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Mysteries of Mass: Some Contrarian Views From an Experimenter

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Abstract. Physics and astronomy are the oldest sciences and the concept of mass is thus a very old concept. We have quite good understanding of the masses of composite elementary particles such as protons using quantum chromodynamics. But we do not understand the nature of the masses of the elementary particles – quarks, leptons, force carrying particles, dark matter particles - and we have no quantitative rules for the magnitude of their masses. In this talk I sketch a number of qualitative questions such as why is there no rule for even the simplest mass sequences -the charged leptons, is there a maximum mass elementary particle, and is the Planck mass idea overrated? I also estimate the upper limits on collider searches in the next few decades for massive particles. This is a summary of my talk at Colliders to Cosmic Rays 2007.

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INTRODUCTION: THE MYSTERY O F MASS

I began experimental research in particle physics in the later half of the 1950's and my concern then was with the elastic scattering of pions and protons. I was content to accept the masses of these particles as given. But as I moved into research on the electron- muon problem in the 1960's using the facilities of the Stanford Linear Accelerator Center (SLAC) I became entranced with the question of why the muon mass was 207 times the electron mass. I also became entranced with the question of the existence of yet heavier charged leptons and their masses. It seemed obvious that the simplicity of these charged leptons would yield an understandable rule for their masses. Also in those early days it was easy to assume that the associated neutrinos had zero mass, thus proposing an apparently simple problem.

But forty years later we know that the neutrinos have non-zero masses, that the relation of their masses to their charged associate masses is speculative, and that we have no understandable rule for the charged lepton masses. It is surprising that we are so ignorant of a quantitative theory for the masses of the known elementary particles. By elementary I mean the leptons, the quarks, the force carrying particles and

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assuming it exists, the dark matter particle or particles. I do not consider in this paper the masses of the composite particles such as the baryons and mesons whose masses are reasonably well understood through quantum chromodynamics and the masses of the elementary particles.

Our ignorance is surprising because this is the best time for doing physics that I have seen in my lifetime. We have better technology in particle physics and astronomy. We know more basic theory and much more phenomenology. The same success pervades the other areas of physics: low temperature physics, solid state physics, device physics, the intersection of biology and physics. We are more open to new thoughts and more speculative and we have tremendous computing power. We should be ashamed of ourselves that we have learned so little of the basic nature of mass. Thus the essence of this paper is to point out qualitatively what little we know of mass and how much we would like to know. This paper is a summary of my talk at Colliders to Cosmic Rays 2007 25 Feb.-1 Mar. 2007, Lake Tahoe, California.

There are few references. A full references list would be equivalent to the Google response to a search on “particle mass”. I say nothing about string theory in this paper because my understanding of string theory is qualitative and I don’t know if string theory will lead to a quantitative law that gives the masses of the elementary particles.

MYSTERY 1: THE GREAT RANGE OF PARTICLE MASSES

Figure 1 gives masses of the known particles. There is much remaining to learn about neutrino masses. Excluding the photon, elementary particle masses extend over at least 15 powers of ten. How is it that particle masses can be so different and yet all the particles are smaller in size than our most delicate size measurements can uncover? And also how is it that particle masses can be so different and yet for each force the force coupling constant is the same for all particles that partake of that force? In most ways the particle mass has nothing to do with the particle’s properties beyond entering decay mode and decay rate calculations.

Going up the quark mass chain from u and d to t certainly involves different physics from going up the nuclear mass chain. the uranium nucleus is more complicated than the proton. But the t quark is probably as simple as the u and d quarks and may be simpler. Is mass an incidental property of a particle?

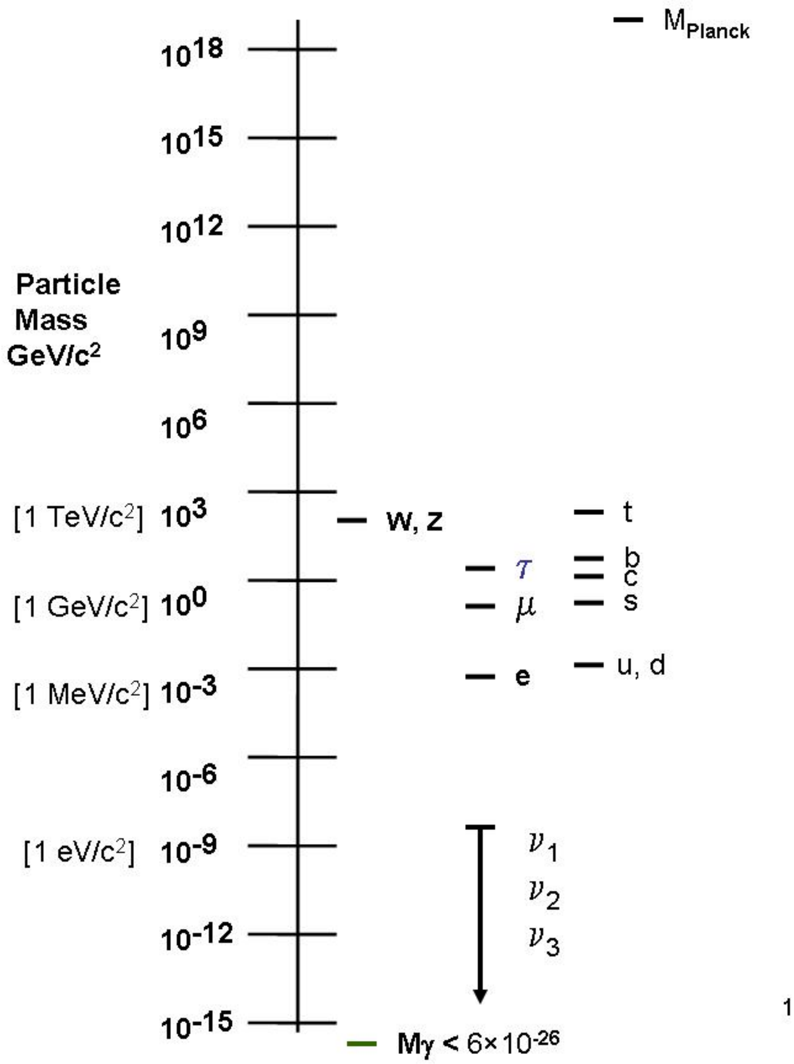

FIGURE 1. Masses of the known elementary particles

There is uncertainty as to how close the photon mass is to zero. $M_\gamma < 6\times10^{-26}$ GeV/c^2 is based on a magnetohydrodynamic study of solar wind.[1] I don't understand the physics. A looser upper limit, $M_\gamma < 7\times10^{-28}$ GeV/c^2 is based on a torsion balance method by J. Luo *et al*.[2], but is disputed by A. S. Goldhaber and M. M. Nieto [3]. They prefer $M_\gamma < 1\times10^{-26}$ GeV/c^2 based on a torsion balance method by J. Lakes [4]. A recent review on photon mass is L-C. Tu, J. Luo and G. T. Gillies [5]

MYSTERY 2: THE MECHANISMS THAT SET PARTICLE MASSES

We have multiple models, too many models, for the mechanisms that set the particle masses, For the photon, Z^0, and $W^{\pm}$ we have the original Higgs mechanism, although the Higgs particle is still a subject for experiment. But even assuming the full validity of the Higgs mechanisms, we do not know how to calculate the masses of the quarks and charged leptons. The mass ratios are peculiar . For example

$$m_e : m_\mu : m_\tau = 1 : 207 : 3477$$

$$m_t / m_u \sim 8 \times 10^4$$

Are these the analogs to the Balmer series. Why are the ratios so large?

The very small neutrino masses seem to call for yet an additional mass setting mechanism, the see saw. This postulating of an additional mechanism has the scent of the Ptolemaic epicycle system. And what if other odd particles exist, for example what if the dark matter particle is not a supersymmetric particle or what if Kaluza-Klein particles exist, what will be the mass setting mechanisms? And what about the “little Higgs” ? The present world of proposed mass mechanisms seems too complicated.

Perhaps I am old-fashioned and should not dream of a simple universal mechanism for setting the masses of particles. Have we somehow missed the basic equations that set masses. Do we have to be content with multiple mechanisms, scraps of equations, fanciful hypothesis and patches? There is plenty of work for experimenters and theorists.

MYSTERY 3: WHAT IS A LARGE PARTICLE MASS

The mass range of the known particles is limited by our technology. We know that the smallest mass would be zero mass by definition and that the photon probably has zero mass. But what would be a large mass? We do speculate about the electroweak mass scale but does that have anything to do with how massive a particle exists? Are our technology- limited-experiments still concerned with particles whose masses are many magnitudes smaller than the most massive existing particles? Are we close to the largest existing particle mass or do we have many factors of ten to go. Again we have no answer.

MYSTERY 4: WHAT IS THE SIGNIFICANCE OF THE PLANCK MASSS?

I have several problems with the significance of the Planck mass.

$$M_{Planck} = \sqrt{\frac{hc}{2\pi G}}$$

So that M_{Planck}=2.2 × 10^{-8} kg =1.2 × 10^{19} GeV/c^2

M_{Planck} is sometimes given as the maximum mass at which a particle can be defined because the gravitational force of the Planck particle distorts too much the space in which we define an elementary particle.

I am not convinced that M_{Planck} has anything to do with the upper limit on elementary particle masses. M_{Planck} mixes a constant from quantum mechanics with two classical constants. So it indeed marks some sort of boundary between classical and quantum physics and may have to do with the problem of the unification of gravitational and electromagnetic forces. But I am not convinced that M_{Planck} has anything to do with elementary particle masses.

MYSTERY 5: COLD DARK MATTER

The present, most popular vision of the cold dark matter particle is that (a) it's mass is of the order of 10^4 GeV/c^2 or smaller, (b) it interacts with all other matter through the conventional gravitational interaction, (c) the production of dark matter in the early universe requires some non-gravitational force, and (d) there may be a weak interaction between dark matter particles and ordinary particles.

Dark matter may be a neutral supersymmetric particle and thus not so different from ordinary matter. But it is also possible that dark matter is an entirely new kind of matter. In that case it is possible that dark matter particles interact with ordinary matter only through the conventional gravitational force. Then terrestrial detection of dark matter will fail and there will be no detectable production of dark matter at colliders. We will have to depend on the limited knowledge we can obtain from astronomical observation.

UPPER MASS SEARCH REACH OF COLLIDERS IN NEXT FEW DECADES

My hope is that experimental discoveries of new massive particles will lead us to more consistent understanding of mass mechanisms and mass series. Looking at the next three decades, how much further can we hope to explore with conventional collider technology?

Consider first proton-proton circular colliders. The Large Hadron Collider with a total energy of 14 TeV can in principle produce particles up to 14 TeV/c^2 in mass, but since each proton's momentum is carried by three partons, copious production of new particles will occur up to the 5 TeV/c^2 range. Indirect evidence for the existence of new massive particles may extend a factor of 10. Thus with the LHC we hope for massive particle searches up to about 50 TeV/c^2. but many of the indirect searches will not be definitive. Still this is a spectacular increase in the mass search range considering that the most massive known particle is 0.17 TeV/c^2 .

Consider next electron-positron linear colliders in the next three decades. These three decades include detailed planning for 0.5 TeV total energy for the International Linear Collider, and initial R&D on a CLIC design with up to 3.0 TeV total energy. Since all the electron-positron collision energy can be used to produce a new particle, I expect direct searches in the 0.5 to 3.0 TeV/c^2 mass range, depending upon what is built. The indirect searches will go up a factor of 10 in mass and will be cleaner than the indirect searches in proton-proton colliders.

After the next three decades, about 2040, we might enter a time of yet larger collider energies. There has been considerable work on the possibility of building a proton-proton circular collider with a total energy of 100 TeV. This would extend the previously given large mass search limits by a factor of 5 to 10. But at present we know nothing about the financial or technical possibilities of such a collider.

Also in the period after 2040 we might be building electron-positron colliders with accelerating gradients 10 to 100 times larger that those used in the International Linear Collider and CLIC. Might it be possible to build a linear collider with a total energy of tens of TeV and with sufficiently small beams to that there is adequate luminosity?

MASS SEARCH REACH IN ASTRONOMY

Our other possible source for the discovery of more massive particles and hence for clues to mass mechanisms is massive particles that may have been produced naturally. There are two production regions:

- Thermal relics from very early universe with masses up to about 0.3 Tev/c^2 [6]
- Non-thermal relics produced after inflation with mass as large as 10^{13} TeV/c^2 [7]
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These massive particles might be found by annihilation lines, for example there might be a γ line from

$$X + \text{anti-}X \rightarrow \gamma + \gamma.$$

I am not hopeful about the power of such searches.

SUMMARY

- Our knowledge of elementary particle masses is limited by our technology. In the next three decades we will learn a tremendous amount more from the LHC and linear colliders about mass and the existence of larger masses.
- The nature of cold dark matter remains to be resolved. It may be a neutral supersymmetric particle and thus not so different from ordinary matter. Or cold dark matter may be an entirely new kind of matter. If dark matter particles

interact with ordinary matter only through the conventional gravitational force, terrestrial detection of dark matter will fail and there will be no detectable production of dark matter at colliders.

- There is a frightening proliferation of theories for mass setting mechanisms. Perhaps a universal theory for setting masses exists and can be found. Or perhaps the world of mass setting mechanisms is just very complicated. In any case we are very dependent on experiments.
- We don't know if there is an upper limit to elementary particle masses and I am skeptical about the significance of the Planck mass.
- Elementary particle mass remains a mystery. Somehow we have not yet understood the essence of mass.

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