyond the SM

String phenomenology – examples, tests

Define string theory –

Any theory that might be a consistent quantum theory of all four forces (gravity, strong, weak, electromagnetic), with the forces acting on particles that emerge from the theory and include our quarks and leptons

Turns out require 10 (or 11) dimensions, natural size is Planck scale ~ 10^{-33} cm [so focus on such small extra dimensions].

Standard Models of particle physics and cosmology are remarkable description, at a fundamental level, of all that we see

STANDARD MODEL OF PARTICLE PHYSICS

- Fundamental form of matter is quarks and leptons – final form
- Interactions via electromagnetic, weak, strong forces (+ gravity) – form of forces determined by theory
- Includes Maxwell’s equations, atomic physics, condensed matter physics, etc
- No basic puzzles, contradictions (but depends on Higgs physics being correct)
- Few parameters – 3 force strengths (“gauge couplings”), Higgs field strengths, some quark and lepton masses
- Quarks bind into hadrons (proton, neutron, etc), p and n into nuclei, nuclei and electrons into atoms, atoms into molecules, molecules into people and coffee and flowers – not just metaphors

HIGGS PHYSICS – last piece of SM

- Accommodating parity violation in the Standard Model implies electrons and quarks are massless

- That’s because electrons and quarks inhabit an “electroweak” space – in that space, left-handed (L) electrons and quarks behave as if they had “EWspin” ½, and right-handed (R) ones as if they had “EWspin” 0

- *Not explained in SM, but accomodated -- that’s just how it is* (this is one of the things we would like to explain)

- Then if e,q have mass, can go to their rest frame, rotate ordinary spin so L ↔ R, but then they have the wrong EW spin, so inconsistent – basically only two ways out
  - e, q massless
  - Add Higgs field with EWspin ½, and claim that energy of universe is lower when that higgs field has non-zero value than when zero – allows RH electron to behave as if had EWspin ½
  - Jargon – Higgs field has non-zero “vacuum expectation value”, breaks the EW symmetry!

- Technically the Higgs physics add-on to the SM works fine
- If Higgs field exists, then quanta of field must exist, Higgs bosons

- Good indirect evidence they do exist! – from LEP electron-positron collider at CERN, 1991-2001 – measured accurately about 20 quantities that should be described by the SM – all SM parameters known except Higgs boson mass – so do fit to all data with one parameter – get good fit if m_h below about 160 GeV
- Also W mass vs top quark mass

Two Independent Analyses!

Should be observed at LHC, or before at Fermilab

STANDARD MODEL OF COSMOLOGY -- REMARKABLE

- The universe begins very small, contains some (unstable) energy density, and 3 space dimensions inflate
- After very short time energy density converts into “radiation”, i.e. (massless) particles → Big Bang
- Universe cools and expands – today ~ 4% neutrons and protons (ordinary matter), ~ 25% dark matter, ~ 70% dark energy
- Description works from world around us to the edge of the observable universe, back to 10^{-35} sec (or even earlier) after universe began – successfully describes structures too

THERE IS MUCH THE STANDARD MODEL(S) CANNOT EXPLAIN

- Neither cosmology nor the SMs can tell us what the dark matter is
- Neither cosmology nor the SMs can explain the matter asymmetry
- Neither cosmology nor the SMs can tell us what the dark energy is
- Neither cosmology nor the SMs can tell us the physical nature of the inflaton field
- The SMs *cannot* tell us why there are 3 families of leptons and quarks
- The SMs *cannot* give us insight into how to unify gravity and the other forces
- The SMs *cannot* explain the origin of the Higgs physics
- The SMs *cannot* allow calculation of the electron or muon or quark masses
- The SMs *cannot* describe neutrino masses without adding a new mass scale
- *The SM has a quantum hierarchy problem, very serious*
- The SM cannot explain parity violation

Remarkably, in past 2-3 decades, have learned that if we hope to understand these things the direction we need to go is to embed our 4D world in additional space-time dimensions

Two approaches show great promise for explaining what cosmology and the Standard Model(s) cannot:

- Supersymmetry – for every space-time dimension add a quantum dimension
- String theory – add 6(7) space dimensions like ours, except that ours inflated, others didn't – all 10 D have a quantum dimension too

Learned from LEP (electron-positron CERN collider) –

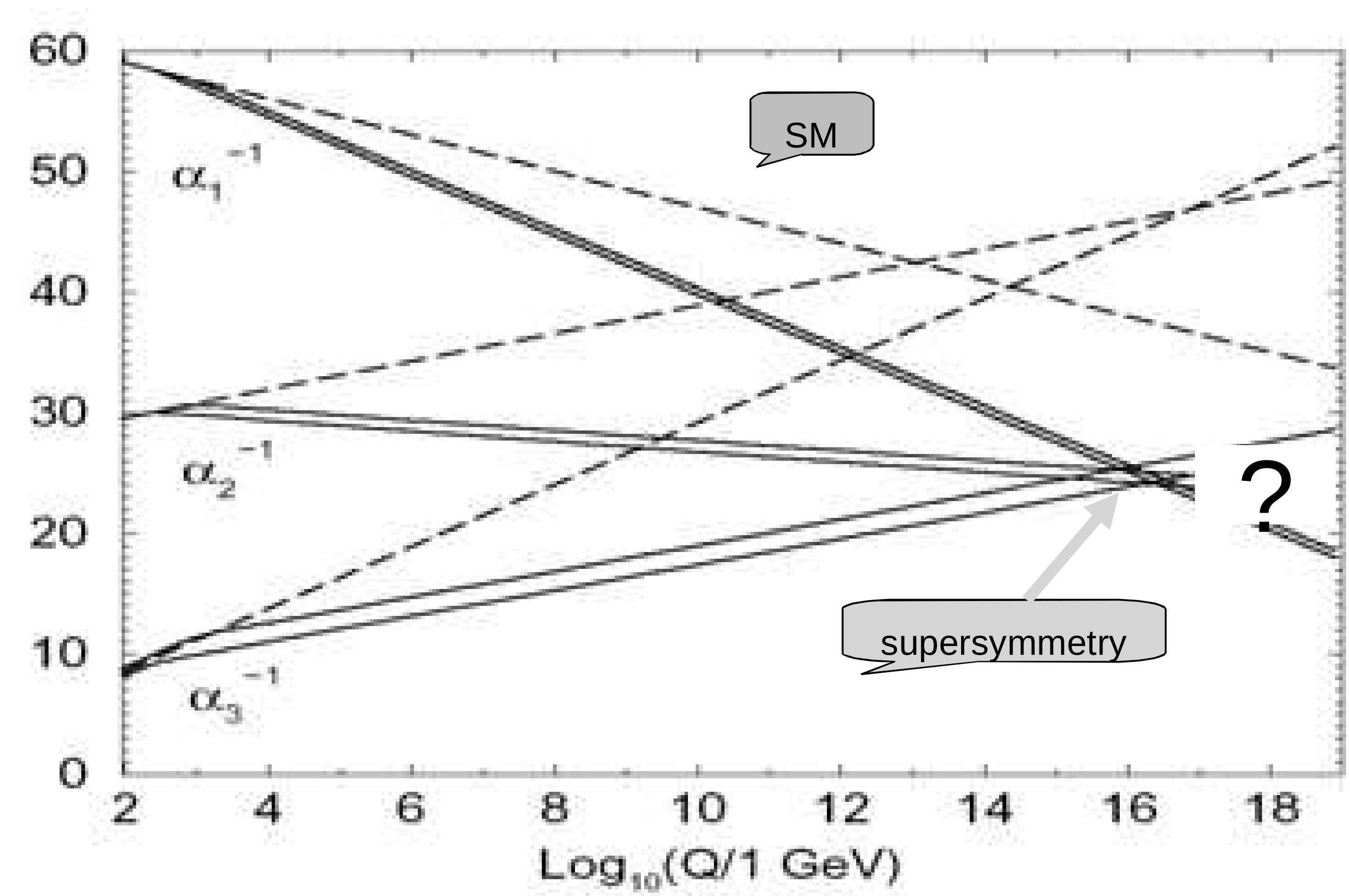
- Upper limit on m_{higgs} ~ 160 GeV
- No deviations from SM predictions at 0.1% level
  → whatever physics explains Higgs physics is probably perturbative, weakly coupled
- Gauge coupling unification
- (Only three light families)

The first 3 strongly suggest supersymmetry

$=e^2/4$

h=c=1

Suggests (1) Theory simpler at ~ 10^{16} GeV
(2) High and low scales connected perturbatively



HIERARCHY PROBLEM!

- In quantum theory, every particle spends some time as virtual combinations of all other particles

- For technical reasons, scalar (spin zero) particle (Higgs bosons) masses are quite sensitive to masses of the virtual particles (but spin ½ fermions or force particles g, W, Z, g are not sensitive)
- So Higgs boson masses driven up to the highest scale of particles and interactions – presumably Planck scale or unification scale
- Masses of e, W, Z, etc proportional to Higgs mass, so all masses should be that heavy

Hierarchy can be stabilized if theory is supersymmetric

- Imagine particle – go around several times, returning wave function to initial place – particles are bosons or fermions if wave function does not (does) change sign [bosons are particles with integer spin, fermions with half integer]
- This is tied to being in 3D – imagine a “superspace” dimension for each of our space-time dimensions
- Then can go into extra dimension and untwist fermion to get boson (or vice versa) – spin changes by ½ unit

- So every fermion gets a superpartner boson, and vice versa

Suggests the idea of supersymmetry (~1973):

THE LAWS OF NATURE DON'T CHANGE IF BOSONS ↔ FERMIONS IN THE EQUATIONS DESCRIBING THE LAWS

Originally very surprising – matter particles (e,u,d…) were fermions, force particles (**g**,g,W,Z) were bosons – in quantum theory they were treated very differently – the idea was studied just to see if it could work

Only idea in history of science that emerged purely from theoretical study rather than from trying to understand data, puzzles, observations – studied because it was a beautiful idea

TURNED OUT IT COULD EXPLAIN MAJOR PROBLEMS

(SOME OF) WHAT SUPERSYMMETRY MIGHT DO FOR UNDERSTANDING THE NATURAL WORLD:

- 1979 Stabilize the quantum hierarchy

  -- particle and superpartner have same mass for unbroken supersymmetry, and fermion mass not sensitive, so scalar mass stabilized

  -- quantum contributions of fermions, bosons have opposite sign, so cancel if superpartner masses not very different from partner masses

→ Superpartner masses can be ˆ 1000 GeV or so and no hierarchy problem

SO ASSUME SUPERPARTNERS ~ 1 TeV -- THEN CAN DERIVE MUCH:

- 1982 Explain Higgs physics
- 1983 Explain why the forces look different to us in strength and properties, but become the same at high energies, so we can make sense of the idea of unifying their description
- → 1983 Provide a dark matter candidate (the lightest superpartner)
- 1991 Allow an explanation of the matter asymmetry of the universe
- 1992 Explain why all current data is consistent with the Standard Model(s) even though we expect new physics at the weak scale

ALL SIMULTANEOUSLY

ALL AFTER INTRODUCTION OF SUPERSYMMETRY

In addition there are theoretical motivations:

- If supersymmetry is a local symmetry it implies General Relativity – if Einstein had not invented General Relativity it would have been (i.e. it was) written in 1975 by studying supersymmetry

  -- supersymmetry transformation affects spin – spin part of angular momentum – generators of angular momentum transformations part of Poincare group – connects to gravity equations

- String theory probably requires supersymmetry if it is relevant to understanding nature

IF SUPERSYMMETRY RELEVANT, SUPERPARTNERS MUST BE DISCOVERED AT COLLIDERS, SUCH AS TEVATRON, LHC

Selectron

photino

gluino $\tilde{e}$

stop squark

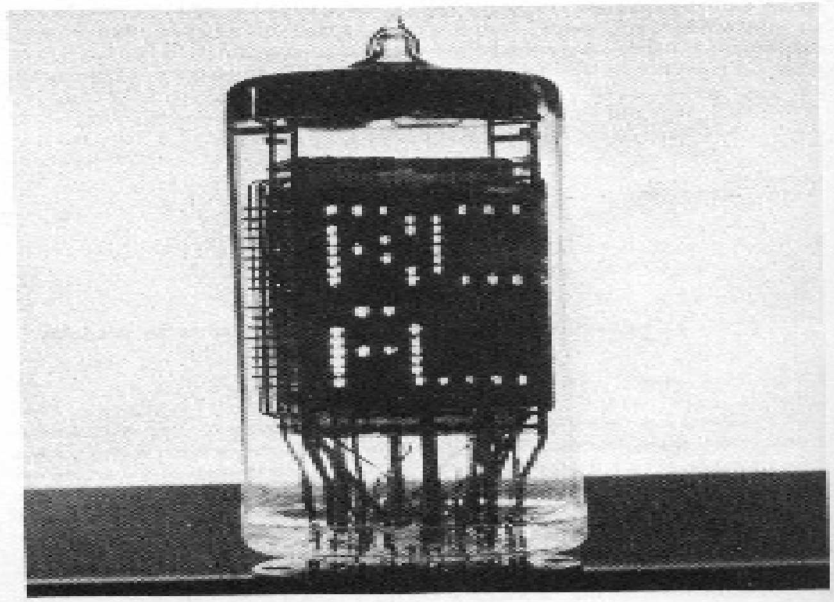
sneutrino etc $\tilde{\gamma}$

They differ by spin ±1/2 and mass from their SM partners

A WHOLE SLANGUAGE $\tilde{g}$

9 - 2 The Selectron

The selectron is a new type of electrostatic storage tube for the registration of on—off signals. The development of this tube was undertaken to meet the need for such a storage or memory device in high—speed, electronic computing machines of the digital type, such as the computer under development at the



The latest model of the selectron tube; the illuminated elements are remembering "on", the dark elements "off". Half of the elements are on the opposite side of the tube and cannot be seen.

Institute for Advanced Study, under the direction of Professor John von Neumann. Early samples of the selectron were designed to register 4096 signals. However, in a subsequent re—evaluation of the mathematical requirements for such a tube for the Institute for Advanced Study computer, it was found that a tube capable of registering a considerably smaller number of signals would be acceptable.

Supersymmetry is a full mathematical theory

Can summarize the perturbative SM by a set of vertices for Feynman diagrams: let

f=e,μ, ,d,s,b,u,c,t l$^{\pm}$=e$^{\pm}$,μ$^{\pm}$, $^{\pm}$ U=u,c,t D=d,s,b

= $_{e}$, $_{\mu}$,

Then all the (perturbative) phenomena in nature that we see involving fermions are described by gravity plus the four vertices:

To make the theory supersymmetric, add the vertices with particles turned into superpartners in pairs, all ways

Everything is known about the supersymmetric SM except the masses of the particles – no theory (except maybe string theory) can predict masses from first principles

γ e^+ e^-

The lightest superpartner (LSP) is very important phenomenologically

- Superpartners produced in pairs at colliders
- LSPs at end of superpartner decay chains
- LSP can be partner of photon, Z boson, Higgs boson, neutrino, gravitino (could calculate this if superpartner masses known)
- LSP interacts at most weakly, electromagnetically
- LSP normally stable

  -- every event has 2 LSPs, both escape detector
- Missing energy a basic signature of superpartners

LSP may also be the dark matter of the universe!

- Big Bang, universe cools – after a while only

  g, e, u, d, , LSP remain

ν

- Calculate relic density of LSPs – some annihilate, e.g.

nuclei

atoms

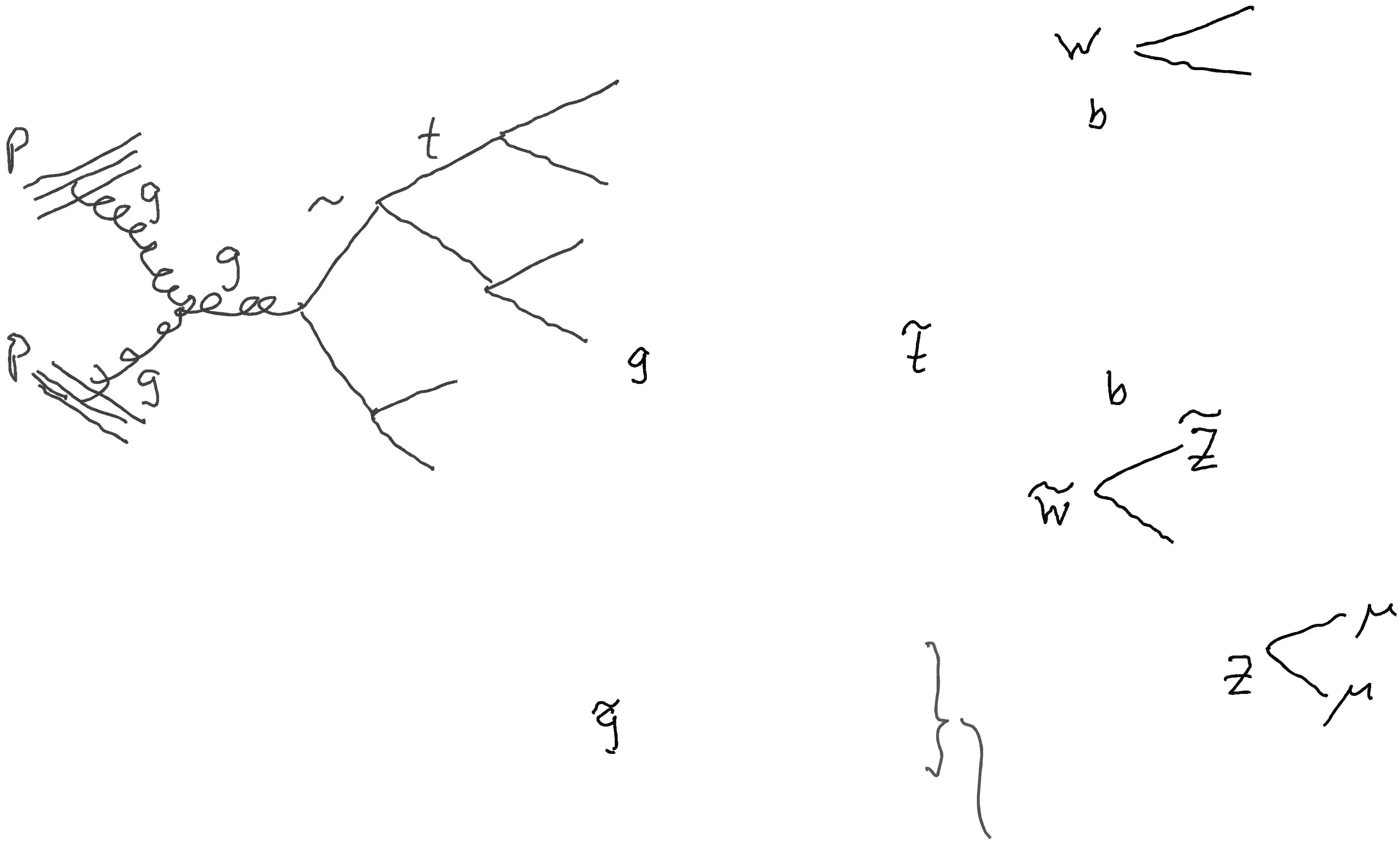
- Need to know superpartner properties to work out numbers – for reasonable values, answer about right

WHAT DATA COULD SOON GIVE EVIDENCE FOR SUPERPARTNERS?

- DIRECT observation of superpartners at Tevatron, LHC
- Indirect, expected from supersymmetry
  - Laboratory dark matter detectors
  - Electric dipole moments of e,n
  - Muon anomalous magnetic moment
  - Lepton flavor violation ($\mu \rightarrow e$ …)
  - $B_s \rightarrow \mu\mu$ at Tevatron or LHC
  - $A_{CP}(B\rightarrow \quad K) \neq \sin(2 \quad)$ at b factories

Collider signatures of superpartners:

e.g.



Large Hadron Collider (LHC)

- 7xTevatron energy,
- ~100x Tevatron luminosity

- Cooling down – below temp of outer space
- Fall 07, commissioning
- October 07, two beams, collisions
- Spring 08, physics run
- Collide protons, 0.9999999 speed of light – produce new particles, interactions

!

CAN WE TEST IDEAS LIKE SUPERSYMMETRY, STRING THEORY?

-- supersymmetry, clearly

-- string theory??

- Distinguish theory from solution

  -- e.g. in quantum theory write Schrodinger equation for a particular Hamiltonian, solve it, test solutions against data

- Testing solutions tests theory

- Don't need to be there to test – always relics – BB, speed of light, dinosaurs

- Test, "see" small extra dimensions?
  - Total energy of world is zero, but for 10D world or 4D?
  - Cosmology of 4D world different from that of 10D world
  - Energy conserved in 10 D or 4D? Maybe particles escape into other D

- Proof? … beyond a reasonable doubt…

- Time scale? Decades – usually best tests come after theory – electromagnetism → light outside visual, radio waves – Big Bang → helium abundance, CMB

Examples of such tests from string theories:

- Inflation
- Cosmic strings – cosmic because magnified by inflation
- Dark matter – not protons, neutrons etc
- LHC – superpartners, Z¢
- Neutrino masses

Inflaton?

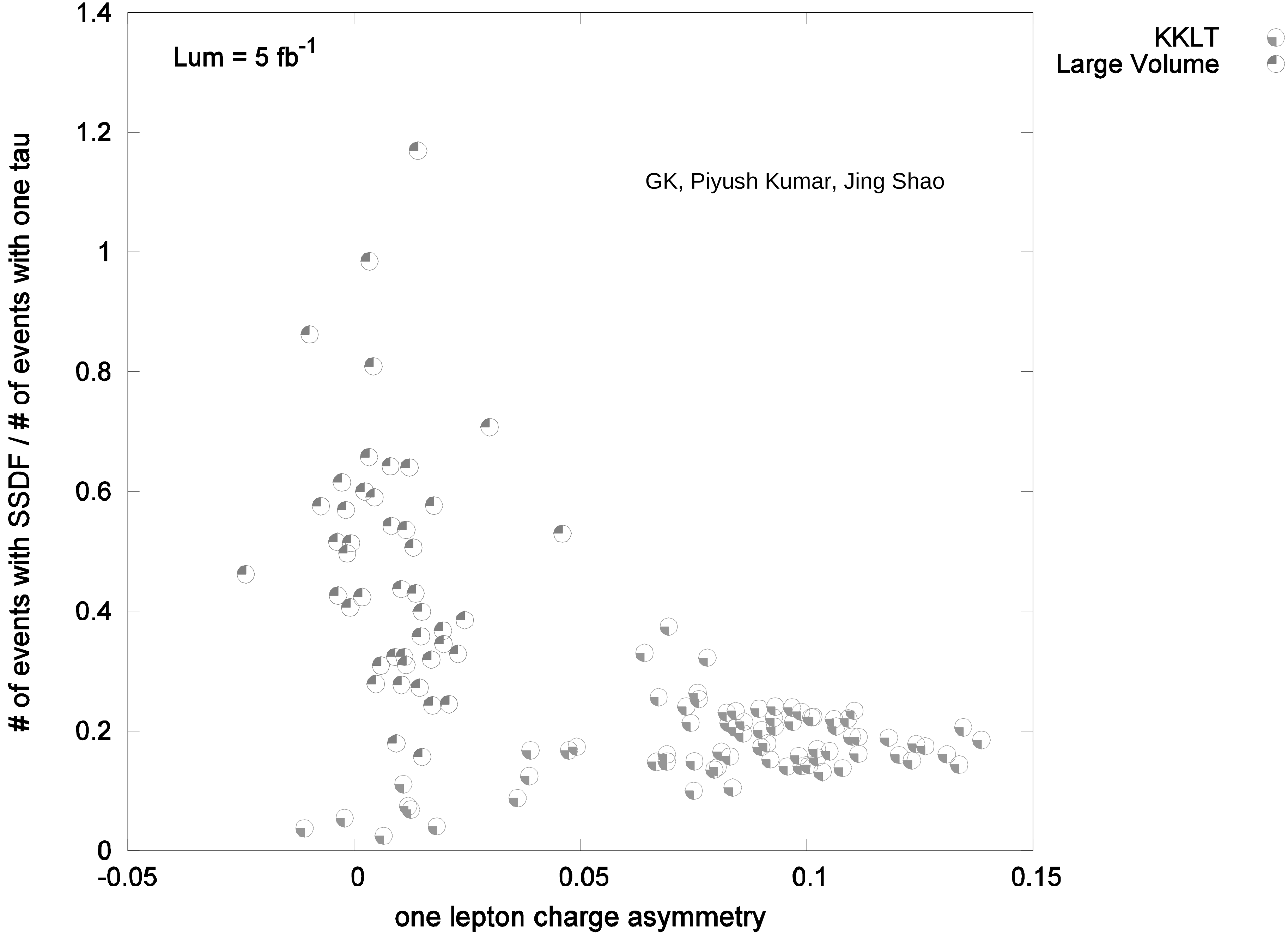
- ~ 1986 suggested that scalars associated with sizes and shapes of regions of small dimensions ("moduli" could be inflaton(s) [Binetruy, Gaillard] – problems with stabilizing them, now under control

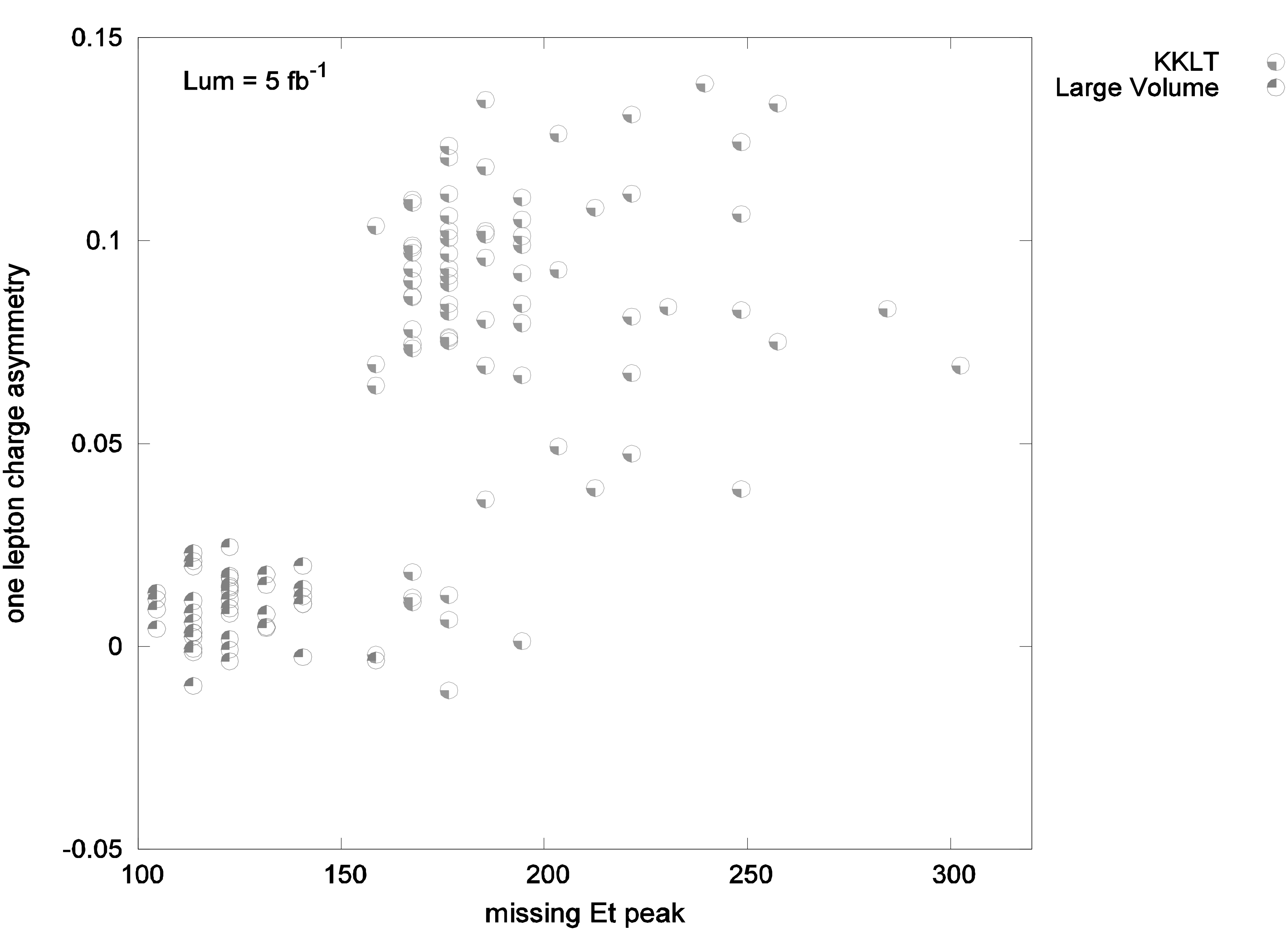
- Inflaton is spacing between "branes", or brane and boundary [Tye, Dvali…]

- Study suggests that essentially all string theories have tensor structure perturbations much smaller than scalar ones, too small to detect

LHC?

- Start with full string theory
- Guess way to “compactify”, characterize small dimensions
- Embed SM and supersymmetric extension
- How is supersymmetry broken
- Construct 4D theory at unification scale
- Calculate Lagrangian at weak scale, predict superpartner masses
- Repeat for different compactification, different way to break supersymmetry
- Look at LHC signatures of each, vary any parameters (all from stringy and supersymmetry-breaking)
- Footprints different!


KKLT
Large Volume
Lum = 5 fb^{-1}
GK, Piyush Kumar, Jing Shao
# of events with SSDF / # of events with one tau
one lepton charge asymmetry
0
0.2
0.4
0.6
0.8
1
1.2
1.4
-0.05
0
0.05
0.1
0.15



Lum = 5 fb^-1
KKLT
Large Volume
one lepton charge asymmetry
missing Et peak
0.15
0.1
0.05
0
-0.05
100
150
200
250
300

Each of those compactifications, supersymmetry-breaking methods gives an LSP

Add its relic density, direct detection to tests

Neutrino masses a good probe of string theory (Giedt, GK, Langacker, Nelson)

- So far no explanation, or derivation of light neutrino masses from string theory (or any theory)
- Take a class of string theories, particular compactification
- Mass term in Lagrangian is product of LH and RH fields (Dirac), or two RH ones (Majorana)
- LHn in SU(2) doublets with electron, μ , **t**
- Identify all RHn and their charges under all symmetries
- Find all operators that could give Majorana and/or Dirac masses allowed by full gauge invariance and symmetries of theory
- Construct n mass matrix
- Eigenvalues small but non-zero?
- For Heterotic string compactified on Z_3 orbifold, No such solutions!

SOME QUESTIONS

√ ***addressed***

√√ answered, ***explained***

~ accommodated

	Standard Model(s)	Supersymmetric SM(s)	String theories
What form is matter?	√		
What *is* matter			Ö
What is light?	√√		
What interactions give our world?	√		√
Gravity			√√
Stabilize quantum hierarchy?	~	√√	
Explain hierarchy?			√
Unify force strengths?		√√	
Higgs physics?		√	√
What is dark matter?	~	√	√
Baryon asymmetry?	~	√	√
More than one family? 3?	~	~	√
Values of quark, lepton masses?	~	~	√
Origin of CP violation?		√	√
What is the inflaton?		√	√
Dark energy?			√
Cosmological Constant Problem?			√
What **is** an electron? Electric charge?			√
Space-time?			√
Why quantum theory?			√
Origin of universe?			√

When string theory does not address or explain, it's because the sub-theory already does

"String phenomenology" is the subfield that studies all the above questions

“explain” – property emerges without being put in – constructing a different and equally arbitrary approach that gives the result being “explained” does not count

If didn’t know about proton, SM would predict it, and it’s charge, spin, mass (~15% now) ***-- inevitable***

If didn’t know about dark matter, supersymmetry would have predicted it, made us look for it – that’s what actually happened for dark matter not made of protons and neutrons

If didn’t know about gravity, families, gauge theory of forces, string theory would have suggested them

WE LIVE IN A STRING THEORY VACUUM, GROUND STATE!

Probably lots of solutions of string theory
-- i.e. many vacua universes might live in

- Strengths of forces, particle masses, different in each?
- Some inflate, have Big Bang?

Implications?

- ***What do we want to understand?***
  - -- standard model(s) of particle physics and cosmology
  - -- supersymmetry, supersymmetry breaking
  - -- dark matter
  - -- matter asymmetry
  - -- dark energy
  - -- families of particles
  - -- quark and lepton masses hierarchical
  - -- higgs physics

And more, are the laws inevitable? Is our world unique? Extra dimensions?

I think we will be able to understand, test our understanding, calculate the things we want to understand