# PHY492: Nuclear & Particle Physics

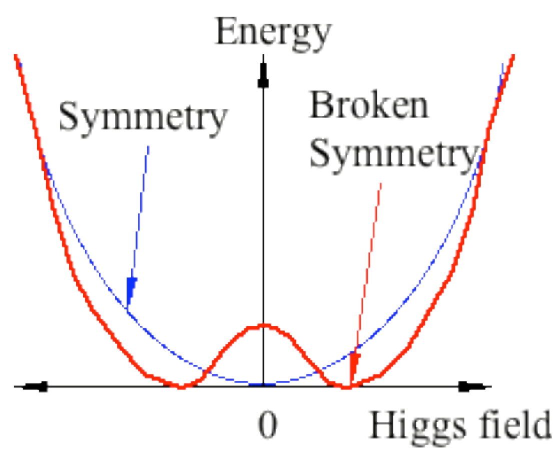
## Lecture 22

Way Beyond the Standard Model
Particle Detectors

# Dynamical symmetry breaking, the Higgs Mechanism

- Weinberg, Glashow & Salam (UNIFICATION OF EM and WEAK)
  - Basic theory has 4 *massless* bosons: triplet $W_1$,$W_2$,$W_3$, and singlet B
  - Dynamical Symmetry Breaking via the Higgs Mechanism
  - $W_1$, $W_2$ become $W^{\pm}$, but $W_3$, and B mix with "Weinberg angle" = $\theta_W$

$$\gamma = B^0 \cos\theta_W + W_3 \sin\theta_W$$
$$Z^0 = -B^0 \sin\theta_W + W_3 \cos\theta_W$$




  - W and Z masses are related

$$m_W / m_Z = \cos\theta_W$$

  - $\theta_W$ measured in neutrino scattering

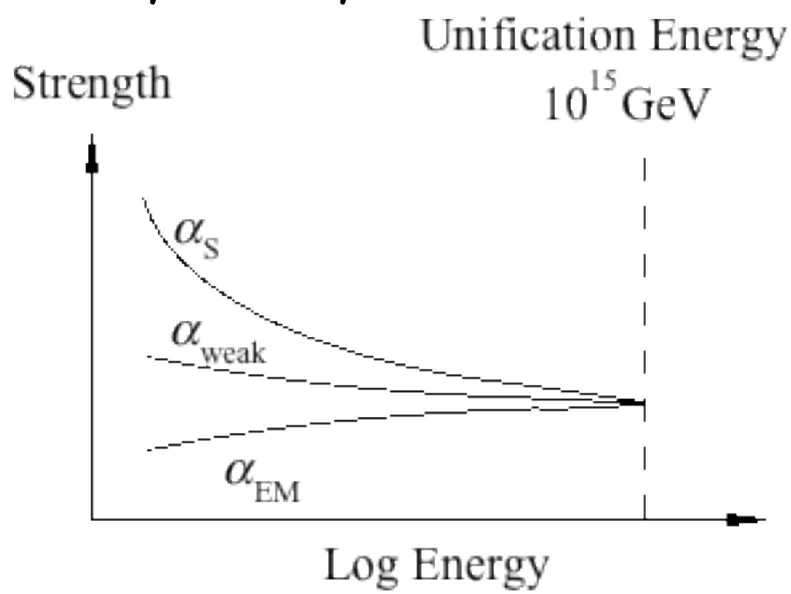
$$\sin^2\theta_W = 0.233$$

  - Predict: $m_W / m_Z = 0.88$ $\quad m_W / m_Z = 80.4/91.2 = 0.88$

- Simplest dynamical symmetry breaking would have 1 Higgs scalar (spin 0) particle $H^0$ $\quad 200\text{ GeV} > m_H > 115\text{ GeV}$ — experimental limit

# Grand Unified Theory (GUT)

- At very high energies everything would be highly symmetric
- All masses and couplings would be the same
- At low energies the symmetry is broken



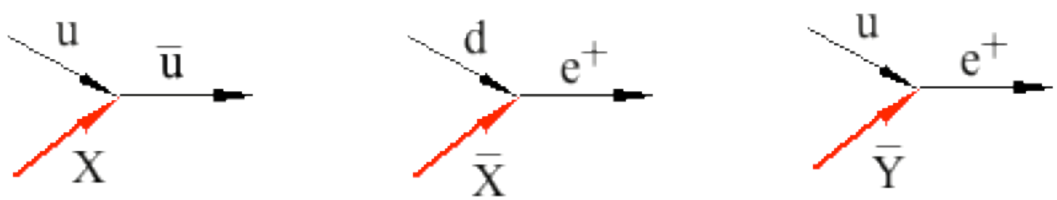

- EW group is SU(2)xU(1): 4 gauge bosons ($\gamma$, $W^+$, $W^-$, Z)
- QCD group is $SU(3)_{color}$:8 gauge bosons(gluons)
- Simplest GUT is SU(5): ---> 24 gauge bosons (12 more bosons)
- What about Gravity !

# SU(5) has 12 more gauge particles

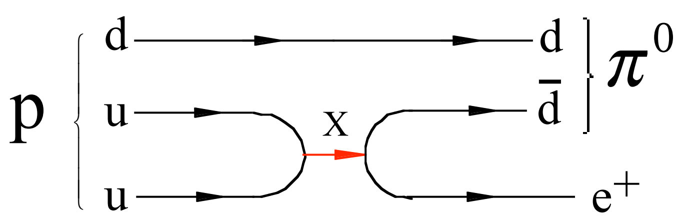
- Three with charge =-1/3, in three"colors" ($Y_R$, $Y_G$, $Y_B$)
- Three with charge =-4/3, in three"colors" ($X_R$, $X_G$, $X_B$)
- Six anti-particles of these

- These gauge particles can change quarks into leptons or change quarks into antiquarks

Examples




- Can lead to proton decay (lifetime is < $6\times10^{30}$ years) N.G.




Measured lifetime lower limit > $10^{31}$ - $10^{32}$ years

- Some success. But no proton decay, no 3 generations, has monopoles

# Supersymmetry (SUSY)

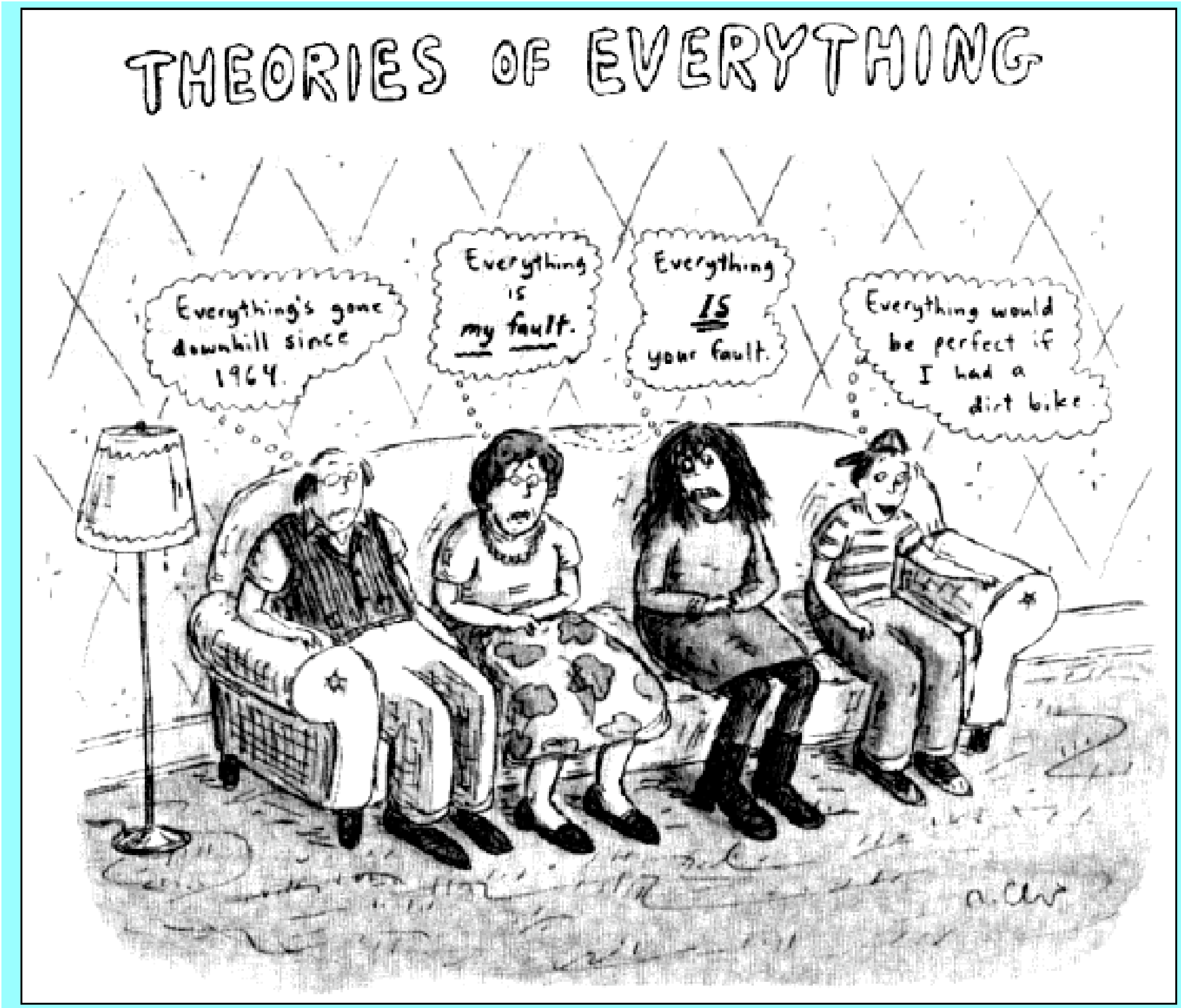
- Every fermion has a supersymmetric boson partner and vise-versa
  - electron (e) ---> selectron ( $\tilde{e}$ )
  - quark (q) ---> squark ( $\tilde{q}$ )
  - photon ($\gamma$) ---> photino ($\tilde{\gamma}$ )
  - gluon (g) ---> gluino ( $\tilde{g}$ )
  - W,Z ---> wino ( $\tilde{W}$ ), zino ( $\tilde{Z}$ )
  - Higgs (H) ---> Higgsino ($\tilde{H}$)
  - Higgs* ($H^{\pm}$ ) ---> Higgsino*($\tilde{H}^{\pm}$ )
- R-parity R=+1 (particles) R=–1 (supersymmetric particles)
- R parity product conserved
  - supersymmetric particles produced in pairs (A + B --> $\tilde{A}$ + $\tilde{B}$ )
    (1 x 1 = –1 x –1)
  - Heavy supersymmetric particles decays ( $\tilde{A}$ --> $\tilde{B}$ + A)
    ( –1 = –1 x +1
  - Lightest supersymmetic particle cannot decay (might be stop quark)
  - Good Dark Matter candidate

# Other qualities of Supersymmetry (SUSY)

- SUSY partners can cancel infinities that arise in calculations
- Unifies fermions an bosons
- Involves angular momentum inherently
  - rotational symmetries --- space translations
  - geometry of spacetime --- GRAVITY

- One major problem -- NOT a shred of evidence for it.
- Mass limit is greater than about 100 GeV
- Still looking at Fermilab Tevatron collider (CDF and D-Zero)
- Will look for it at LHC

# Theories of everything



# The Planck scale

- Fundamental constants

$$G = 6.7 \times 10^{-11}\ (\mathrm{m^3\ kg^{-1}\ s^{-2}})$$

$$\hbar = 1.05 \times 10^{-34}\ (\mathrm{m^2\ kg\ s^{-1}})$$

$$c = 3 \times 10^{8}\ (\mathrm{m\ s^{-1}})$$

- Only one combination with $G$ gives a length (The Planck Length)

$$L_P = \sqrt{G\hbar / c^3} = 1.6 \times 10^{-35}\ \mathrm{m}$$

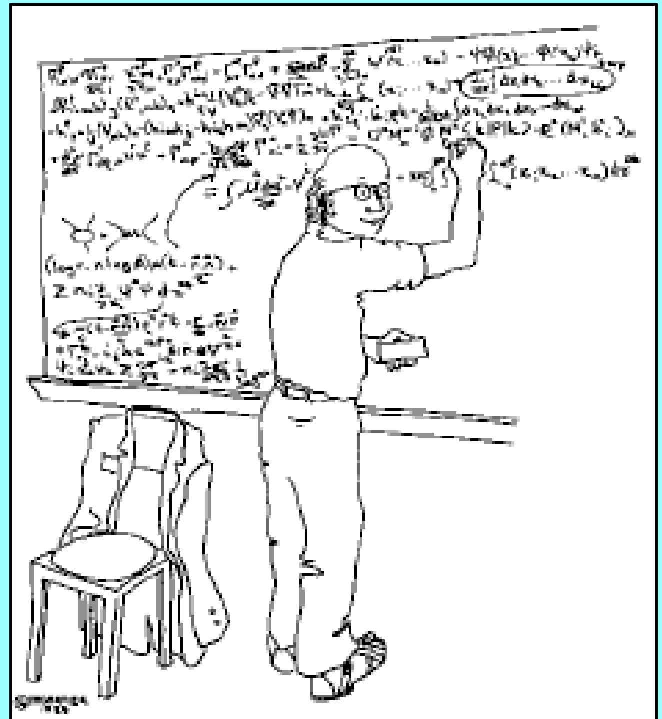
- Combine again to get energy or mass, (The Planck Mass)

$$\hbar c / L_P = 1.2 \times 10^{19}\ \mathrm{GeV}$$

- GUT scale was $10^{15}$ GeV (Did not include gravity)
- Quantum Gravity
  - exchange spin 2, massless gravitons, gives an attractive force
  - scattering cross sections give infinities
  - gravitino (spin 3/2) helps to cancel these out
  - still lots of problems that are not solved

# String Theory

- Fundamental particles appear point-like
- Point-like particles give infinities
- String theory postulates particles have a size and have string-like properties
  - Theory is formulated in 10 (or more) dimensions
  - Based on 1920's work by Kaluza & Klein
  - Particles can be closed or open strings
  - All extra dimensions except 3 space and 1 time are curled up



*"At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions."*

# Why is String Theory so popular?

Table 1.

| QUESTION | SM | SSM | String Theory | Other |
|---|---|---|---|---|
| what is matter | √ | | | |
| what is light | √ | | | |
| what interactions give our world | √ | | | |
| what stabilizes $m_{pl}/m_W$ | | √ | √ | ? |
| gauge coupling unification | | √ | | |
| explain EWSB, the Higgs mechanism | | √ | | ? |
| how is supersymmetry broken | | | √ | |
| is there a grand unified theory | | | √ | |
| proton decay | | √ | √ | |
| what is the origin of flavor physics | | | √ | |
| values of q,$l^{\pm}$ masses | | | √ | |
| values of neutrino masses | | | √ | ? |
| physics of $\mu$ | | | √ | |
| R-parity conservation | | | √ | |
| cold dark matter | | √ | | √ |
| value of tan$\beta$ | | √ | √ | |
| weak CPV | | | √ | |
| strong CPV | | | √ | ? |
| baryogenesis | | √ | | |
| what is the inflaton | | √ | √ | |
| cosmological constant is small | | √ | √ | |
| what is the dark energy | | √ | √ | |
| what are quarks and leptons | | | √ | |
| what is electric charge | | | √ | |
| how does space-time originate | | | √ | |
| how does the universe originate | | | √ | |
| why does quantum theory give the rules | | | √ | |

# Stay tuned

- The direction these theories will take is driven by Experiments
  - Fermilab/Japan Neutrino Oscillations (CP violation in leptons?)
  - Proton decay (decay modes involving K mesons)
  - Dark matter searches (nuclear recoils in cryo liquids )
  - Tevatron collider (Higgs, supersymmetry, CP violation, etc.)
  - Large Hadron Collider (ATLAS & CMS at 14 TeV)
  - International Linear Collider (the cleanest way to look)

- Next part of the course explains the operation of particle detectors and accelerators that are needed do these experiments.
- Materials Physics (Condensed Matter, Solid State, ...) plays a large role in understanding detectors and accelerators.

# How to detect particles

- Particles are detected by making them ionize atoms!
- Detecting charged particles
  - The electric field of a moving charged particle can ionize the atoms of the material in which it moves.
  - Ionization electrons are small and low mass, and can be collected by an electric field. Positive ions are big and heavy, and sluggish.
  - A charged particle accelerated by a magnetic or electric field radiates photons that can ionize atoms and release electrons
- Detecting neutral particles
  - Interact the neutral particle with matter and in the process release ionization electrons.
  - Sometimes you must completely destroy the neutral particle, but its energy has been used to create ionization.
- Must study Ionization to understand detectors

# Ionization

- Ionization potential minimum energy to ionize (outer e shell)
  - Hydrogen 13.5 eV
  - Helium 25 eV
  - Lithium 5 eV
  - Neon 22 eV

- Average ionization potential, includes inner shells
  - reaction dependent
  - for charged particles (e.g., electrons)
    - $\sim 16Z^{0.9}$ (eV) for Z>1
    - Low Z Nobel Gases (He, Ne, Ar, a little higher)

# Photon induced ionization

- Photon (<20 eV) induced
  - Only valence electrons (a few)
  - Non-penetrating
  - Gases & surfaces
    - high temperature
      - thermionic emission
    - high electric fields
    - ultraviolet light
      - photoelectric effect
      - ozone
    - photo-cathodes (Cs)
    - silicon photodiodes
- X-ray (<1 MeV) induced
  - All electrons (Z)
  - Penetrating
  - Gases & solid interiors

- Useful conversion

$$\lambda - \text{wavelength}, \ \nu - \text{frequency}$$
$$hc = 2\pi(\hbar c) = 2\pi(200 \text{ MeV} \cdot \text{fm})$$
$$= 1.2\times10^{3}(\text{eV}\cdot\text{nm})$$

- Photon energies

$$E = h\nu = \frac{hc}{\lambda} = \frac{1200(\text{eV}\cdot\text{nm})}{\lambda}$$