IS THERE A FUTURE FOR HIGH ENERGY ACCELERATORS?

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Abstract

The question of continuing viability of high energy accelerators as instruments of fundamental physics is discussed. It is seen that the next decade in elementary CM energies beyond SSC may be achievable with accelerators that can be imagined now. Beyond that there is room for doubt that accelerators will be the instrument of choice. History teaches that there is a good likelihood that our perspective on the matter will be much different when we see the results from the few TeV region of elementary collision energies.

I. Imperatives

The frontier of elementary particle physics has always been defined by the smallest distance scale achievable in the laboratory, i.e., the highest achievable collision energies. This inverse relationship between spatial resolution and momentum implies that the cross sections of interest will descend as the inverse square of the achievable CM collision energies. Known and projected cross sections for our current and near future parameter space are shown in Figure 1.

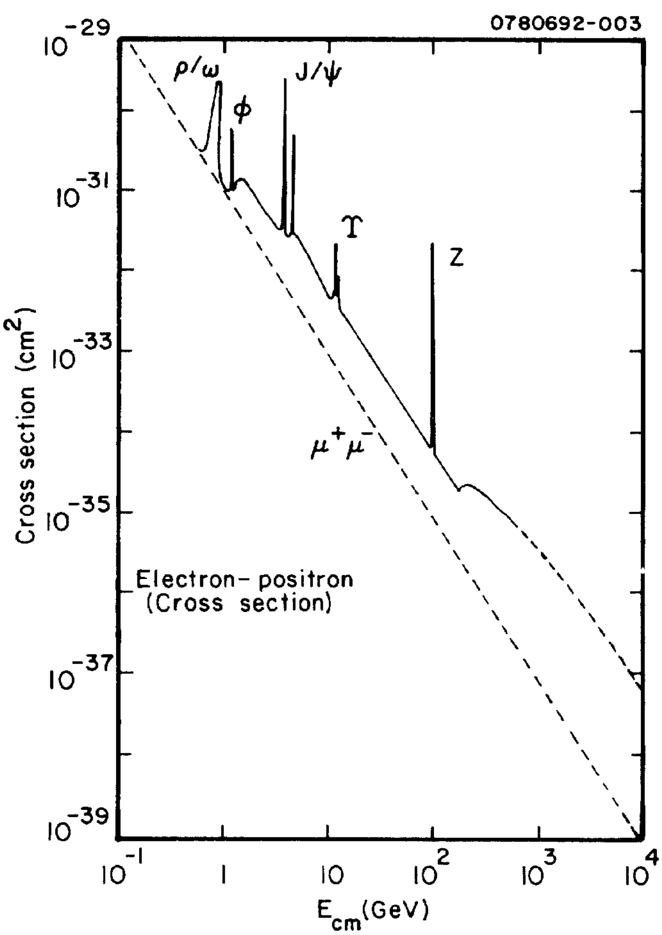

Figure 1: The elementary cross section as a function of collision energy

II. Goals

In the "near term" we need to find and explore the t, the Higgs mechanism, the gauge structure of the Standard Model and what ever else might crop up in the range between 100's of GeV and a few TeV. The vehicles will be SSC/LHC and perhaps a 1/2 TeV or more electron positron linear collider (LC). These we will consider here to be more or less in hand.

In the "mid term" we have the energy decade beyond that, say a few hundred TeV for pp and 10 Tev for electron positron collisions. Perhaps we'll be deep into supersymmetry and the final expose of the SM or seeing the first manifestations of strings or more likely something that we haven't imagined yet.

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While our imaginations are not really capable of dealing with the "far term" at all we do have the notion that something manifesting the unification of all the known interactions may come to pass at the 10^{19} GeV level, the Planck scale.

We have to ask, are these energies and the luminosities implied even thinkable today? For the regions just beyond SSC there is already a body of literature which grapples with some of the important issues[1, 2, 3, 4]. In trying to see even further beyond we need to study some basic constraints on accelerators that play together with the imperatives of energy and luminosity.

III. Further Accelerator Constraints

Important but not to be considered here are continuing world interest in elementary particle physics, world economy, other human factors and accelerator and detector technology. Here we will focus narrowly on energy(power) requirements. While the details are different for PP and e^+e^- collisions the overall conclusions are similar.

In the case of pp we note that a certain amount of energy is dissipated through lost particles at the IP. This is basic and is characterized by the total inelastic cross section. (For purposes of illustration we shall assume for a moment that the wall plug to beam power efficiency of the machine is 100%.) The minimum power spent ,or dissipated, is

$$\check{P}_{\rm dis} = \dot{N}_{\rm lost} \cdot E_{\rm cm};\ (\sim 1kW {\rm atSSC}). \quad \dagger \tag{1}$$

Putting that together with

$$\dot{N}_{\rm lost} = \mathcal{L} \cdot \sigma_{\rm inel} \tag{2}$$

and the fact that luminosity must scale as energy squared we find immediately that the dissipated power is roughly proportional to the cube of the energy. If we assume that the luminosity is 10^{33} in cgs units at 40 TeV in the CM and use the high energy limit of the Particle Data Book formula for the inelastic cross section we get a formula for the dissipated power as a function of energy

$$\check{P}_{\rm dis}\,[W] \sim 3.5 \times 10^{-5} E_{\rm cm}^3 \ln^2\left[5 \times 10^5 E_{\rm cm}^2\right];E_{\rm cm}\,[{\rm TeV}]. \tag{3}$$

IV. Consequences for PP

If for the moment we assume that we need, for economic reasons, to limit the dissipated power to O(1 GW) then we can solve our equation for center of mass energy to find

$$E_{\rm cm} \sim 0\,(4000{\rm TeV})\ {\rm or}\ 100 \times {\rm SSC/LHC}, \tag{4}$$

an interesting technical challenge for both detector and accelerator but far short of the Planck scale.

V. Further Accelerator Constraints for e^+e^-

While this situation is a bit more complex in detail for e^+e^- we can begin with similar considerations. The first basic phenomenon to be considered is beamstrahlung the radiation of colliding particles in the collective field of the oncoming bunch. This process is characterized by an rms fractional energy loss

$$\delta = \left\langle \frac{\Delta E}{E} \right\rangle \simeq \frac{0.22 r_e^3 N^2 \gamma}{\sigma_l} \cdot \left(\frac{2}{\sigma_h + \sigma_v}\right)^2. \tag{5}$$

For physics utility this energy spread must be kept more or less constant at the few % level. The specific luminosity is thus limited. (A similar phenomenon occurs in pp collisions but only at energies well beyond those considered above.)

For single pass linear colliders such as are now being considered

$$P_{\rm dis} = \delta \cdot P_{\rm B(eam)}. \tag{6}$$

Also, as is well known, basic relations lead to

$$\mathcal{L} \propto \frac{P_B \cdot \delta^{1/2}}{\gamma \epsilon_{v,n}^{1/2}}. \tag{7}$$

(Ideal focusing is assumed, i.e., no Oide limit). Remembering that luminosity must rise with energy squared

$$P_B \propto \gamma^3 \epsilon_{v,n}^{1/2} \delta^{1/2}. \tag{8}$$

Again the cube of energy appears in a difficult place.

VI. Consequences for e^+e^-

Before converting into a scaling formula for max. energy in terms of available power we should take account of accelerator efficiency

$$P_B = \eta_{\rm ac-beam} \cdot P_{\rm ac}. \tag{9}$$

If we take for our luminosity calibration point a figure of 10^{34} cgs at 1 TeV CM and use beam power from the highest specific luminosity version of LC(1/2 TeV), [O(1 MW)], together with the efficiency from the highest efficiency version (0.2) we can get and use a scaling formula for E as a function of ac power

$$E\,[TeV] \simeq \frac{1}{2}\left[\frac{P_{ac}}{10^6} \cdot \left(\frac{\epsilon_n(\frac{1}{2})}{\epsilon_n(E)}\right)^{1/2} \cdot \left(\frac{\delta(E)}{\delta(\frac{1}{2})}\right)^{1/2} \cdot \frac{\eta(E)}{\eta(\frac{1}{2})}\right]^{1/3}. \tag{10}$$

Assuming that, for fixed energy spread, that in the future we can get 10 fold improvement in emittance and 2 fold improvement in efficiency and that again we are limited to about 1 GW in ac power, we find the maximum allowed energy of about 5 TeV.

In that great beyond you might imagine that, since energy spread due to beamstrahlung is small that we might recover beam energy with some efficiency, [η_R] which is defined to include energy lost to beamstrahlung. Our formula is then modified in a transparent way to

$$E_{\mathrm{Rec}} = E_{\mathrm{noErec}} \cdot \sqrt[3]{\frac{1}{1-\eta_{\mathrm{R}}}}. \qquad (11)$$

For a 90% recovery efficiency we get a CM energy of about 11 TeV.

These examples are beamstrahlung limited. Suppose that we are able to apply some sort of beam neutralization using, for example, 4 beams ($e^+e^-e^+e^-$)[5] and thus avoiding beamstrahlung to a large degree. We still have the individual particle collisions (Bethe-Heitler cross section) to make radiation which will be lost from the system. The power dissipated at the assumed luminosity at 1 TeV will be about 2kW. This leads to an ultimate limit of 85 TeV if we restrict ourselves to 1 GW dissipation.

Before leaving this subject one might note that the EM process we're confronted with would be much eased if we could collide muons. This has not been included because the problem of production and damping seem too daunting the face of the need for energy squared scaling of the luminosity. Perhaps the future will show this too dim a view. Also there are proposals for photon colliders but from the present perspective the energy requirements seem even more restrictive than cases mentioned. Again, perhaps the future will find a way around this restriction.

VII. Further Considerations

We have somewhat, but not completely, arbitrarily chosen 1 GW as our allowed power consumption limit. Noting that

$$\hat{E} \propto P_{\mathrm{ac}}^{1/3}, \qquad (12)$$

we see that a large change in allowed power would be needed for even a modest change in top energy. Nevertheless, perhaps we're thinking too small. In the Amateur Scientist column of the April 1989 Scientific American[6] it is suggested, albeit tongue in cheek, that the power from the sun might be the appropriate limit for a Planck mass accelerator at 10^{26} W. However using our third power scaling law we'd need something like 10^{54} W to have the scaled luminosity it appears we would need. Perhaps an intergalactic collaboration is needed to do the job.

VIII. Outlook

One should not take the details of such predictions too seriously nor should one be overly discouraged by them. After all our forbears have spent the last 50 years building what was seen by the sages of each generation as "the last machine". Our visions are clouded by the limitations of current understandings and can only be used as a hint in which direction we should try to progress. It does seem from the above considerations that one strong emphasis needs to be energy consumption per important discovery. Perhaps we could help ourselves focus on energy or integrated power, IP, by rating our designs with an integrated power factor, IPF, giving the energy needed to produce one interesting event. One would use some standard elementary cross section like the annihilation cross section into muon pairs at the CM energy of momentary interest. For example, at 0.5 TeV our most optimistic "design" for scaling required about 5 MW at 10^4 mu pairs per 10^7 s year or 5^{13} J per 10^4 events for an IPF of 5 GJ/event.

In closing, let's borrow an analogy from Prof. Okun[7]. He sees the progress of physics as the building of a cathedral of physical understanding. Accelerator based scientists are building up from the foundation and the cosmologists and "theoretical" theorists are building from the top down. We can hope that they will actually be able to meet somewhere inbetween in a region accessible to accelerators. In this way we might hope to complete the cathedral even though accelerators can only cary us part way to the Planck scale.

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[†] In the formulae I have followed the common notations also used in refs. 1–4.