LEPP UNDERGRADS: Beyond the SM

**SM**: Grown-up version

<table>
<thead>
<tr>
<th>(u_l)</th>
<th>u_r</th>
<th>B</th>
<th>Z</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d_l)</td>
<td>d_r</td>
<td>W^{\pm,3}</td>
<td>Z</td>
<td>2</td>
</tr>
<tr>
<td>(\nu_l)</td>
<td>\nu_r</td>
<td>g</td>
<td>g</td>
<td></td>
</tr>
<tr>
<td>(e_l)</td>
<td>e_r</td>
<td>h, H^0, H^\pm</td>
<td>h</td>
<td></td>
</tr>
</tbody>
</table>

**Higgs**: EW symmetry breaking
- B, W, H^0, H^\pm \rightarrow \gamma, Z, W
- f_\ell \rightarrow f
- --- x Feynman rule for h

**Today**: Reasons why we expect something more

**CAFEAT**: Maybe there is no Higgs? (Maybe EW symmetry never existed?)

**NO**: Must have something like the Higgs.

\[ \frac{m_W}{E} \sim \frac{E}{m_W} \]  

**What happens at high energy?**
In SM:

\[ \nu \bar{\nu} + \bar{\nu} \nu + U \nu \]

This is well behaved, even though each diagram \( \sim E/M_{\nu} \).

In principle, three diagrams must sum to be exactly cancelling!

EW Unification

| Miracle? No. |
| The problem is that massive spin-1 particles aren't well behaved. |
| But: \( @ \) the SM massive particles are really massless spin 1 + Higgses! |

\[ H \bar{H} \]

This is well behaved.

It just got mixed up in the above diagrams into pieces which individually misbehave.

"Unitarization of WW scattering."

So: Any extension of SM must include Higgs or something like it!
Problems of SM

1. Neutrino Mass:

\[
\begin{align*}
\nu_e + e^- & \rightarrow \nu_{massive} \\
\nu_e + e^- & \rightarrow e_{massive}
\end{align*}
\]

because \( \nu \) is neutral, it might be its own antiparticle!

so option 1:

\[
\nu_e \times \nu_e \times \nu_e
\]

or option 2:

\[
\nu_e \times \text{anti-} \nu_e \times \nu_e
\]

we don't know.

Further: why is \( M_{\nu} \) so small?

maybe it comes from some virtual loop?

\[
? \quad \text{? very heavy?} \quad 10^{15} \text{ GeV}?
\]

note: option 2 violates lepton #!
2. **Flavor**

Why are there 3 generations?
Why are they heavier?

\[
\begin{array}{c}
\text{bigger \#} \\
\text{smaller \#}
\end{array}
\]

\[
\begin{array}{cc}
h & \rightarrow & b \\
\downarrow & & \uparrow \\
& \text{bigger \#} & \\
& \uparrow & \\
h & \rightarrow & e \\
\end{array}
\]

*grown-up version:*

\[
\begin{array}{c}
\nu_e \\
\rightarrow \\
\nu_R \\
\rightarrow \\
\nu_L \\
\rightarrow \text{changes spin}
\end{array}
\]

\[
\text{Higgs vev}
\]

So **flavor** HAS TO DO WITH HOW THE HIGGS TALKS TO FERMIONS! good Q: why don't electrons oscillate? → ask Josh!
(3) related to flavor: \[ CP \leftrightarrow \text{antimatter} \]

Why is there more matter than antimatter?

FACT: Laws of physics are NOT \[ CP \]-invariant.

WHAT'S THE PROBLEM? SM does not seem to predict the right amount of \[ CP \] violation.

\[ \rightarrow \text{non-perturbative effects ("sphalerons, } \Theta \text{ angle")} \]

related to: \( \geq 3 \) flavors

(4) DARK MATTER \( \sim 20\% \) of energy of universe
definitely not SM.
leading candidate: Weakly Interacting Massive Particle (WIMP)

lots of evidence for a NEW particle!
if it interacts \( \sim \) weak force \( \Rightarrow M \sim 100, 000 \text{ GeV} \)
\( \rightarrow \text{same scale as EWSB! Coincidence?} \)

\[ \text{Maybe...} \]
**Unification**

\[ e^\text{M} + (W, Z) \rightarrow \text{Electroweak} \rightarrow \text{Grand unification} \rightarrow \text{QCD} \]

This is usually accompanied by a picture:

\[ \begin{array}{c}
\text{g}_3 \\
\text{g}_2 \\
\text{g}_1
\end{array} \]

Coupling "constants" \( \leftrightarrow \) strength of force

Charge \( \leftrightarrow \) length scale

\( \rightarrow \) vacuum polarization by virtual particles

But real unification also means:

\[
\begin{pmatrix}
\nu_e \\
\nu_x \\
\nu_d
\end{pmatrix}
\rightarrow
\begin{pmatrix}
\nu_e \\
\nu_x \\
\nu_d \ldots
\end{pmatrix}
\]

Some force

Particle will \( \rightarrow \) 4 changes

Can convert between these!
IMMEDIATE PROBLEM:

\[ d \rightarrow x \rightarrow \overline{e} \text{ positron!} \]
\[ u \rightarrow \overline{u} \text{ anti-up!} \]
\[ d \rightarrow \pi^0 \]

PROTON DECAYS! (i.e. fairly quickly)
of PROTON LIFETIME > 10^{32} years

\[ \Rightarrow \text{suggests } M_x > \text{really heavy} \]
(This is why Baryon # cons is important)

\[ \text{GRAVITY: What if we wanted to be even more ambitious? Unify particle physics and gravity?} \]

\[ \text{MYTH: CANNOT WRITE A QUANTUM THEQ OF GRAVITY.} \]

\[ \text{FALSE: \quad \begin{array}{c}
\text{all fermions} \\
\text{all gauge} \\
\text{self interactions}
\end{array}\quad \text{Here it is: quantum gravity}.} \]
But: this theory breaks down in the same way that SM and Higgs breaks down.

\[\rightarrow\text{very hard to write down a fundamental} \]
\[\text{theory of quantum gravity.}\]

An easier way to see this:

\[\text{short distances} \leftrightarrow \text{high energy}\]

... but this means that at very short distances and very high energies ... high energy density

\[\rightarrow \text{gravity predicts black holes!}\]

GR in a hard time describing these.

\[\rightarrow \text{see Nina Arkani-Hamed's 2nd messenger lecture!}\]

**Leading candidate:** string theory

\[\rightarrow \text{see talk by Paul McGovern}\]

**But:** all this is very far away from any kind of experimental verification.
Cosmology: many topics here

→ Yulsn will discuss a few

e.g., Baryogenesis: where did all of our baryons come from?

also: cosmological constant ↔ vacuum energy

QFT:

\[ \text{(prediction for cosmological constant)} \]

\[ \cdots \sim M_{\text{Pl}}^4, \quad 10^{120} \text{ too large!!} \]

also: inflation ↔ & "inflaton" field which makes this happen.

"fine-tuning problem"
The Higgs mass: $\sim 125$ GeV?

As we said earlier, Higgsy @ 100's of GeV → required for WW scattering to make sense.

But then we also have:

\[ \text{Each of these is an infinite sum (integral).} \]

\[ \text{eq.} \quad \text{sum over all internal momenta!!} \rightarrow \text{end up w/ } M^2 \sim (\text{GeV})^2 \]

By the way: why is \( \mu \) a mass?

Imagine going to rest frame. This is the "self energy" of the particle.

\[ \text{n.b. technically, not all of this is mass...} \]
looks like Higgs mass diverges!!

→ No infinities in physics... appearance of infinity is a sign that our description of physics is failing.

high momentum ↔ high energy (↔ short distance)

so at some scale, SM breaks down
eg definitely by M_{pl}.
(b/c maybe cut breaks down there!)

suppose M_{H}^2 \sim (M_{pl})^2 ... finite... but too heavy!

→ maybe the coefficients of these is:

\[ S + D + E + \ldots \]

Miraculously cancel c.t. M_{H}^2 \sim (125 \text{ GeV})^2 ?

\[ \uparrow \]

UNLIKE W+ scattering, no reason for this!

So: we are looking for a REASON
for Higgs to be light.
Two approaches:
Both extend spacetime!

"weakly coupled"

\[ \text{Susy} \]

extra quantum dimension

every su particle has a partner w/ different spin

\[ \text{PBHs} \]

\[ \text{Anhors to antiparticles} \]

"strongly coupled"

\[ \text{Compositeness} \]

extra space dimension

every su particle has a tower of resonances (bound states)

\[ \text{Some lighter scale, higgs stops behaving like higgs!} \]

\[ \text{Looks like pair of fermions} \]

Jack, next key lecture

Yuhan, in 2 weeks.
Susy Names

\[ \begin{align*}
(u_d^u) & \rightarrow d^e \\
(l_d) & \rightarrow e^e
\end{align*} \]

\[ \rightarrow \beta \]

\[ \gamma \text{, } W^\pm \text{ or } B, \gamma \]

\[ g \rightarrow \text{ neutralinos} \rightarrow \text{ charginos} \]

\[ h_u \rightarrow H_u \rightarrow \text{ Higgsinos} \]

\[ h_d \rightarrow H_d \rightarrow \text{ Higgsinos} \]

Roughly: \[ \gamma \rightarrow W W, \gamma \rightarrow W Z, \gamma \rightarrow Z Z \]

Rule: change fermi to superpartners

\[ \text{conserve angular momentum.} \]
Holographic Principle

What is this?

a) big guy + little guy
b) close guy + far guy

Recall: o and is hard to describe w/ Feynman diagrams

> STRONGLY COUPLED

Form bound states w/ tower of masses

But I can also do Feynman diagrams in extra dimensions. eg suppose extra "circular" dimension

\[ \text{particle on a large } \chi D. \]

\[ \text{particle on small } \chi D. \]

"Higher kT #"

or "Higher mass bound state"