PARTICLE PHYSICS AT FUTURE COLLIDERS

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Abstract

The search for physics beyond the Standard Model motivates new high-energy accelerators, which will require high luminosities in order to produce interesting new heavy particles. Using the Higgs boson and supersymmetry as examples, we discuss the capabilities of the LHC and e^+e^- linear colliders in the TeV and multi-TeV energy ranges to discover and study new particles.

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1 THE NEED FOR NANOBEAMS

The primary motivation for future colliders, and the only one likely to find favour with funding agencies, is to search for new physics beyond the Standard Model. This may be done either by going to higher energies, or by colliding beams with higher luminosities in the energy range already probed by previous colliders. In general, the cross sections for interesting new physics processes decrease at higher energies:

$$\sigma_{\rm interesting} \sim \frac{1}{E_{\rm CM}^2}. \qquad (1)$$

The basic reason for this decrease with energy is that the interesting cross sections are those for point-like particles whose effective sizes are determined by their Compton wavelengths $R \sim 1/E_{\rm CM}$. Likewise, interesting new particles with masses $M_{\rm new}$ have production cross sections

$$\sigma_{\rm new} \sim \frac{1}{M_{\rm new}^2}. \qquad (2)$$

A suitable standard of comparison for high-energy future colliders is provided by LEP, which reached a maximum luminosity $\mathcal{L} \sim 10^{32}$ cm^{-2}s^{-1} at $E_{\rm CM} \sim 200$ GeV. The pair-production of heavy particles such as the $W^\pm$ and Z^0 at LEP 2 was not overly generous, so we assume that a new collider should provide a similar number of events. In this case, its luminosity should increase as $E_{\rm CM}^2$ compared to LEP.

Thus, the LHC with a luminosity $\mathcal{L} \sim 10^{34}$ cm^{-2}s^{-1} will be able to produce pairs of new particles each weighing ~ 1 TeV. Likewise, a linear e^+e^- collider operating at $ECM \sim 5$ TeV, such as CLIC, should be designed with a luminosity $\mathcal{L} \sim 10^{35}$ cm^{-2}s^{-1}. Such large luminosities are also required for advanced 'factories' at lower energies: a rule of thumb is that an n'th-generation factory should have a luminosity $\sim 10^n$ times greater than the first collider to explore the same energy range. This is why the present B factories aim at $\mathcal{L} \sim 10^{34}$ cm^{-2}s^{-1}, and one talks about $\mathcal{L} \sim 10^{35}$ cm^{-2}s^{-1} for the next generation, *et seq*.... Nanobeams will certainly be in great demand.

2 THE STANDARD MODEL OF PARTICLE PHYSICS

LEP and the lower-energy colliders that preceded it have established beyond question the Standard Model of particle physics. It comprises three generations of fundamental fermions to make up the matter in the Universe, each consisting of two quarks, a neutrino and an electron-like charged lepton. Four fundamental forces act on these matter particles: the electromagnetic, strong, weak and gravitational forces. Each of these is carried by messenger particles: the photon, the gluons, the $W^\pm$ and Z^0, and (we believe) the graviton, respectively. As seen in Fig. 1, the experimental data from LEP agree (too) perfectly with the theoretical curves, at all energies up to above 200 GeV [1]. This sounds great, but there are plenty of questions left open by the Standard Model.

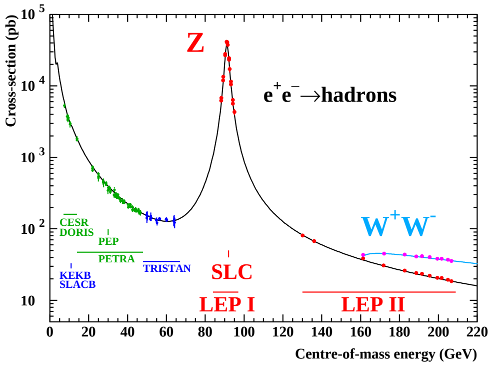

Figure 1: Data from LEP and other e^+e^- experiments agree perfectly with the predictions of the Standard Model [1].

Why are some fundamental particles, such as the photon and gluons, massless, while others are massive, weighing as much as good-sized nuclei in the cases of the $W^\pm$, Z^0 and top quark? Are the different fundamental forces unified, as long hoped by Einstein? Why are there so many different types of 'elementary' particles? Could they all be composite states made out of more fundamental constituents? How to explain all the different parameters of the Standard Model: 6 quark masses, 3 charged-lepton masses, 2 weak-boson masses, 4 weak mixing angles and phases, 3 interaction strengths and a non-perturbative strong-interaction vacuum parameter? These total 19 parameters, even without describing neutrino masses and mixing angles.

Some more fundamental physics must surely lie beyond the Standard Model, and the next sections of this paper describe some candidates for this new physics.

3 THE PROBLEM OF MASS

This is probably the most pressing problem raised by the Standard Model. Indeed, it can only be solved by introducing new physics at some energy scale below ~ 1 TeV. The most likely culprit for generating particle masses is thought to be a Higgs boson with a mass in this range. A massless vector particle such as the photon has two polarization states: $\lambda = -1, +1$. On the other hand, a massive vector particle such as the $W^{\pm}$ or Z^0 must have three polarization states: $\lambda = -1, 0, +1$. Thus, in order for a massless vector particle to acquire a mass, it must combine with some zero-polarization state, such as could be provided by a spin-0 field via the Higgs-Brout-Englert mechanism [2].

In the Standard Model, the minimal such model contains a complex doublet of Higgs fields, with a total of four degrees of freedom. Of these, three are eaten by the $W^{\pm}$ and Z^0 to become their third polarization states, leaving one degree of freedom to appear as a separate physical state, the Higgs boson. In order for it to perform its task of giving masses to other particles, its couplings to them should be proportional to their masses: $g_{H\bar{f}f} \propto m_f$. However, the mass of the physical Higgs boson itself is not fixed in the Standard model without any extra input.

Direct searches for the Higgs boson at LEP have established that the Higgs boson weighs more than 114.4 GeV [3]. Precision electroweak data from LEP and elsewhere also provide indirect information on the possible mass of the Higgs boson, as seen in Fig. 2 [1]. Quantum corrections in the Standard Model would disagree with the precision measurements unless the Higgs boson weighs less than 193 GeV at the 95 % confidence level, with a mass $\sim$ 115 GeV being the most likely value, as seen in Fig. 3 [4]. This probability distribution makes no use of the ‘hint’ from direct Higgs searches at LEP of a signal at ~ 116 GeV [3].

Now that LEP operations have been terminated, what are the prospects for Higgs searches with future colliders? The Tevatron collider has a chance, if it can accumulate sufficient luminosity, particularly if the Higgs boson weighs $\sim$ 115 GeV [5]. The LHC will be able to discover the Higgs boson, whatever it mass below about 1 TeV, as well as observe two or three of its decay modes and measure its mass to 1% or better, as seen in Fig. 4 [6]. The days of the Higgs boson are numbered!

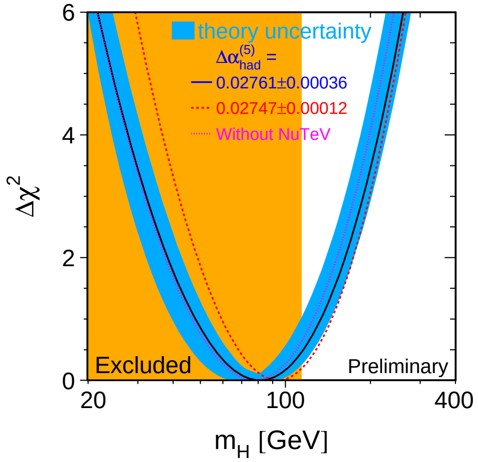

Figure 2: The χ^2 curve for a global fit to the precision electroweak data from LEP and elsewhere, with the uncertainties shaded in blue [1], favour a relatively light Higgs boson with mass close to the range excluded by experiment, shaded in yellow [3].

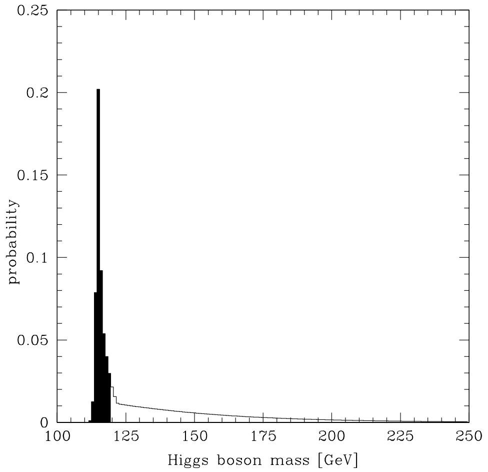

Figure 3: An estimated probability distribution for the Higgs mass [4], obtained by convoluting the blue-band plot in Fig. 2 [1] with the experimental exclusion [3].

4 SUPERSYMMETRY

The Higgs boson is confidently expected even within the Standard Model, but theorists think it should also be accompanied by some new physics beyond the Standard Model. The reason for this is to help understand the hierarchy of different mass scales in physics, and in particular why $m_W \ll m_P \sim 10^{19}$ GeV, the Planck mass scale where gravity is expected to become strong and the only candidate we have for a fundamental mass scale in physics. Equivalently, we might ask why there is a hierarchy of different interaction strengths: $G_F \sim 1/m_W^2 \gg G_N = 1/m_P^2$, or why the Coulomb potential $\sim 1/r$ inside an atom is so much larger than the Newton potential $\sim G_N m^2 = (m/m_P)^2$.

You might think one could just ‘set and forget’ the mass

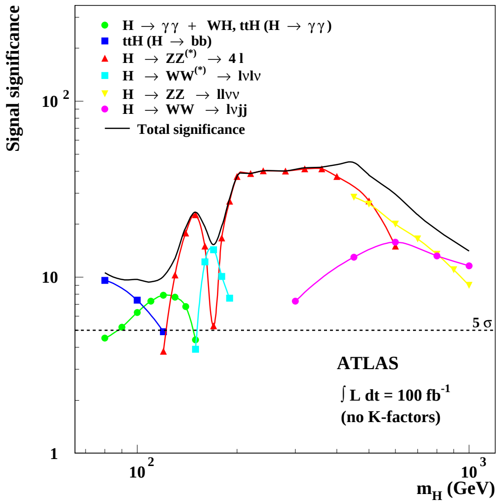

Figure 4: The LHC experiments will be able to discover the Higgs boson with high significance, whatever its mass, and may observe several of its decay modes [6].

hierarchy, but then it would be upset by quantum corrections. Typical one-loop diagrams in the Standard Model make contributions to the Higgs and $W^\pm$ masses that diverge quadratically:

$$\delta m^2_{H,W} \;\sim\; \mathcal{O}(\frac{\alpha}{\pi})\Lambda^2, \tag{3}$$

where Λ is a cutoff representing the energy scale at which new physics should appear. The quantum 'correction' (3) would be much larger than the physical value of m_W if the new physics scale $\Lambda \sim m_P$. However, the 'correction' (3) could be made naturally small by postulating equal numbers of bosons B and fermions F (whose loop diagrams have opposite signs) with equal coupling strengths α. In this case, (3) would be replaced by

$$\delta m^2_{W,H} \;\sim\; \mathcal{O}(\frac{\alpha}{\pi})\left(m^2_B - m^2_F\right), \tag{4}$$

which would be comparable to $m^2_{W,H}$ if

$$|m^2_B - m^2_F| \;\sim\; 1\ \mathrm{TeV}^2. \tag{5}$$

This is the motivation for low-energy supersymmetry [7].

There is no direct evidence for supersymmetry, but there are several indirect hints that supersymmetry may indeed appear at some energy scale below about 1 TeV. One is provided by the strengths of the electromagnetic, weak and strong interactions measured at LEP, which do not extrapolate to a common unified value in the absence of supersymmetry, but do unify at high energies if supersymmetric particles wighing $\sim$ 1 TeV are included in the renormalization-group equations [8], as seen in Fig. 5. Another hint is provided by the likely mass of the Higgs boson. In models with low-energy supersymmetry, it is calculated to weigh less than about 130 GeV [9], highly consistent with the range suggested by the precision electroweak data. A third hint may be provided by the dark matter thought to abound in the Universe. The lightest supersymmetric particle (LSP) is stable in the minimal supersymmetric extension of the Standard Model (MSSM), and would be an ideal particle candidate for dark matter if it weighs less than about 1 TeV [10].

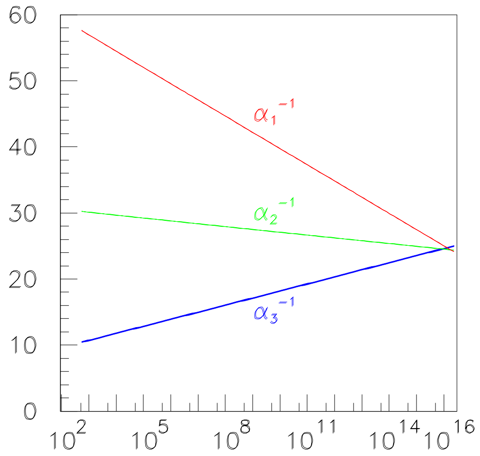

Figure 5: The measurements (vertical axis) of the gauge coupling strengths of the Standard Model at LEP and elsewhere can be evolved up to high energies (horizontal axis, in units of GeV) using renormalization-group equations incorporating supersymmetry. They are consistent with unification at a very high energy scale, but not with unification without supersymmetry [8].

On the other hand, no sparticles have ever been seen, in particular at LEP, imposing important constraints on the MSSM [11]. For example, charginos - the supersymmetric partners of the $W^\pm$ - must weigh more than about 103 GeV, and slectrons - the supersymmetric partners of the electron - must weigh more than about 100 GeV. The lower limit on the mass of the Higgs boson, mentioned above, also imposes an important constraint on the MSSM parameter space, as does the agreement between Standard Model calculations and the experimental rate of $b \to s\gamma$ decay, as seen in Fig. 6 [12].

As also seen in Fig. 6, a further experimental constraint is provided by the recent measurement of the anomalous magnetic moment of the muon, $g_\mu - 2$, even if it does not disagree significantly with the Standard Model [13]. As things stand, the measured value of $g_\mu - 2$ disagrees by 3 standard deviations with the best estimate based on $e^+e^- \to$ hadrons data [14], though the discrepancy with estimates based on $\tau \to$ hadrons data is less than 2 standard deviations.

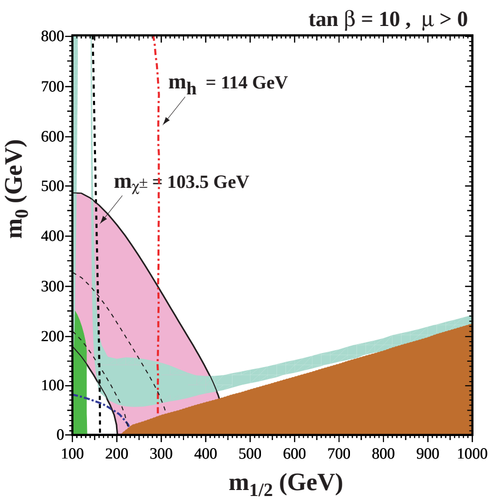

Figure 6: The parameter space of the MSSM projected onto the $(m_{1/2}, m_0)$ plane for $\tan\beta = 10$ and $\mu > 0$. The LEP lower limits on the Higgs, chargino and selectron masses are shown as (red) dot-dashed, (black) dashed and (blue) dash-dotted lines, respectively. The region at small $(m_{1/2}, m_0)$ excluded by $b \to s\gamma$ is shaded (green). The dark (red) shaded region is excluded because dark matter must be neutral, and the region where its relic density falls within the range preferred by cosmology has light (turquoise) shading. The region preferred by the BNL measurement of $g_\mu - 2$ and low-energy e^+e^- data is shaded (pink) [12].

5 BENCHMARK SUPERSYMMETRIC SCENARIOS

As seen in Fig. 6, all these constraints on the MSSM are mutually compatible. As an aid to understanding better the physics capabilities of the LHC, various linear e^+e^- linear collider designs and non-accelerator experiments, a set of benchmark supersymmetric scenarios have been proposed [15]. These are compatible with all the accelerator constraints mentioned above, including the LEP searches and $b \to s\gamma$, and yield relic densities of LSPs in the range suggested by cosmology and astrophysics. These benchmarks are not inteneded to sample 'fairly' the allowed parameter space, but rather to illustrate the range of possibilities currently allowed, as shown in Fig. 7.

In addition to a number of benchmark points falling in the 'bulk' region of parameter space at relatively low values of the supersymmetric particle masses, we also proposed some points out along the 'tails' of parameter space extending out to larger masses. These clearly require some degree of fine-tuning to obtain the required relic density [16] and/or the correct $W^\pm$ mass [17], and some are also disfavoured by the supersymmetric interpretation of the $g_\mu - 2$ anomaly, but all are logically consistent possibilities.

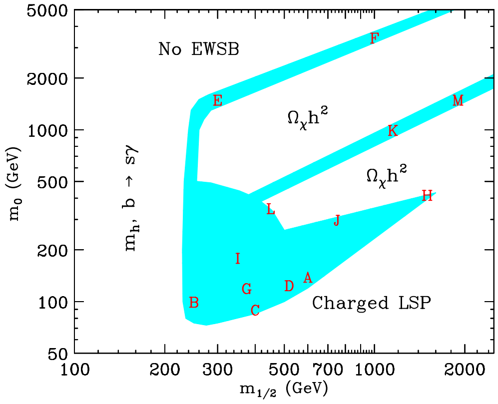

Figure 7: Sketch of the distribution of proposed CMSSM benchmark points in the $(m_{1/2}, m_0)$ plane [15]. These points were chosen as illustrations of the range of possibilities in the CMSSM, rather than as a 'fair' sample of its parameter space.

6 LHC PHYSICS

The cross sections for producing pairs of supersymmetric particles at the LHC decrease with increasing masses. Nevertheless, the signature expected for supersymmetry - multiple jets and/or leptons with a large amount of missing energy - is quite distinctive. Therefore, the detection of the supersymmetric partners of quarks and gluons at the LHC is expected to be quite easy if they weigh less than about 2 TeV [6]. Moreover, in many scenarios one should be able to observe their cascade decays into lighter supersymmetric particles [18]. As seen in Fig. 8, large fractions of the supersymmetric spectrum should be seen in most of the benchmark scenarios, although there are a couple where only the lightest supersymmetric Higgs boson would be seen [15].

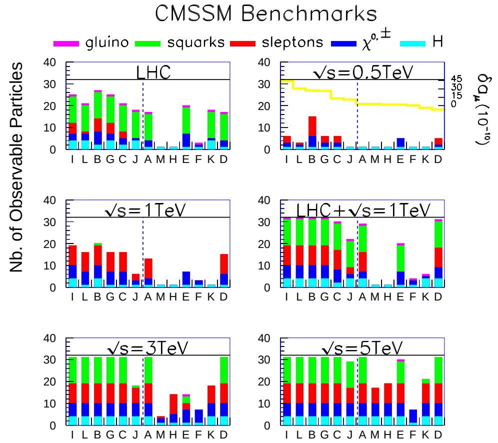

Figure 8: Estimates of the numbers of different CMSSM particles that could be seen in each of the benchmark scenarios [15], at each of the indicated colliders. The points are ordered from left to right by their decreasing compatibility with the BNL $g_\mu - 2$ measurement.

7 E^+E^- LINEAR COLLIDER PHYSICS

Electron-positron colliders provide very clean experimental environments, with egalitarian production of all the new particles that are kinematically accessible, including those that have only weak interactions. Moreover, polarized beams provide a useful analysis tool, and $e\gamma$, $\gamma\gamma$ and e^-e^- colliders are readily available at relatively low marginal costs.

The $e^+e^- \to \bar{t}t$ threshold is known to be at $E_{\rm CM} \sim 350$ GeV. Moreover, if the Higgs boson indeed weighs less than 200 GeV, as suggested by the precision electroweak data, its production and study would also be easy at an e^+e^- collider with $E_{\rm CM} \sim 500$ GeV. With a luminosity of 10^{34} cm^{-2}s^{-1} or more, many decay modes of the Higgs boson could be measured very accurately [19], and one might be able to find a hint whether its properties were modified by supersymmetry [20].

However, the direct production of supersymmetric particles at such a collider cannot be guaranteed [21], as seen in Fig. 8 [15]. We do not yet know what the supersymmetric threshold energy may be (or even if there is one!). We may well still not know before the operation of the LHC, although $g_\mu - 2$ might provide an indication, if the uncertainties in the Standard Model calculation can be reduced.

If an e^+e^- collider is above the supersymmetric threshold, it will be able to measure very accurately the sparticle masses. By comparing their masses with those of different sparticles produced at the LHC as seen in Fig. 9, one would be able to make interesting tests of string and GUT models of supersymmetry breaking [15]. However, independently from the particular benchmark scenarios proposed, a linear e^+e^- collider with $E_{\rm CM} < 1$ TeV would not cover all the supersymmetric parameter space allowed by cosmology.

Nevertheless, there are compelling physics arguments for such a linear e^+e^- collider, which would be very complementary to the LHC in terms of its exploratory power and precision. It is to be hoped that the world community will converge on a single project with the widest possible energy range.

8 CLIC

CERN and its collaborating institutes are studying the possible following step in linear e^+e^- colliders, a multi-TeV machine called CLIC [23]. This would use a double-beam technique to attain accelerating gradients as high as 150 MV/m, and the viability of accelerating structures capable of achieving this field has been demonstrated in the CLIC test facility [24]. Parameter sets have been calculated for CLIC designs with $E_{\rm CM} = 3$ and 5 TeV, and luminosities of 10^{35} cm^{-2}s^{-1} or more.

In many of the proposed benchmark supersymmetric scenarios, CLIC would be able to complete the supersymmetric spectrum and/or measure in much more detail heavy sparticles found previously at the LHC. CLIC produces more beamstrahlung than lower-energy linear e^+e^- colliders, but the supersymmetric missing-energy signature would still be easy to distinguish, and accurate measurements of masses and decay modes could still be made, as seen in Fig. 10 [25].

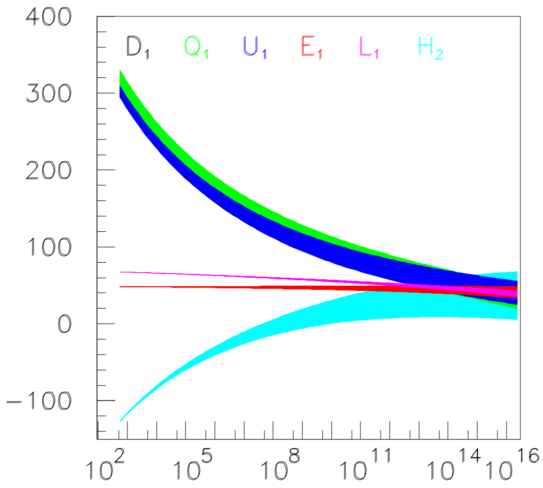

Figure 9: Analogously to the unification of the gauge couplings shown in Fig. 5, measurements of the sparticle masses at future colliders (vertical axis, in units of GeV) can be evolved up to high scales (horizontal axis, in units of GeV) to test models of supersymmetry breaking, in particular whether squark and slepton masses are universal at some input GUT scale [22].

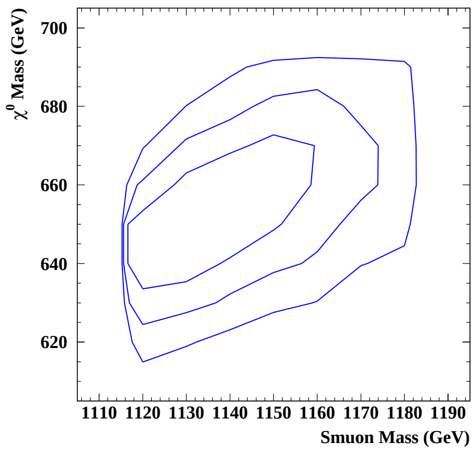

Figure 10: Like lower-energy e^+e^- colliders, CLIC enables very accurate measurements of sparticle masses to be made, in this case the supersymmetric partner of the muon and the lightest neutralino χ^0 [25].

9 PERSPECTIVES

In this brief talk, I have tried to explain why higher-energy physics requires higher luminosities and hence smaller beams. I have used the Higgs boson and supersymmetry as examples of the new physics that may be awaiting us at the TeV scale, and shown how they could be explored by colliders with luminosities that are sufficiently high. Other examples, including extra dimensions, are considered in [26]. One can already say that linear e^+e^- colliders with energies in the sub- and multi-TeV ranges would both be interesting.

What ideas exist for colliders to achieve even higher energies? One possibility might be a VLHC with $E_{\rm CM} \sim 100$ TeV or more. In order to realize its full kinematic potential, such a machine should have a luminosity of 10^{35} cm^{-2}s^{-1} or more, favouring very small beams. As for leptons, e^+e^- colliders with $E_{\rm CM} \sim 10$ TeV or more are very difficult to imagine. An alternative might be a very high-energy $\mu^+\mu^-$ collider, but this would have to surmount the hurdles of muon cooling and neutrino radiation.

Even before such futuristic devices, there will be plenty of work for the nanobeam community.

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