FRONTIERS OF PARTICLE PHYSICS

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I. THREE SCALES IN PARTICLE PHYSICS

Among the known energy scales in particle physics, it is natural to single out the three most important ones: the hadronic scale ~ 1 GeV, the electroweak scale, often called the Fermi scale, $\sim 10^2$ GeV, and the Planck scale $\sim 10^{19}$ GeV.

The hadronic scale is set by the mass of light hadrons: ρ-mesons and nucleons. The Fermi scale is set by the Fermi coupling constant G_F or by the value of the hypothetical higgs vacuum expectation value $\eta = (\sqrt{2}G_F)^{1/2} \approx 246$ GeV (in units $\hbar, c = 1$).

The Planck scale is set by the Planck mass m_P expressed in terms of G_N, $\hbar$, c ($m_P = \sqrt{\hbar c/G_h} \approx 10^{19}$ GeV), where G_N is the Newton gravitational constant.

II. THE TOP QUARK MASS: ITS DIRECT AND INDIRECT VALUES

The most important experimental achievement of recent years is definitely the discovery of the top quark at the Tevatron. We anxiously waited for it for two decades. Now we have this long-awaited fundamental fermion with its largest and most natural value of mass (in the Fermi scale). But our understanding of particle physics does not seem to have changed substantially by its discovery.

What were the main hopes connected with the top, besides the obvious completion of the third generation? They were based on the expectation that by measuring directly the top mass m_t with accuracy, say, better than 10 GeV, and by comparing it with the value of m_t derived indirectly from the precision measurements of the electroweak radiative corrections, we would be able to figure out the most probable value of the mass of the higgs m_h. (Both m_t and m_h enter into the expressions for electroweak radiative corrections to such electroweak observables as m_W/m_Z and the decay amplitudes of the Z boson, which were and are measured with highest achievable precision by UA2, CDF, D0, four famous detectors at LEP, and SLD at SLAC.)

A discrepancy between the direct and indirect values of m_t could even have served as a signal of new physics. We have now

$$m_t(\text{direct}) = 180 \pm 12 \text{ GeV}\,,$$

$$m_t(\text{indirect}) = (160, 180, 200) \pm 9 \pm 5 \text{ GeV}\,.$$

The direct value is derived by a straightforward averaging of CDF and D0 results; the indirect by a global fit of all electroweak observables in the framework of the Minimal Standard Model. The three central values correspond to $m_h = 60,\ 300$, and 1000 GeV, respectively; ± 9 is statistical uncertainty, ± 5 is due to the uncertainty in $\bar{\alpha} \equiv \alpha(m_Z) = 1/128.89(9)$.

We see that we are, in a sense, unlucky: the direct value is right in the center of the indirect interval.

III. THE HIGGS AND SUPERSYMMETRY

If the higgs is heavy, then farewell to supersymmetry, which requires a light higgs. Theorists of course would prefer a light higgs, with $m_h < 130$ GeV, accompanied by many supersymmetric partners of our particles: neutral and charged.

There may be a hint of the existence of light squarks and gluinos, with masses of order 100 GeV. I refer here to the 2σ discrepancy between experimental data and theoretical expectations on the decay of Z bosons into $b\bar{b}$ pairs. Another discrepancy which may be cured by light sparticles is the difference in the values of the strong coupling constant $\alpha_S(m_Z)$ extracted 1) from the global fit of the Z boson decays (0.125(5)) and 2) from the sum rules involving masses and electronic decay widths of the known upsilon states, and also from deep inelastic scattering (0.110).

If the higgs is very light, below 95 GeV, it could be produced and detected at LEP 200 (or more precisely LEP 195; note that LEP 210 could reach $m_h = 110$ GeV). (The lightest charginos could be also detected by LEP 200.) For the discovery of a heavier higgs, the Next Linear Collider, with energy 2×250 GeV would be the best. The point is that a light higgs decaying mainly into $b\bar{b}$, $\tau\bar{\tau}$, and $\gamma\gamma$ is a very difficult target for the LHC. If the higgs is not light enough for LEP 200, then the discovery of this pivotal particle will be postponed until the next century. Many of us will pass away with a question mark in our minds on the central point of particle physics—on the origin of mass and symmetry breaking in Nature.

IV. NEUTRINO OSCILLATIONS

Great progress has been made in recent years in neutrino physics, first of all in solar neutrinos. As you know, there are several major kinds of solar neutrinos: so called boron neutrinos (from the β decay of ^8B), beryllium neutrinos (from the electron capture in ^7Be), and proton neutrinos (from the reactions $pp \to de^+\nu_e$ and $pe^-p \to d\nu_e$.) In spite of having different names, all of them are ordinary electron neutrinos ν_e and differ only by their energy spectra.

For many years the Homestake chlorine experiment, which is sensitive to the boron and beryllium neutrinos, has signalled a flux about one-third of what was expected. This was traditionally considered to be a deficit of boron neutrinos. The water detector Kamiokande, sensitive to boron neutrinos only, has shown a deficit close to half. But the most intriguing are the data from two gallium detectors sensitive mainly to proton and beryllium neutrinos (Gallex and Sage) which see a signal of about two-thirds of that expected. The main suspects are now beryllium neutrinos, which seem almost to disappear on their way to the detectors. The most probable explanation for this disappearance is the transformation of ν_e into ν_μ or ν_τ or in a new unknown sterile form ν_s during the travel inside the sun.

In order to undergo such transformations, the neutrinos must have a nonvanishing mass difference, $\Delta m^2 \approx 10^{-5}$ eV^2. Another interesting phenomenon is the deficit of muonic neutrinos created in the atmosphere of the earth. This deficit, seen at Kamiokande, may be caused by the transformation $\nu_\mu \to \nu_\tau$ and/or $\nu_\mu \to \nu_s$. There are two CERN experiments searching for the $\nu_\mu \to \nu_\tau$ transformation; they are short-based. Additional long-base experiments using beams of neutrinos from accelerators and far away detectors may be very interesting. It is not clear at present what is the scale at which the neutrino masses are determined in Nature. Possibly it is the Grand Unification Scale around 10^{16} GeV.

V. OTHER FRONTIERS

I have touched on a number of the experiments which mark the frontiers of present day particle physics. I don't have time to speak about many other extremely important experiments, which either have been carried out or will start running in the near future. I can only list some of them:

- Studies of CP violation, especially in the decays of B mesons.
- Studies of hadron structure with lepton beams. (Recently, a vast new kinematical region was opened by HERA.)
- Studies of soft and hard hadron collisions.
- Attempts to create the quark-gluon plasma in heavy ion collisions (many physicists hope to see it at RICH).
- Quantitative measurements of the heavy flavour hadron's properties.
- Spectroscopy of light flavour hadrons, including glueballs.
- Searches for very rare decays of kaons and muons, which may uncover flavour-changing neutral currents and/or higher order electroweak effects.
- Searches for the dark matter particles in space and on the earth.

VI. THREE FUNDAMENTAL CONSTANTS

The frontiers of particle physics are multidimensional and have a very complex topology. Assume all of the experiments listed above have already been performed and are immortalized in the Particle Properties Data volume. Particle physics will still be far from complete. This follows from the simple fact that none of the above experiments deals with gravity—one of the most fundamental physical forces. Since Newton, we have known that this force, both on the earth and in the skies, is characterized by the same Newtonian coupling (interaction) constant G_N.

Our century has brought us a plethora of physical constants—particle masses, interaction constants, scales, etc. But it seems obvious that the most fundamental of them, in addition to G_N, are c, the maximal velocity of particles in vacuum, and $\hbar$, the quantum of action and of angular momentum (in fact, the latter is $\hbar/2$). The numerical values of G_N, $\hbar$, and c, when expressed in grams, seconds and meters, have no deep meaning, because grams, seconds and meters are man-made units: they were fixed historically, but physically are quite arbitrary. What is of paramount importance is the very existence of G_N, $\hbar$, and c.

VII. THE CUBE OF THEORIES

Consider three orthogonal axes x, y, and z. Put $1/c$ on x, $\hbar$ on y, and G_N on z at equal distances from the origin. Now we are ready to contemplate the cube of physical theories associated with the name of Matvey Bronshtein, the Soviet theorist executed in 1938 at the age of 32.

At the origin we have non-relativistic mechanics (NM). When velocity is on the order of c, we have special relativity (SR). When action or angular momentum is on the order of $\hbar$, we have Quantum Mechanics (QM). Thus we have marked three corners of a square in the xy plane. The fourth corner represents quantum field theory (QFT) which came from the merging of SR and QM.

VIII. THE STANDARD MODEL OF QFT

QFT is the quintessence of present day particle physics. All experimental frontiers discussed or mentioned above are described in the framework of QFT, in its language. Non-relativistic atomic, molecular, and solid state physics, classical electrodynamics, optics, etc., are limiting cases of QFT. It also describes nuclear phenomena, and strong and weak interactions of hadrons and leptons. All of these treasures of knowledge have a rather bureaucratic dry name: the Standard Model. The SM is based on a famous gauge symmetry group $SU(3) \times SU(2) \times U(1)$. The gauge bosons—photon, $W^\pm$, and Z^0 bosons and gluons—each have couplings which in units $\hbar$, c are dimensionless. Their squares are denoted by α, α_W, and α_S for electromagnetic, weak, and strong interactions, respectively. These couplings are functions of momentum transfer q^2: they are running. For example, $\alpha(q^2 = 0) = 1/137.039895(61)$, while $\alpha(m_Z^2) = 1/128.89(9)$.

In spite of all its successes, the Standard Model is far from being the Ultimate Theory of Physics. It has a few dozen free dimensionless parameters (or even more if superparticles exist), while we expect that the Ultimate Theory will have no free parameters at all. The Higgs mechanism of the origin of masses still awaits its experimental test. But what is much more important, the SM does not incorporate gravity.

IX. QUANTUM GRAVITY AND THE TOE

As you remember, the Newton constant G_N is not in the xy plane, it is on the z axis, where it represents non-relativistic gravity (NG). By merging NG and SR, Einstein created general relativity (GR)— the relativistic theory of gravity. He spent the subsequent forty years of his life trying to create a unified theory of electromagnetism and gravity in the xz plane. As electromagnetism is a part of QFT, it is common knowledge today that the unified theory of electromagnetism and gravity should be a part of the Theory of Everything (TOE), which should be created by merging GR with QFT, in particular by creating Relativistic Quantum Gravity, which also would be a part of the TOE.

Note that the inclusion of the Newton constant G_N brings to the cube of theories the dimensions of mass, energy, momentum, length and time, which cannot be constructed from $\hbar$ and c alone. The mass, corresponding to G_N, was first calculated by Planck at the turn of our century and is called the Planck mass:

$m_P = \sqrt{\hbar c/G_N} \approx 10^{19}$ GeV, and the corresponding Planck length $l_P \approx 10^{-33}$ cm.

The enormous value of m_P compared with the heaviest known masses ($\sim 10^2$ GeV) and with the energies of our accelerators may make you despair. No imaginable technology will ever bring such center-of-mass energy to a physical laboratory. Even daydreaming about experiments at Planck energy is out of the question. And at the same time it looks as if the answers to the most fundamental questions in physics are hidden at the Planck scale.

What are the brightest and the most active young theorists doing nowadays? They are trying to create the future TOE by brainstorming. Since the early eighties their main hope has been superstrings—tiny objects with a characteristic Planck length l_P. They have developed a special branch of mathematics to describe these objects and their interactions.

In connection with superstrings a question is under discussion in the literature. Do we really need three basic dimensional constants c, $\hbar$, and G_N, or would only two of them be sufficient: c and l_P—the length of the string, while $\hbar$ is redundant? According to that point of view, string theory deals only with space and time, but not with energy, momentum, or mass. Momentum for instance has the dimension of inverse length, while action has that of area. The fact that action has, in certain units, the dimension of area does not mean that action can be discarded as a physical quantity and that its role can be assigned to area. It seems to me that statements to the contrary stem from a kind of blurring of such notions as parameters, dimensions, units, and fundamental dimensional constants. For superstrings there should be no free dimensionless parameters. As for the natural units, they are $\hbar$, c, and l_P Thus, the equations should contain neither dimensionless parameters, nor fundamental dimensional constants. However, to connect superstrings with the traditional parts of physics, one needs all three fundamental dimensional constants: $\hbar$, c, and G_N.

Creating the TOE is a very hard and a very risky job. Many physicists looking from outside complain that a whole generation of young theorists has lost contact with real-world physics, have become pure mathematicians. I am not qualified enough to be a judge. Maybe there is some truth in these complaints. But the process of increasing specialization is a universal phenomenon in all scientific fields, and Planck physics is no exception.

X. FROM QFT TO TOE

While we cannot reach the Planck scale with beams of particles, we may reach it with beams of thought, beams of ideas. If somebody is able to think constructively about the Planck scale, the farthest frontier of physics, let him do it.

On the other hand, the richness of particle physics indicates that it would be impossible to formulate the TOE without experimental inputs. How can one make such an input to the region of 10^{19} GeV while being limited to 10^3 GeV or even 10^6 GeV? A possible answer is logarithmic dependence on energy, such as demonstrated by the running alphas. In the Standard Model, masses are also running logarithmically with energy. Thus, by starting with a broad interval of initial conditions at, say, 10^{17} GeV, one ends up with m_t lighter than 200 GeV and m_h lighter than 130 GeV in a minimal supersymmetric standard model. Hopefully the main vehicle is the logarithm.

There is also slight chance of small power terms of order E/m_P. Note that the CPT theorem has been proved only in the framework of QFT, which deals with pointlike particles. It may be not true for strings. Then small differences between masses of particles and corresponding antiparticles would appear. Of course, if we are unlucky and they are proportional to $(E/m_P)^2$, we will be unable to observe them.

XI. THE FUNDAMENTAL IMPORTANCE OF THE FERMI SCALE PHYSICS

Thus we need experimental inputs in order to extrapolate them logarithmically to the Planck scale. But is it not enough to have as inputs the data which have already been obtained? The answer is a definite NO! We have too many loose ends. We still have not seen higgs (or higgses) and superparticles. We still do not know the mechanisms of symmetry breaking at the Fermi scale. We know that this scale starts at masses of W and Z bosons, stretches to the top mass, to the value of the hypothetical higgs vacuum expectation value $\eta = 1/(\sqrt{2}G_F)^{1/2} \approx 246$ GeV (in units $\hbar, c$) and further through the spectrum of supersymmetric particles to multiTeV energies.

Without full understanding of physics at the Fermi scale, we will be unable to construct the logarithmic superhighway to the Planck scale, to the ultimate theory of physical world, including the origin of the universe. That is why we so deeply feel the loss of the SSC. (The first version of this talk had a dedication: *In memory of the SSC*.) That is why most of all we need the energy and luminosity of the future sub-TeV and multi-TeV accelerators!