5. Topical Issues

5.1 Neutrino Masses

What is the possibility that neutrinos have any mass at all?
They were previously thought to be massless. All experiments that claimed to find mass for the neutrino were later found to be flawed.
The standard model doesn't need a neutrino mass. But what about experiments?

We have two problems:

a) Solar Neutrino Problem (ν_e)

We know that the sun, in its' nuclear reactions, produces electron neutrinos (the number of which is predicted by the standard solar model SSM). Use a detector buried underground (which screens from cosmic rays) to detect them.
The number of ν_e detected is roughly 1/3 of the total number of ν_e that was predicted at the earth.

b) Atmospheric Neutrino Problem (ν_μ)

These are produced by cosmic rays (primarily a proton) when it interacts with the atmosphere and produces a spray of particles. The most common particles are π's. This is short-lived, and will decay to a $\mu + \nu_\mu$. The muon is also short-lived, and will decay to $e + \nu_\mu + \nu_e$.

So we expect that $\frac{\nu_\mu}{\nu_e} = 2$.

These are higher energies than the solar neutrinos, hence it's a separate problem. Again using an underground detector. You get both the particles from above you, plus the particles from the other side of the earth. Experiments have found that $\frac{\nu_\mu}{\nu_e} \sim 1.3$ (which is global). Looking at the particles that have traveled through the earth, experiments have found $\frac{\nu_\mu}{\nu_e} \sim 1.1$.

So here we have too few ν_μ.

Possible (preferred) explaination:
If the neutrinos have mass, and $m_{\nu_e} \neq m_{\nu_\mu} \neq m_{\nu_\tau}$, then quantum mechanical oscillations can occur between neutrino types. E.g. $\nu_e \leftrightarrow \nu_\mu$. This violates specific lepton number conservation.

For solar neutrinos, some of the ν_e go to ν_μ and ν_τ on the journey to the earth (predominantly in the mass of the sun). Then, too few electron neutrinos are detected. "Naively" the numerical factor also makes sense…

For atmospheric neutrinos, some of the ν_μ, ν_e from cosmic rays oscillate to ν_τ - detect fewer ν_μ. "the effect is bigger for antiparhelian neutrinos."

Neutrino oscillations would solve the solar neutrino and the atmospheric neutrino problems. It would also imply that the neutrinos have mass. Through comparing the data to the predictions, you can calculate the differences between the masses of the particles – but not their actual masses. It is expected that the masses are very small, in the order of eV.

However, this creates a problem – there are 10^9 more neutrinos than there are hadrons in the universe. This means that they would have the same gravitational effects on the universe than the observable matter does. So this could explain at least part of the Dark Matter problem.

5.2 The Higgs Boson

The simple standard model has no way of predicting than any particle has any mass. Indeed, the simplest standard model says that particles should have no mass. This is blatantly not true. So we need a theory which says where the particles get their mass from.

This theory was provided by P. Higgs; he said that there is an all-pervasive Higgs field, which all particles interact with in different amounts. The stronger they interact, the more mass they acquire. Compare this with a resistance to motion of an object through a viscous gas / liquid. Let this resistance be equivalent to mass.

Fields imply interaction bosons. These are all real and detectable. So by implication, the Higgs field should give us the interaction boson called the Higgs boson. It should be real and detectable.

Some properties of the Higgs boson are predicted. The main property is that it couples strongest to the heaviest, most massive particles. This is how we expect to see it. The most important property is probably the mass – this is not uniquely / accurately predicted. It's expected to be less than $125 GeV$.

$$e^+e^- \to Z^0\left(virtual\right) \to \underbrace{H^0}_{\to b\bar{b}} + \underbrace{Z^0\left(real\right)}_{\to \ell^+\ell^-}$$

The highest energy that we've managed to put into this is ~200GeV, which is at the LEP. $b\bar{b}$ is the heaviest possible decay particles (there isn't enough energy (?) for top). These can be detected by the jets they produce. → no H^0 found. Lower limit on mass of $H^0 > 114 GeV$.

Therefore expect a H^0 with mass between $114 \to 125 GeV$. Searching at the Tevatron (USA), which has CM energy of $2 TeV$. Expect possible discovery but very low cross-section. Not found it so far, after a couple of years. Still looking.

Future search will be at the LHC at CERN, which comes online in 2007. This has a CM energy of $14 TeV$. If not found then theorists have a mass-suicide. If not discovered there, then Higgs will not get a Nobel prize (you have to get awarded the Nobel prize while you're alive; Mr. Higgs is currently 75).

5.3 GUT's

These are Grand Unified Theories. It is an attempt to unify the interactions that we know about – the Strong, the EM and the Weak. The EM and the Weak are already combined to the Electroweak. Strong, EM and Weak are called GUTS. Combining GUTS with gravity is TOE's (theories of everything).

Remember that the EM and the Weak were unified at energies of around 100GeV. They could be unified because they were very similar interactions, the only difference being the range (infinite for EM, 10^{-18} m for weak). You need energies of around 100GeV to get into the range of the W and the Z. It is not incidental that the W and Z particles have a mass of ~ 100GeV.

We know that the strong interaction gets weaker as the energy increases, as the distance that is being probed gets smaller. You can consider the strong interaction as Gluons. If the particles are near to each other, you get a coil that is bent around, and hence weak. If they are further away, then the coil between them is taut.

Electroweak?
α_{EM} increases with energy.

$$\alpha_{EM} = \alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c}$$

These contradict – the latter only has constants, and constants can't vary. So how can this be true?
Take an electron E with charge e^-. This has a cloud of virtual photons. These photons can now produce a virtual e^+e^- pair, similar to gluons producing gluon pairs. As these are charged, the positron will be attracted to the electron. So all the e^+ will be on the inside, and all the e^- on the outside. Then take a test particle at B, outside the gluon field. If you then measure the field from E at B, you will find that it is "screened" by the cloud of e^+e^- pairs, and B sees a weaker charge from E. If you then take a particle at A, inside the gluon field, then it will see a higher "bare" charge on E.

So, the constant that isn't constant is the electric charge. It is constant at all normal energies, but when you get to 100GeV you start to probe distances within the photon hence e apparently changes.
Therefore EW increases with energy.

(IMG)

The GUTS unification energy is $\sim 10^{15} GeV$. New bosons X and Y, with masses $\sim 10^{15} GeV$. $Q = -4/3, -1/3$. These have energies far too high for any potential direct observations. However, they predict that the proton should decay (via X and Y), in $10^{31} yrs$. (cf. β decay, which happens at lab energies but via W of mass $80 GeV$).
This is the main test of GUT's. One proton decaying in roughly $10^{31} yrs$ is equivalent to 1 proton in 10^{31} protons decaying in 1 year.
The big problem: the interaction strengths don't extrapolate to a point. The three lines miss each other! Also, the proton is stable to at least 10^{33} years. So maybe GUTs is in trouble…

5.4 SuperSymmetry (SUSY)

For every half-integer Fermion, there exists an integer partner.
e.g. a Quark (e.g. top) → a Squark (e.g. stop)
e.g. a Lepton (e.g. Muon) → Sleptons (e.g. Smuon)
Neutrino → neutralino

For every integer Boson, there exists a half-integer partner.
Photon → photino
W → Wino
Higgs → Higgsino

There are 3 main consequences of this.

1) It symmetrises last asymmetric frontier
2) It makes the Strong and EW interactions meet at a point, at an energy of $\sim 10^{16} GeV$.
3) Extends the Proton lifetime from 10^{31} to 10^{33} years.

So this gives a reprieve to GUTs.

The SUSY particles are expected to have masses of a few TeV (>2007)

5.5 Matter vs. Antimatter?

Big Bang → expected equal creation of matter and antimatter.
At $t \le 10^{-35} s$, the temperature of the universe was around $10^{28} k$ → energies around $10^{15} GeV$. → produce X and $\bar{X}$, as well as Y and $\bar{Y}$. After this time, the universe has expanded, the temperature has gone down, and there is no longer the energy to produce this.
$X \to \overline{qq}$ or $q\ell$ pairs.
$\bar{X} \to qq$ or $\bar{q}\bar{\ell}$
But CP violation gives the X and $\bar{X}$ decays in different ways.
We assume $X \to \overline{qq} < q\ell$. $\bar{X} \to qq > \bar{q}\bar{\ell}$. So there is an excess of matter over antimatter.
When matter and antimatter annihilate → γ which are responsible for the 3k CMB.
Left with the small excess of matter over antimatter. This is our universe. This excess only needs to be 1 in 10^9 to explain the complete disappearance of antimatter.

Current experiments prove the existence of CP violation, but the amount needed is not yet verified. It's currently looking a bit low…