Course evaluation Wednesday, Review Friday

Final Exam

- Thursday, Dec. 21: 2:45 - 4:45 pm
  113 Psychology Building
- Note sheet: **one** double-sided page
- Cumulative exam-covers all material, 40 questions
  - 11 questions from exam 1 material
  - 11 questions from exam 2 material
  - 11 questions from exam 3 material
  - 7 questions from post-exam 3 material

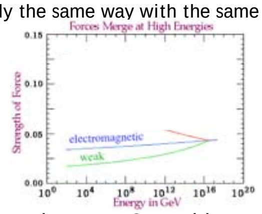
Study Hint: download blank hour exams from web site and take them closed-book, with note sheet only. Solution for Exams will all be posted this week.

From the last time…

- The forces
  - Matter particles interact via the forces according to the types of charge they carry.
  - Each force carried by a particle.
  - Matter particles are fermions, force carriers are bosons. Described by quantum field theories.
- Unification
  - Noticed that electromagnetic force and weak force carried by Z boson are nearly identical.
  - At high energy they are identical. Same types of interactions and same strength
  - Requires an extra particle. The Higgs boson.

Symmetry and Symmetry breaking

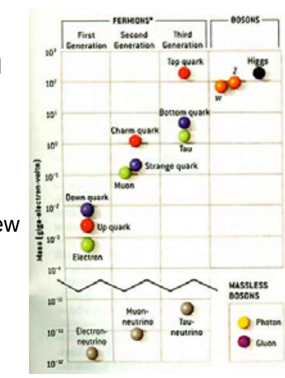
- The standard model says that at high energies, this **symmetry** is apparent
  - We see a single electroweak interaction.
  - Z^0 and γ interact exactly the same way with the same strength.
- At low energies the **symmetry** is **broken**
  - We see distinct electromagnetic and weak interactions



- However needs one more element. Something to give the W and Z mass

Mass

- Here's the experimental masses of SM particles.
- Original SM gives zero mass for all particles.
- But can give particles mass by coupling to a new field, the Higgs field.
- Higgs boson is the (unobserved) quanta of the Higgs field.

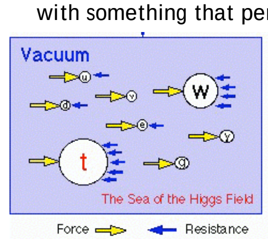


What is mass?

- Think of inertial mass:
  - inertial mass is a particle's resistance to changes in velocity.
- When you apply the same force to particles, the smaller the mass, the larger the acceleration.
- What is the origin of mass?

Mass in the SM

- In the standard model (SM), particles have mass because they interact with something that pervades the universe.



This something is the Higgs field

Particles 'hit' the Higgs field when you try to accelerate them

Mass = $\underbrace{\text{(chance of hit)}}_{\text{Coupling constant}}$ x (Higgs density)

Mass and the Higgs field

Imagine a party in a room packed full of people.

Now a popular person enters the room, attracting a cluster of hangers-on that impede her motion

she has become more massive

The Higgs boson

The Higgs boson is a quantum excitation of the Higgs field.

In analogy, suppose an interesting rumor is shouted in thru the door.

The people get quite excited.

They cluster to pass on the rumor, and the cluster propagates thru the room.

Looks very similar to the popular/massive person who entered the room

Good way to think of other quantum excitations. All the other force carriers

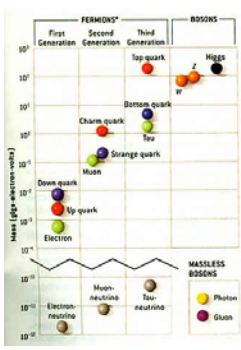
The Higgs Boson

How much mass do you thing the Higgs Boson has

A. No mass

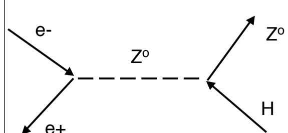
B. Light like an up or down quark

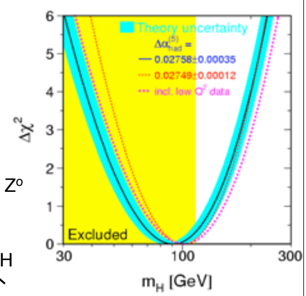
C. Very massive like a top quark



How can we 'see' the Higgs?

- The Higgs boson needs to be created in order to see it. $E = mc^2$
- Not found yet
- m_H > 114GeV
- m_H < 186GeV





Grand Unified Theories

- What do we really need to unify particle physics?
- Maxwell unified the electric and magnetic interactions into electromagnetic (EM)
- The standard model unified the EM and weak interactions into the electroweak interaction
- Start with the strong force.
- What kind of theory is needed to unify this?

Not all that easy

"Putting a box around it, I'm afraid, does not make it a unified theory."

Grand Unified Theories

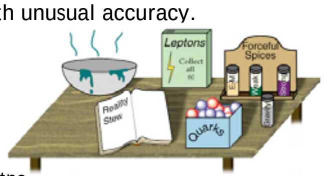
- Flavor changing interactions in quarks (e.g. changing a top quark to a bottom quark by emitting a W^+) suggest that quarks can be viewed as different ‘orientations’ of the same object.
- Have found the same thing for leptons.
- But maybe there should be a lepto-quark field?
  - Quarks could turn into leptons, leptons into quarks
  - All matter particles would be different ‘orientations’ of the same fundamental object.
- If we unify leptons and quarks then weak and strong forces may be shown to be two aspects of one force.

The price of unification

- When the SM unified EM and weak interactions, we ended with more force-carrying bosons (e.g. the Z^o)
- This is because our fundamental ‘particle’ increased in complexity
  - e.g. from an electron to an electron-neutrino pair
- If our ‘particle’ now encompasses both leptons and quarks, the interaction also becomes more complex.
- In one particular GUT, we get 24 exchange bosons (W^+,W^-,Z^0, photon, 8 gluons, and 12 **new** ones)

Beyond the standard model?

- Standard model has been enormously successful.
- Consistent picture of particles and their interactions.
- Predictive power with unusual accuracy.



- Questions:
  - Why 3 generations?
  - What determines all the mass values and interaction strengths?
  - Can we relate the quarks and leptons and the forces?

What does the SM say?

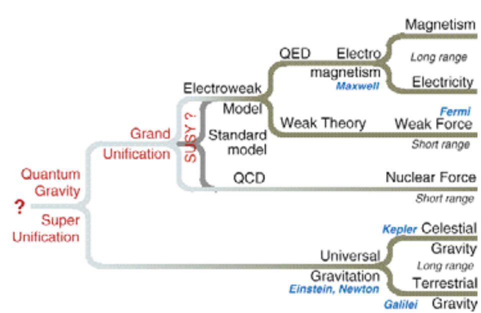
- We can calculate how interactions would work at energies like those of the big bang.
  - **The results don’t make sense.**
- Astrophysics observations indicate that there is more mass in the galaxy and universe than we can see: Dark Matter
  - **No standard model particle could explain this**.
- All the standard model interactions create electrons and positrons or quarks and antiquarks in pairs.
  - However, everything around us is made of quarks and electrons. **Where did the positrons and antiquarks go?**

None of these things can be explained by the SM!

<u>G</u>rand <u>U</u>nified <u>T</u>heories: GUTs

- Unify all the forces: strong force and gravity
- Quantize the forces - QFT very successful
- Unify the particles: quarks, leptons - 3 generations
- Explain all the different masses and strengths
- Explain dark matter
- Explain why universe is mostly mater
- Explain physics at very high energy - big bang

Unifications: now and the future



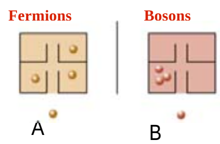
Fermions and bosons

- Matter (fermions) and forces (bosons) behave differently.

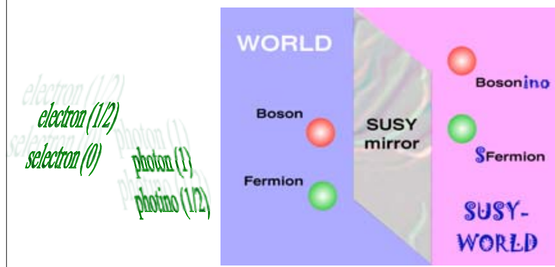
Which drawing below best represents fermions?

$\boxed{\text{A. A}}$

B. B



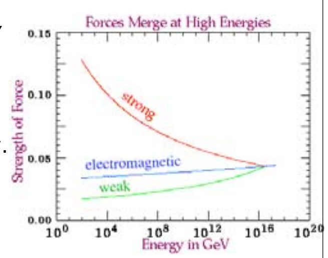
Supersymmetry (SuSy)



Superpartners (compare to anti-particles)
Every fermion has a boson partner and vice versa
Starts to relate the fermions and bosons

Supersymmetry Successes

- Designed to explain behavior at very high energy
- Forces merge in SUSY
  - Same strength at high energy.
- Lightest SUSY particles don't decay.
- Dark Matter



Checklist SUSY

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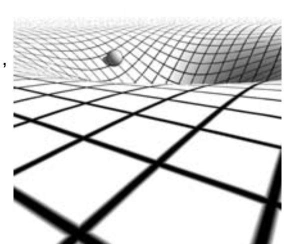
Gravity

- Haven't talked recently about gravity.
- Gravity not particularly relevant at the scale of particle physics, because the particles are not massive enough to interact gravitationally.
- But shouldn't we be able to explain gravity in framework as particles and interactions?
- Can't we unify both quantum mechanics and gravity into a theory of everything?

Einstein's gravity

General Relativity is a classical theory.

- Einstein was a classical guy, even though he received Nobel for photoelectric effect, general theory of relativity has nothing to do with quantum mechanics.
- General relativity has to do with curved space-time, and motion of objects in that curved space time.



Gravity Question

What fundamental property of gravity makes it so hard to fit in with the other forces?

A. Gravity is so weak.

B. Gravity is only attractive.

C. Gravity has infinite range.

D. Mass and weight are different.

Gravity is only attractive.

How can you have a mass charge?

Opposite charges attract.

If you have two objects with a plus and minus mass charge then a third object should be repelled by one and attracted to the other.

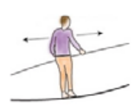
Kaluza-Klein: EM & gravity

- Connect electromagnetism and gravity in a classical relativistic theory.
- Kaluza and Klein found a theory in five dimensions (four space & one time) with one interaction (5-dimensional gravity).
- When one of the dimensions was 'compactified', two interactions resulted: gravity and electromagnetism.
- What appears to us as two distinct interactions originate from only one.

Kaluza & Klein, 1920

Extra dimensions?

- How can there be extra dimensions?
- Can imagine more physical dimensions, but we do not see them
- We would be unaware of them if they were very small, e.g. very strongly curved a la GR



An acrobat can only move in one dimension along a rope..

...but a flea can move in two dimensions.

The 2nd dimension was curved so much we do not notice it.

Compactificaton in Kaluza-Klein

- The process of 'rolling up' the extra dimension to leave four space-time dimensions…
- …made the 5-dimensional geometrical gravitational interaction appear as two different interactions in 4D:

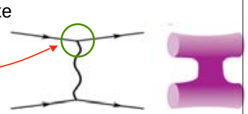
Electromagnetism — Gravity

Another unification!

QFT and GR don't mix

Gravity waves

- GR leads to gravitational waves.
- These are classical waves that should appear as particles in a quantum field theory.
- But "quantizing" GR gives untamable infinities
- **Interactions** in QFT are point-like



Point-like and smeared interactions

Checklist Kaluza-Klein

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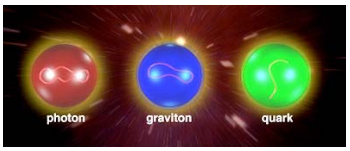
String theory

- A string is a fundamental quantum mechanical object that has a small but nonzero spatial extent.
- Just like a particle has a mass, a string has a ‘tension’ that characterizes its behavior.
- Quantum mechanical vibrations of the string correspond to the particles we observe



•Strings can vibrate in different ways, can be quantized also!

For example:

Guitar string

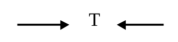
Different vibration → Different sound!

•Fundamental string

Different vibration → Different particles!

What are these strings?

We describe them only in terms of a fundamental tension – as for a rubber band



How big are they?

A particle of energy E has a wavelength

$$E = h\, c / \lambda = 1240 \text{ eV-nm} / \lambda$$

So can probe down to scales of order λ…. So far we’re down to much less than the size of atomic nucleus… strings could be much smaller!

Scales we can probe

As high energy experiments went up in energy they were able to probe smaller and smaller distances scales - Atoms, nucleus, quarks.

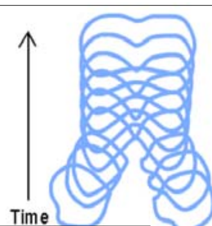
The Fermilab Tevatron operates at 1TeV. What length scale can it probe?

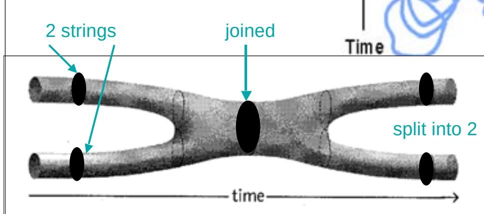
A. 1.24 nm
B. 1.24 pm
C. 1.24 fm
D. 1.24 am

The nucleus is order fm, femto-meters. Current experiments can look for things 1000 times smaller than than. Strings could be up to 10^{19} smaller.

String Interactions

- Strings interact by joining and splitting





Some problems

- Strings are collections of points — an infinite number of points
- This can make for very complex behavior.
- Theory for a classical relativistic string worked
- But quantizing the string leads to a physical theory only in 26 dimensions!

Results of the theory

- The first string excitation is a particle with *imaginary* mass — a tachyon (negative mass squared = negative energy)
  - Could go backwards in time: seems unlikely!
- But the next excitation is a massless spin-2 particle satisfying general relativity
  - The graviton!
- So string theory became a theory of gravity

Superstrings

- Combine string theory with some of our other theories.
- Imposing supersymmetry on strings gets rid of the tachyon - it is no longer a solution.
- Additionally, the number of dimensions required for consistency drops from 26 to 10!
- Fundamental object is now a 'superstring'
- Get some of results of SuSy
  - Fix behavior at high energy
  - Dark matter

Extra dimensions in string theory

- Superstring theory has a 10 dimensional spacetime,
- How do we get from 10 dimensions down to 4?
- Introduce some of the ideas from Kalaza-Klein theory
  - Roll up the extra dimensions into some very tiny space of their own.
    Kaluza-Klein compactification.
- Add some of the advantages of Kaluza-Klein theory
  - Unification of electromagnetism force and gravity

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