

SUPERSYMMETRY, STRING THEORY, AND OUR QUEST TO LEARN THE UNDERLYING LAWS OF NATURE

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OUTLINE

- Some things we've learned about the physical universe
- The Standard Models of particle physics and cosmology
- What more do we want to understand about the physical universe?
- What ideas may let us gain that understanding – supersymmetry and string theory
- LHC – testing understanding
- Testing string theory
- What do/might the Standard Models and supersymmetry and string theory explain?
- Unifications of understanding

➤ WHAT HAVE WE LEARNED ABOUT THE PHYSICAL UNIVERSE?

- there is very good evidence for the whole list
- not metaphors, quantitative theories

- The universe is governed by a few (or maybe even one) irreducible universal natural laws that describe all there is and all that happens in the natural world – people can discover and understand them 😊

- The universe formed as a tiny region of energy density, then expanded very rapidly (“inflation”) – energy density unstable, turned into matter particles (“Big Bang”) – universe expanded and cooled – matter clumped, formed galaxies, stars and planets – carbon, oxygen, and other elements necessary for the chemistry of life on earth were made in stars that exploded before our earth formed

- All we see in the universe *is* made of just three fundamental particles (electrons, up quarks, down quarks), interacting via a few forces
- quarks combine via the strong force to make protons and neutrons,
- they combine via the residual strong force to make nuclei
- nuclei and electrons combine via the electromagnetic force to make atoms
- atoms bind via the residual electromagnetic force into molecules, which combine to make people and flowers and chocolate
- Nuclei and atoms make planets and stars

- The quarks and electrons in us are essentially all from the Big Bang, and many have been in every person who ever lived 😊

➤ The universe and the earth and life have histories – each began and developed – we mostly know and understand these histories 😊

(began to be known for earth few centuries ago, for life maybe two centuries ago, for universe less than a century ago))

- There is much we do not see – the world is not just the part of it that humans evolved to sense
 - Electromagnetic spectrum extends beyond visible
 - 4 forces, we sense only two
 - Small things – viruses...atoms...quarks
 - Extra dimensions?

We extend our awareness with technology – telescopes, microscopes, cameras, detectors

TODAY SOME BIG QUESTIONS ARE ANSWERED, THE REST ARE BEING *ADDRESSED* SCIENTIFICALLY

- first time in history – exciting time

- usually when topics become subjects of scientific research they become understood within decades

- while developing, an area changes, maybe a lot, then eventually settles down (e.g., sound and heat are motion of atoms, everything around us is made of atoms, age of universe, sun works by fusion, origin of 92 chemical elements), becomes textbook science

- while it's changing there are lots of ideas that are tested, and data that needs confirmation

Research **I**n **P**rogress

Science is about *understanding*

What do we want to understand?

What are we and the things around us made of?

Why are there protons and nuclei and atoms?

Where do stars and galaxies and the universe come from, how do they work

What makes life possible?

Etc.

Today, after about 400 years, we have achieved the “Standard Model(s) of particle physics and of cosmology” – actually answers most of those questions

Amazing progress

- When Shakespeare wrote there was no understanding of how any aspect of the natural world worked!
- Today a full quantitative description of the world around us, of all that we see!
 - Matter is made of electrons + quarks that interact via electromagnetic, strong, and weak forces to make the world around us
 - “Relativistic quantum field theory” of these forces (plus gravity)
 - Universe is composed mainly of electrons + quarks matter, **dark matter**, and **dark energy**

We have *description*, and *how*, but most **why** missing

There is much more we want to understand

- What is the dark matter
- Why is the universe made of matter, not antimatter?
- What is the dark energy?
- What causes inflation?
- Why are there the forces (gravity, strong, weak, electromagnetic) and can we relate them?
- Why are there more particles?
 - Extra quarks, muons, neutrinos, Higgs bosons
 - We know how the extra particles behave, but not why they exist

And even – are the underlying laws of nature inevitable? – is our world unique?

The goals of science have changed in past ~20 years! Now that we have the Standard Models we can formulate the “why” questions

What ideas beyond the Standard Model(s) can explain such questions?

Supersymmetry

String theory

Are they enough? – Maybe!

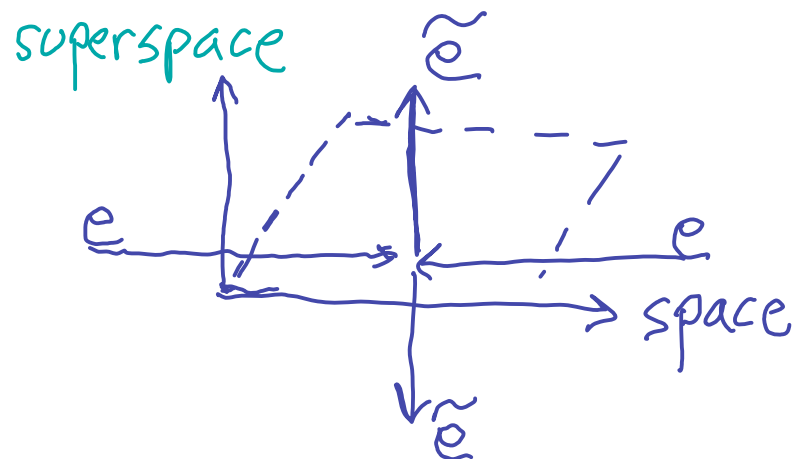
SUPERSYMMETRY

We know our world is described by the rules of quantum theory

But we don't describe our space dimensions by those rules

Supersymmetry is the idea that for every space dimension there is an associated quantum dimension, and that the laws that describe nature don't change if you interchange those dimensions

If you collide two particles, e.g. electrons, with enough energy, you can knock them into the quantum dimensions, where they become their "superpartners" – e.g., selectrons



Every particle should have a superpartner if this is right

A complicated slide...about supersymmetry successes

- ❑ The Standard Model has a conceptual problem:
 - To be a complete theory consistent with experiment the SM requires a new kind of particles to exist, a Higgs boson (good evidence it does)
 - In quantum theory all particles spend some time connecting to other particles “virtually”
 - Higgs boson masses are very sensitive to masses of particles they connect to, and can lead to huge masses [*the “hierarchy problem”*]
 - But in a supersymmetric theory this problem is solved – contributions of particles *plus* superpartners is not sensitive to the other masses!
- ❑ Superpartners remember they are superpartners, but are unstable and decay to lighter superpartners plus SM particles – but no lighter one for lightest superpartner [LSP] to decay to so it is stable
 - very good candidate for dark matter of universe!
- ❑ In SSM [supersymmetric SM] may be able to explain matter asymmetry
- ❑ In SSM have candidates for “inflaton”

And more...

ALL SIMULTANEOUSLY

ALL REALIZED AFTER SUPERSYMMETRY INTRODUCED

MAYBE NEXT BIG DISCOVERY

So supersymmetry can allow a universe where protons are so small, and stars so large, and people in between

The lightest superpartner may also be the dark matter of the universe!

- Big Bang, universe cools, unstable particles decay – after a while left with only

$\gamma, e, \underbrace{u, d, \nu}_{\text{quarks}}, \text{LSP}$

$\eta, p,$
nuclei

atoms

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

Selectron \tilde{e}

photino $\tilde{\gamma}$

gluino \tilde{g}

stop squark \tilde{t}

sneutrino $\tilde{\nu}$ etc

They differ by spin $\pm 1/2$ and mass from their SM partners

A WHOLE SLANGUAGE

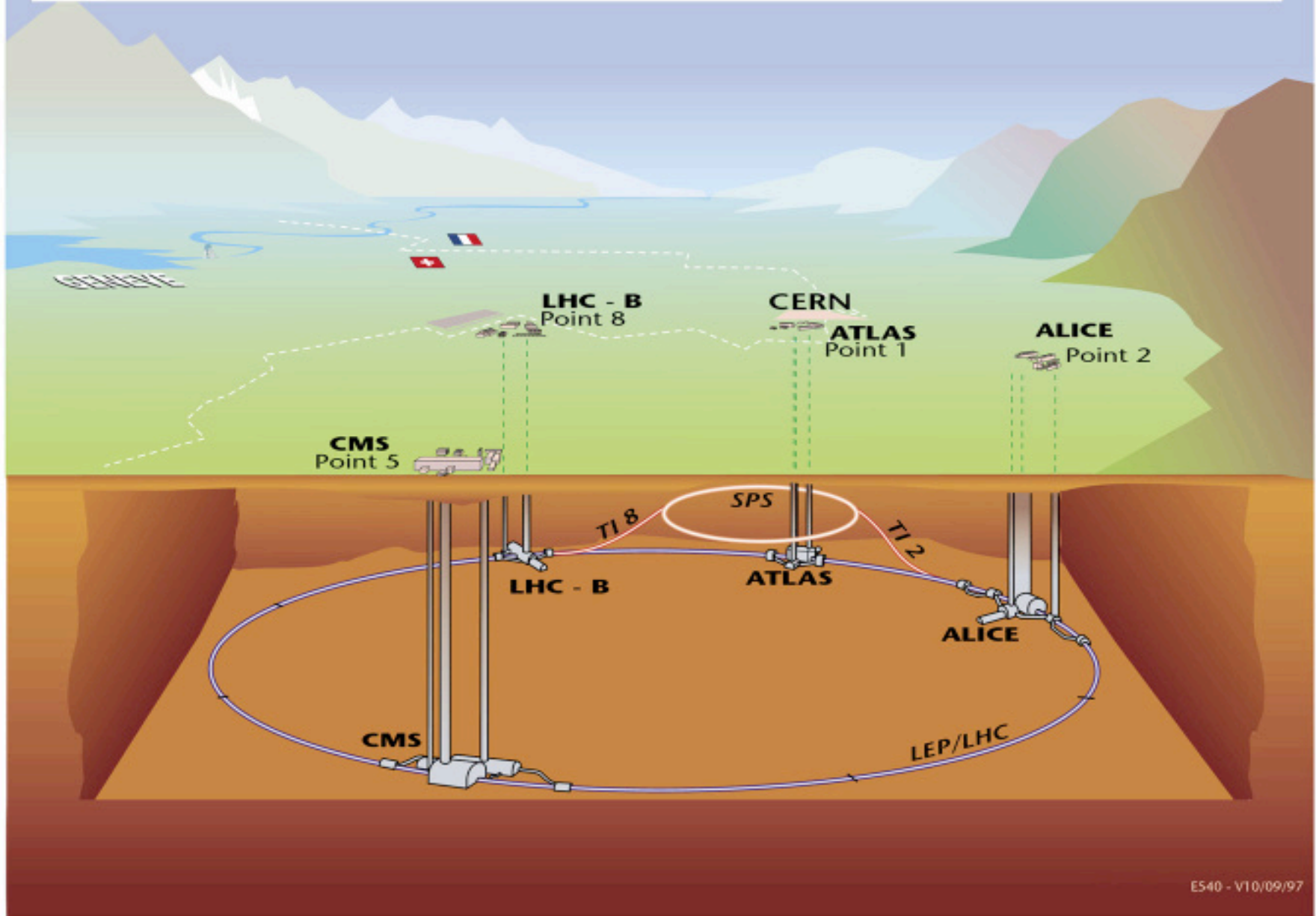
LHC (Large Hadron Collider, CERN, Geneva)

-- extraordinary scientific device – “why” machine

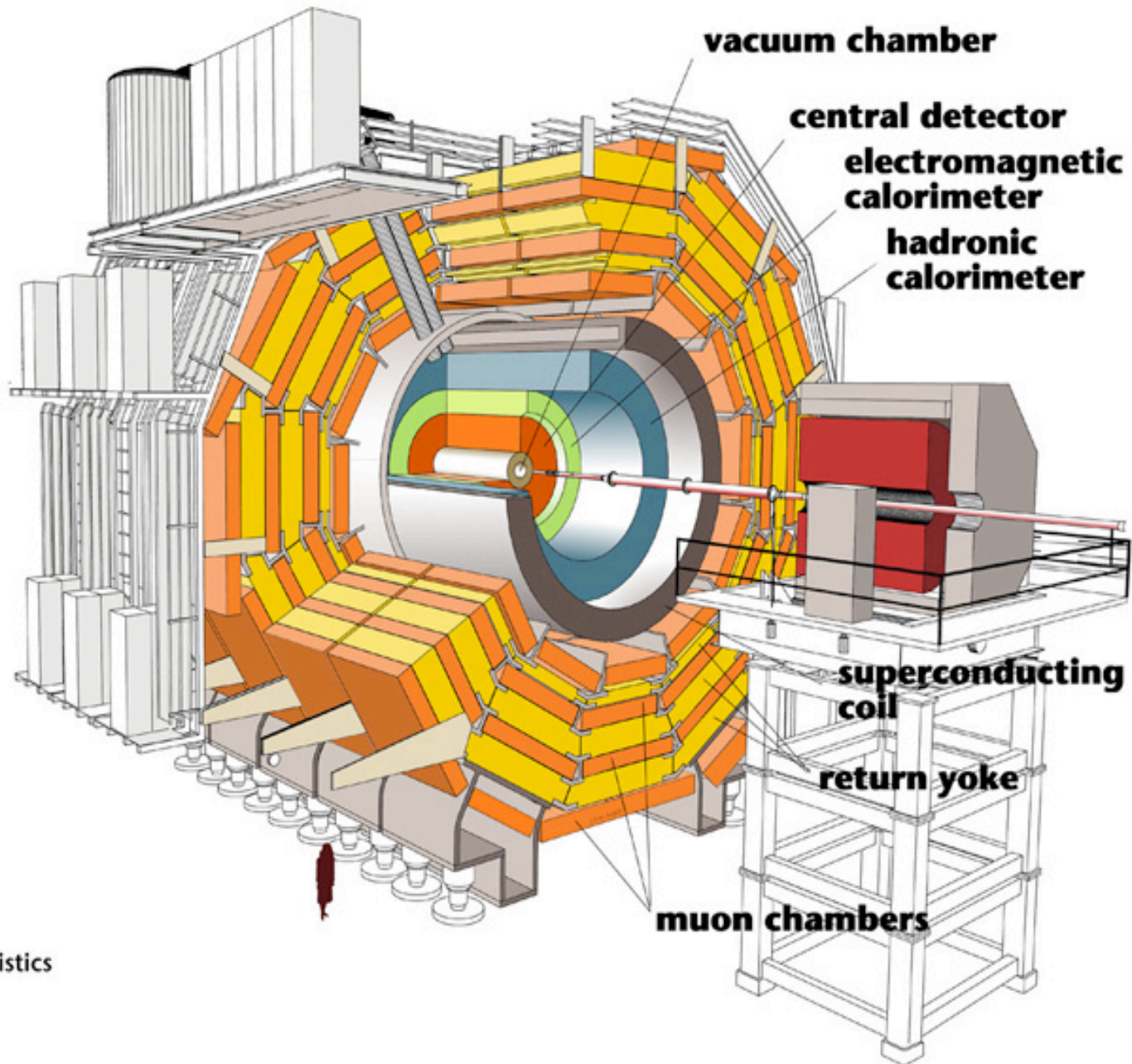
- Want to study particles and their interactions – not so much for their own sake, but because they tell us stories we can interpret
- Accelerate protons, collide them, inside a “detector” – take a picture of what comes out, look for new things
- 10^{11} bytes a second, more than all telecommunications on earth – every second for years
- Billion collisions a second, less than one “interesting”
- Hopefully find superpartners (2008), Higgs bosons (2009)
 - still maybe first detect them at Fermilab collider



Overall view of the LHC experiments.



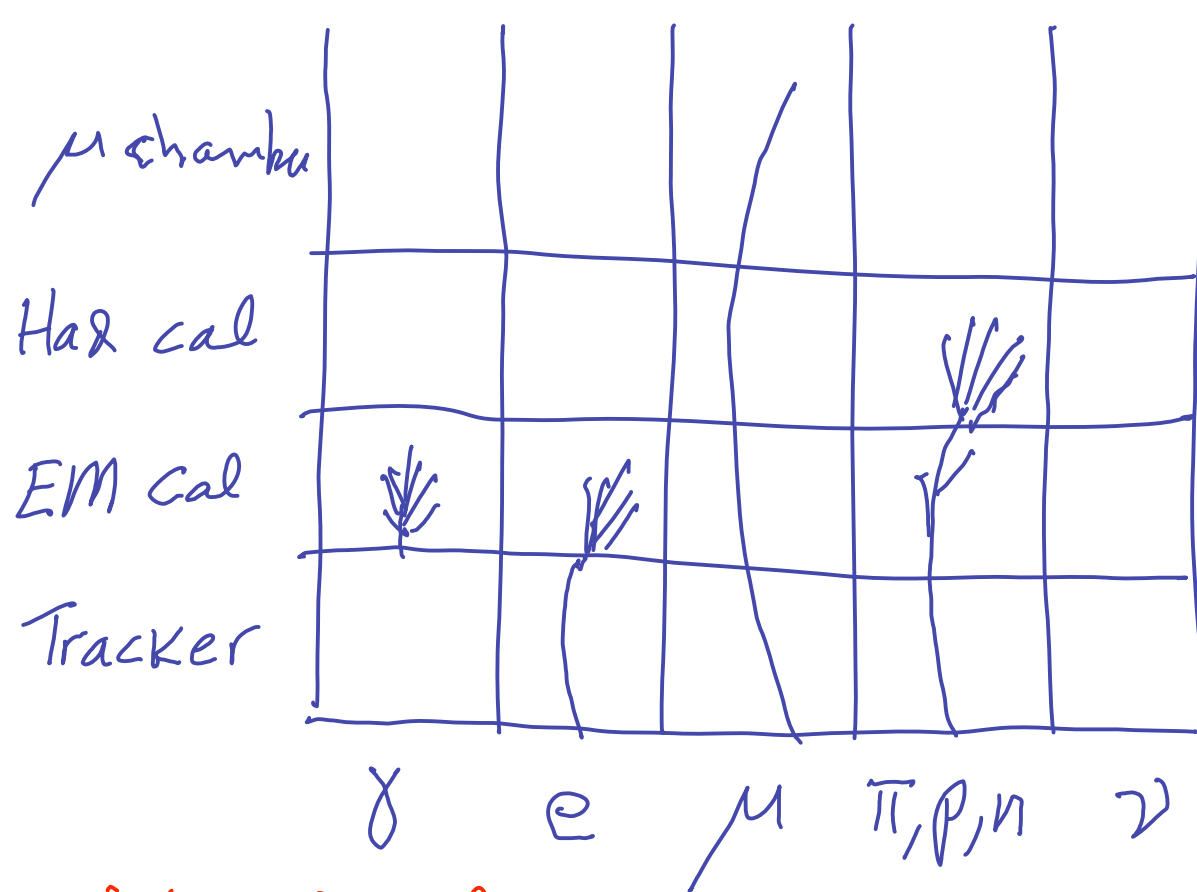




Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

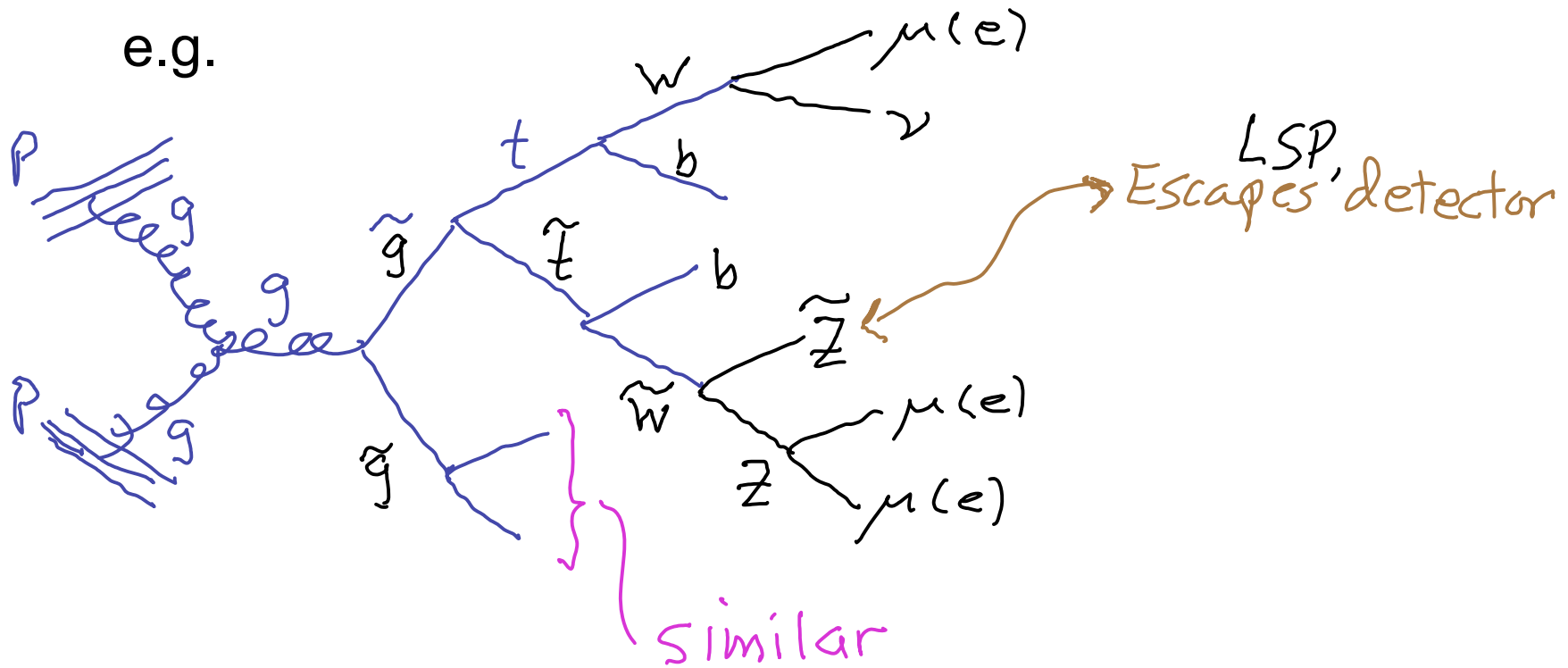
Detector



particles with electric charge curve in magnetic field

Collider signatures of superpartners:

e.g.



→ 4 b's, 6 Q^\pm , large missing P_{Trans}

NO SIMILAR SM EVENTS

STRING THEORY

A quantum theory consistent with general relativity, and incorporating the electromagnetic, strong, and weak forces, and the particles these forces act on are leptons and quarks that the theory requires to exist

Possible to write such a theory, IF ten dimensions!

Reinterpret electron as a string of energy density instead of a point particle, but still an electron

Contains Supersymmetric Standard Model

Test string theory?

- Distinguish theory from solutions

Suppose theory is $a+b=16$

Solutions $a=8, b=8$; $a=12, b=4$; $a=4, b=12$; etc

Which solution describes nature? Why?

Can test if solutions describe nature, but not theory as such

- Test $F=ma$? No, not directly, must specify F – pick a force, test for lots of forces
- Testing solutions tests theory
- Don't need to be there to test – always relics – Big Bang, speed of light, dinosaurs
- ...beyond a reasonable doubt
- Test, “see” 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
- Time scale? Usually decades – best tests often come after have theory, e.g. for electromagnetism light outside visible spectrum, radio waves – for Big Bang, helium abundance, cosmic microwave background radiation
- String theory addresses, makes predictions about, inflation, LHC, neutrino masses, supersymmetry, dark matter, cosmic strings, and much more

“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)

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

~ accomodates

✓ addresses

answers, explains

SMs

SSMs

string theory

QUESTIONS

Gravity

#

what form does matter take

#

What is matter

✓

What is light

#

What interactions give our world

~

✓

Stabilize quantum hierarchy

#

Explain hierarchy

✓

Unified understanding of forces

#

Higgs physics

~

#

✓

Explain higgs physics

✓

✓

What is dark matter

~

#

✓

Why matter asymmetry

~

#

More than e,u,d (3 families)

~

✓

What causes inflation (universe old, cold, structured)

✓

✓

Dark energy

✓

No large cosmological constant

✓

Space-time, quantum theory, universes

✓

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

-- zero total energy

- **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.

ANOTHER PERSPECTIVE – UNIFICATIONS

-- 400 years ago many forces, phenomena – then unified understanding of:

- Motion on earth and in heavens
- Motion and heat
- Motion and sound
- Electricity and magnetism
- Different forms of energy
- Everything we see made of atoms
- Chemistry and physics
- Everything we see made of electron and quarks
- Electromagnetism and light
- Space and time
- Special relativity and quantum theory
- Electromagnetism and weak interactions
- “Grand” unification of strong, weak, and electromagnetic interactions?
- String theory – grand unification plus gravity plus quarks and leptons?

Einstein’s goals of understanding achieved (if correct...)

All cultures addressed big questions – for thousands of years invented myths – no myth considered idea the universe or life could arise in an extremely simple form and evolve over a long time into a beautiful and complex system

Myths are satisfying -- science testable, and right or wrong -- and satisfying too! – understanding *why* 😊

-- universe is old and cold and dark, and maybe has extra dimensions – but now we understand that life only possible if universe old and cold and dark (and has extra dimensions?) 😊

-- humans evolved to need to understand – so understanding the world can be a source of confidence and dignity 😊

