Report of the Hadron Experiments Group[+]

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Summary

This group considered in a general way the scope and limitations of some specific strong-interaction experiments that might be performed in the early days of a 20-TeV proton accelerator, both fixed-target and $\bar{p}p$-colliding-beam experiments. The group was loose-knit with individual members working rather independently on various topics, including secondary beams. The general conclusion is that many of the present-day experiments can be easily extrapolated to higher energies. While these experiments will be somewhat more costly, the cost will not be linear with energy and will represent a smaller investment compared with the accelerator than at present laboratories.

[+] Talk presented at the workshop on "Accelerator and Detector Possibilities and Limitations" sponsored by the International Committee for Future Accelerators (ICFA) and held at Fermilab, October 15-21, 1978.

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Introductory Remarks

We first get a feeling for some of the angles likely to be encountered at the Very Big Accelerator (VBA) for a proton beam of 20 TeV. Typical angles for elastic scattering are:

$$\text{Coulomb interference} \qquad \theta \sim \frac{40\ \text{MeV/c}}{20\ \text{TeV}} = 2\ \mu\text{rad},$$

$$\text{Diffraction peak} \qquad \theta \sim \frac{300\ \text{MeV/c}}{20\ \text{TeV}} = 15\ \mu\text{rad}.$$

Instead of the more familiar mrad units, we are now in the realm of μrad,

$$1\ \mu\text{rad} = 1\text{mm/km},$$

and a Coulomb interference experiment might need a few kilometers of drift distance (relatively cheap vacuum pipe). Note that these are typical laboratory angles for both fixed target and colliding beams.

For fixed target operation at 20 TeV ($\sqrt{s} = 200$ GeV), 90° in the center of mass corresponds to 10 mrad in the laboratory.

For 20 on 20 TeV colliding beams, $\sqrt{s} = 40$ TeV. This is a huge increase over present day energies and represents a total rapidity interval of

$$\Delta y \approx \ell n s = 21 \text{ units of rapidity.}$$

This energy is equivalent to a fixed-target lab energy of $\sim 10^{18}$eV, far beyond even most cosmic ray experiments. (With 8 Tesla magnets a fixed target machine of this energy would require a radius of 400,000 km, the distance from the earth to the moon!)

Five years ago Panofsky[1] made the compilation of machine energies versus time shown in Fig. 1. His straight line through the envelopes of the individual curves shows a factor of 10 increase in energy ($E_{lab} \propto s$) every

6 years. Such an exponential increase cannot continue forever, but if we can get the Very Big Accelerator (VBA) built by the year 2004, we will keep pace with the projection. This date certainly seems possible, and it would be fun to race the curve and beat it.

A compilation of multiplicities is shown in Fig. 2. An unimaginative extrapolation of the ISR fit would give $\langle N \rangle = 63$ charged particles per interaction at 20 on 20 TeV. The Centauro events with their high multiplicity of strongly-interacting secondaries, as well as the high multiplicities observed in extensive air showers (EAS), suggest a much steeper dependence, perhaps leading to some utterly spectacular interactions, radically different from those observed at present accelerators.

Beam Lines

As the beam energy increases and the particles become stiffer, beam lines get longer and require more magnetic field. In general, there is a tradeoff possible between the overall length of a beam and the length of the magnetic elements needed for focusing and momentum dispersion.

To study this in more detail we have taken a standard point-to-point beam stage shown in Fig. 3 with a parallel central region containing bending magnets (and possibly Cerenkov counters). The focal length ℓ of the quadrupole doublet has a dependence on momentum p

$$\ell \propto \frac{p}{B' L_Q}$$

where B' is the field gradient in the quadrupoles. If we fix B' and let all distances (both drift distances and magnet lengths) scale as $\sqrt{p}$, we maintain the same focusing properties (in this case point-to-parallel-to-point). This scaling works to all orders and is not just a thin-lens approximation. If the length of bend magnet is also scaled as $\sqrt{p}$, then the dispersion, $D = \Delta x/\Delta p/p$, is also constant. For a fixed magnet aperture a, the angular acceptance in this scaling goes as

$$\Delta\theta \approx a/\ell \propto 1/\sqrt{p}.$$

Of more interest is the transverse momentum bite

$$\Delta p_x = p\Delta\theta \propto \sqrt{p}.$$

Using this scaling for a secondary beam, one eventually gets to a point of diminishing return when Δp_x becomes larger than the typical transverse momentum in the production processes of $\sim \pm 0.4$ GeV/c. One could then go to smaller magnets and/or longer drift distances.

As an example, we consider a 20-TeV beam stage of total length 2.3 km. Most of this distance would be in two 1-km drift lengths of buried vacuum pipe. The main cost of the beam would be in the ~300 m of tunnel filled with quadrupoles and bending magnets. The focusing could be achieved with each element of the two quad doublets being 8 meters long (32 m for all four quadrupoles) with a strength that of the Fermilab Doubler quads, 80T/m (we have taken a separation of 10 m between the quadrupole centers in each doublet).

The acceptance for an aperture of 2 cm radius would be

$$\Delta p_T = 20\ \text{TeV} \times \frac{\pm 2\,\text{cm}}{1000\,\text{m}} = \pm 0.4\ \text{GeV/c}.$$

This would cover most of the forward peak at 20 TeV (but correspondingly less at lower momenta). While this has the obvious advantage of very high rates, it also means that unlike present-day machines which often have several beam lines looking at the same production target, at the VBA each secondary beam will need its own target and primary beam.

If we were to fill the central region with 200 meters of 8 Tesla bending magnets, the bend angle would be 24 mrad; with the focal length of 1100 m this becomes a displacement of 26 meters at the final focus. While 200 meters of 8 Tesla sounds like a lot of magnet, it is only 0.4% of that needed for the accelerator and can probably be obtained from the factory rejects - magnets not quite of accelerator quality, but adequate for beam lines. If we assume that multiple scattering effects are not important, and assume that we can make a $\pm$ 70 μm measurement at both the initial and final focus, we then get the spectacular resolution

$$\frac{\sigma_p}{p} = \frac{\pm\sqrt{2} \times 70\ \mu\text{m}}{26\text{m}} = \pm 4 \times 10^{-6}\ ,$$

$$\sigma_p = 20\ \text{TeV} \times 4 \times 10^{-6} = \pm 80\ \text{MeV},$$

still better than one pion mass! For many purposes we could obviously get by with less bending.

At the energies being discussed here, charged hyperon beams should be relatively straightforward to construct. As an example of a relatively short beam stage, consider that sketched in Fig. 4; this example was kindly calculated by Jon Sauer (Argonne) using the program TRANSPORT. By using superconducting quadrupoles of ~ 28 kG/cm gradient, we can achieve a suitable beam stage in only 232 m. At 15 TeV the mean free decay length for Ξ^- is 560 m, and about half of the Ξ^-'s would survive two such stages.

As shown, there is space for 60 m of sweeping magnet before the first quadrupole, enough to displace the 20-TeV proton beam by 5 cm at the first quadrupole, assuming a 15 kG sweeping field. If we used quads with an aperture of radius 1 cm, the acceptance would be

$$\Delta\theta = \pm 0.079 \text{ mrad} \qquad \Delta p_x = \pm 1.18 \text{ GeV/c}$$

$$\Delta\phi = \pm 0.130 \text{ mrad} \qquad \Delta p_y = \pm 1.96 \text{ GeV/c}$$

at 15 TeV (less at lower momenta)

The $\Delta p/p$ acceptance would be limited by the last quad to ±3.2% for a ± 1 cm aperture. The momentum resolution would be dominated by the primary-beam spot at the production target. Scaling the ±0.5 mm spot at the Fermilab Meson Area target by $p^{-1/2}$ would give a spot of ±70 μm. The dispersion at the focus is 0.89 cm/% and this leads to $\sigma_p/p = 0.0083\%$ or $\sigma_p = \pm 1.2$ GeV/c.

The physical layouts of the ZGS and Fermilab are compared with a highly conceptual layout for the VBA in Fig. 5. As the energy increases, the external beam lines occupy a smaller fraction of the site, as suggested by the square-root scaling. The exception to this may be the ν beam whose length tends to scale more linearly with energy, as discussed at this workshop by Amaldi. At the VBA a smaller fraction of the total cost of the accelerator complex will go to the external beams, and (assuming no major advance in accelerator technology), the machine itself will dominate both the costs and real estate.

Fixed Target Experiments

Sensitive Target

The use of a small rapid cycling hydrogen bubble chamber was considered by C. Fisher[2] as a track sensitive target for a hadron spectrometer. Such a system would allow the study of multiplicities, correlations, rapidity distributions, etc., in this new energy range, much as the 30-inch hybrid bubble chamber explored the Fermilab energies.

To minimize secondary interactions of the outgoing particles, the chamber would be kept fairly small, say a 20-cm diameter. Good separation of tracks would still be achieved by using two sets of cameras, one with high resolution and the other with a greater depth of field. With a cycle rate of 100 Hz, several thousand interactions per hour could be recorded, quickly filling up the world's analysis capability. Various beams could be used, including charged hyperons. Eventually, one might try to devise specific triggers in order to study particular classes of events. For example, triggers on K_s^o's and/or leptons might be used to enrich the sample with flavor cascades.

The high resolution system would also be useful in searches for particles with relatively short lifetimes. For example, a particle produced at rest in the center of mass and with a 10^{-13} sec lifetime would have a decay length of 3mm in the laboratory. This would allow studies of charm-producing events as well as searches for new, heavier particles produced at these high energies.

Exclusive and Inclusive π CEX and η Production

These processes have been studied at Fermilab by a Caltech-Berkeley collaboration using a segmented shower counter.[3] The resolution σ_E/E of such a counter improves with energy, and the counter would be moved back from the target, the drift length proportional to momentum to give the same separation of γ rays in the detector.

A sophisticated veto system would be used to suppress the inelastic background when studying the exclusive processes

$$\pi^- p \to \pi^o n,$$
$$\to \eta n .$$

The cross sections for such exclusive processes fall with energy and are well described over the range from a few GeV to 200 GeV by the form

$$d\sigma/dt \propto s^{2\alpha(t)-2}$$

where $\alpha(t)$ is the $\rho(A_2)$ Regge trajectory for $\pi^o(\eta)$ production. Going from 200 GeV to 10 TeV is a factor of 50 increase in s, and at $t = 0$ where $\alpha \approx 0.5$ we expect a loss in cross section of a factor of ~ 50; at $t \approx 0.6$ GeV^2 where $\alpha = 0$, this becomes a factor of 2500. Since the Fermilab experiment was able to collect 20,000 $\pi^o n$ events at each of several energies, an experiment at 10 TeV will still be able to achieve reasonable statistics in the forward region, but it will be difficult to collect data at $t \gtrsim 0.6$ GeV^2 if the present energy dependence continues unabated - of course, this is the reason for doing the experiment, to see if some other more-slowly-varying mechanism eventually comes into play.

The same apparatus was used to measure the inclusive reactions

$$\pi^- p \to \pi^0 X,$$
$$\to \eta X,$$

both for X = anything, the usual full-inclusive reaction, and for X = neutrals only (zero-prong events). The cross sections were well fit by the Triple Regge formulae

$$d^2\sigma/dtdx \;\alpha\; (1-x)^{1-2\alpha(t)} \quad \text{full inclusive,}$$
$$\alpha\; (1-x)^{1-2\alpha(t)}/s \quad \text{neutrals only.}$$

The trajectories are again expected to be those of the ρ and A_2 for π^0 and η production, respectively, and qualitative agreement was in fact obtained between the trajectories from the exclusive and inclusive reactions. The full-inclusive experiment should, if anything, be easier at the higher energy (better σ_E/E), while the neutrals-only will suffer from the factor-of-50 reduction in cross section, but should still be feasible.

Scattering off Electrons

The elastic scattering of pions and kaons off electrons in liquid hydrogen targets has been studied at present machines to obtain information on the meson form factors. A 15-TeV beam incident on a stationary electron will develope a $\sqrt{s} = 4$ GeV, equivalent to an 8-GeV e^-p interaction at SLAC. This is enough energy to not only improve considerably our knowledge of the meson elastic form factors, but to also begin studies of the "deep inelastic" characteristics of mesons for the first time.

Total and Elastic Cross Sections

These experiments should be straightforward extrapolations of present-day experiments, with drift distances proportional to energy. In addition to the standard set of particles ($\pi^{\pm}$, $K^{\pm}$ and $p^{\pm}$), we will have beams of hyperons ($\Sigma^{\pm}$, Ξ^{-}, Ω^{-}) and antihyperons available for these measurements.

Colliding Beam Experiments

Given the small angles characteristic of diffractive processes, measurements of small angle elastic scattering and even the total cross section will be difficult. Such experiments will require very parallel beams (high β) at the intersection point with some of the detectors embedded in the machine lattice at a position where the beam is focused down to a small spot. As an example we take the emittance $\epsilon = 13\,\pi/p$ mm mrad (p in GeV/c) found at Fermilab (basically, we assume that a machine such as that at Fermilab might be used as an injector for the VBA and that there is no dilution as the beam is accelerated). Then at 20 TeV and for $\beta = 1000$ m, the beam would have rms values of $\sigma_{p_x} = \pm 7$ MeV/c and $\sigma_x = 0.3$ mm. An elastic scatter of, say, $p_\perp = 100$ MeV/c will clearly take the particle outside the beam envelope, but it may prove difficult to devise a suitable detector which can be sensitive close enough to the beam to actually see such a scatter unless very long effective focal lengths can be used.

Observation of particles at large angles is certainly easier, and is presumably more interesting in that new heavy particles would likely give decay products with high $p_\perp$ in this region. Detectors could look much like those presently planned for colliding beams at Fermilab and the SPS. A large magnet, either solenoid or dipole, would measure well the charged particles with $p_\perp \leq 50$ GeV/c, while higher energies would be measured in a hadron calorimeter. The electrons and γ-rays would be precisely measured in shower counters. Fig. 6 shows the resolutions for various particles calculated for a solenoid configuration at Fermilab.[4] The combination of magnetic field plus calorimetry works nicely for most particles over a broad range of energy. In particular, the measurement error on the energy of a jet is $\sigma_E/E = (2$ to $4)\%$ for all energies above a few GeV. At the higher energies the main limitation will likely come from the systematics in keeping a large calorimeter properly calibrated; with care and present technology one can probably do a factor of two better than the ±3% assumed in Fig. 6.

Present theoretical prejudices lead us to believe that the cross sections for particle and jet production at large $p_\perp$ will increase dramatically at these energies. Rick Field (Caltech) has kindly extended his QCD calculations[5] to $\sqrt{s} = 40$ TeV for this Workshop, with the results shown in Fig. 7. At $p_\perp = 200$ GeV/c the cross sections rise by 4 or 5 orders of magnitude in going from $\sqrt{s} = 1$ TeV to 40 TeV. Although the extrapolation is a long one, the calculations suggest that we should be able to see single particles with $p_\perp = 1000$ GeV/c even with modest luminosities. For example, consider a large-angle detector covering 15° to 165° ($\Delta y = 4$ rapidity units). Then

$$\frac{d\sigma}{dp_\perp} = 2\pi \, \Delta y \, p_\perp \left(E \frac{d\sigma}{d^3p} \right)$$

$$\approx 25\, p_\perp \left(E \frac{d\sigma}{d^3p} \right)$$

Taking a bin of width $\Delta p_\perp = 100$ GeV/c at $p_\perp = 1000$ GeV/c, the curves in Fig. 7 indicate a corresponding cross section of

$$\Delta\sigma = 1 \times 10^{-36}\ \text{cm}^2 \text{ for } \pi^0\text{'s},$$

$$= 0.5 \times 10^{-33}\ \text{cm}^2 \text{ for jets.}$$

A run of several months with an average luminosity of 10^{30} cm^{-2} sec^{-1} would give an integrated luminosity of 10^{37} cm^{-2} and thus 10 π^0's and 5000 jets in this bin. At 200 GeV/c, a bin with $\Delta p_\perp = 20$ GeV/c would have 8000 π^0's and 4×10^6 jets. Clearly we will need to suppress common garden-variety jets with such "low" $p_\perp$!

Limitations

Since the title of this Workshop includes the word "limitations," we have gone looking for them:

1) Particle identification. This has been discussed in detail by Willis.[6] Although transition radiation and synchrotron radiation are useful at very high energies, there are intermediate values of γ which are awkward. Already at present day energies it is quite difficult to identify particles over more than a very limited solid angle, so this is not really a new limitation for many types of experiments.

2) Beam splitting. As mentioned in an earlier section, each secondary beam will require its own target and thus its own primary beam. If more than one beam is to run simultaneously, the external beam must be split, presumably with electrostatic wire septa. This already poses problems at

Fermilab, and at 50 times the energy will be much more difficult at VBA.

3) Small-angle colliding beam experiments. Experiments to measure diffractive processes will need to be able to see down to $\leqslant 10$ μrad, and will require a long drift space, difficult to find in an accelerator. Even with a lens system with an effective focal length of 1 km a proton scattered by 10 μrad will still only be 1 cm from the beam. Coulomb interference with an angle of typically 2 μrad at 20 TeV will be especially challenging.

Conclusions

Many hadron experiments at the VBA will be straightforward extrapolations of experiments at present energies. In general, these experiments will be somewhat more costly, but scaling more slowly than linear with energy. The beam lines will also share this type of cost dependence. A simple scaling of beam line lengths is proportional to $\sqrt{p}$, but optimization and advances in magnet technology may well result in an even slower scaling of costs. Assuming no major advances in technology, it seems that beam lines and experiments will be a smaller fraction of the total cost of the accelerator complex than is true today.

Acknowledgments

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References

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2. C. Fisher, these proceedings.
3. A. V. Barnes et al., Phys. Rev. Letters 37, 76 (1976); O. I. Dahl et al., Phys. Rev. Letters 37, 80 (1976); A. V. Barnes et al., CALT-68-664 and CALT-68-667 (1978).
4. C. Ankenbrandt et al., Fermilab Note CDF-11 (1978).
5. R. D. Field, Plenary talk at the Tokyo Conf., CALT-68-683 (1978).
6. W. Willis, these proceedings.

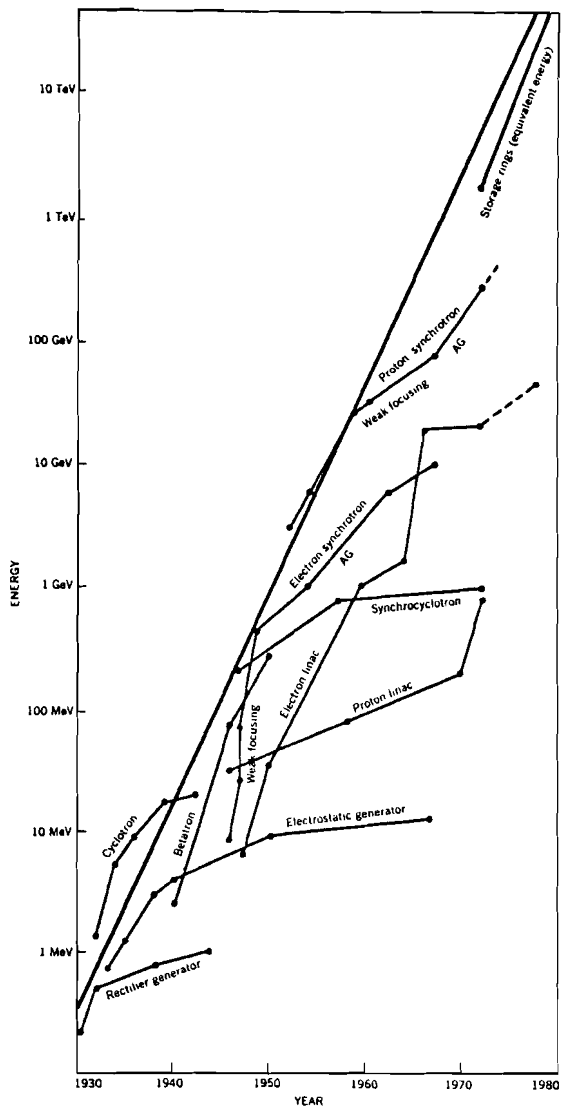

Fig. 1. Energy growth of accelerators compiled by Panofsky in 1973 (Ref. 1).

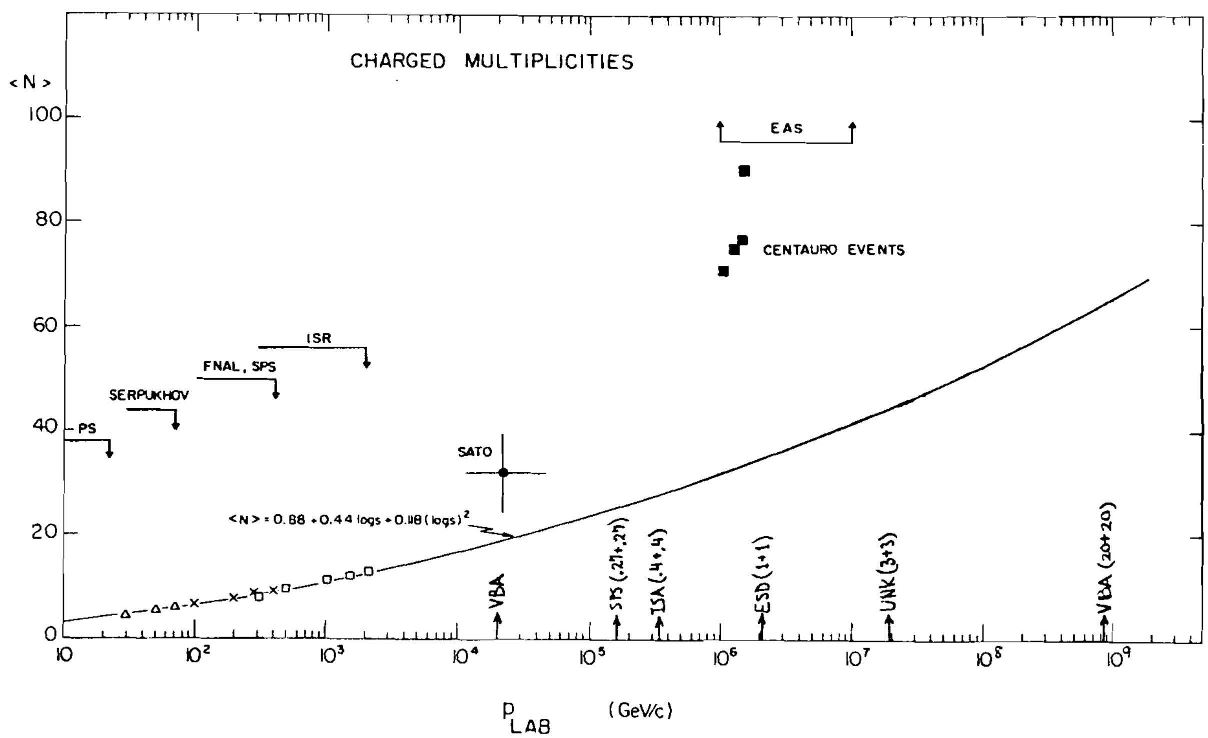

Fig. 2. Charged particle multiplicities plotted as a function of laboratory energy. The Centauro points show strongly interacting particles per event and are taken from Paper 434 submitted to the Tokyo Conference. The quadratic fit found at the ISR has been extrapolated to higher energies.

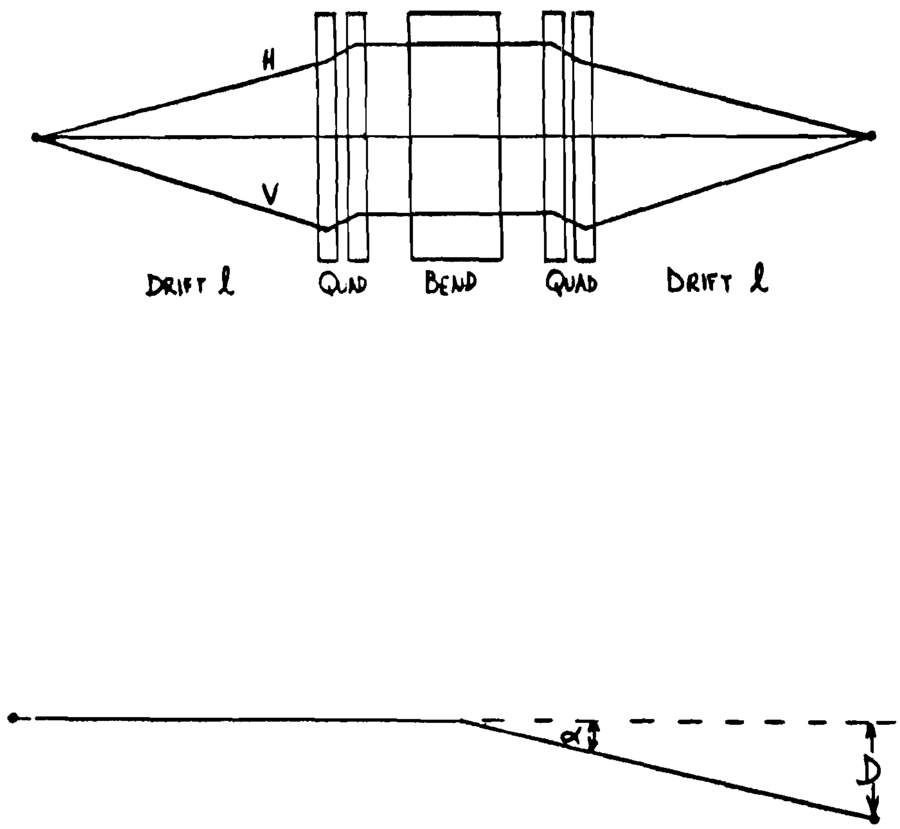

Fig. 3. Point-to-point beam stage.

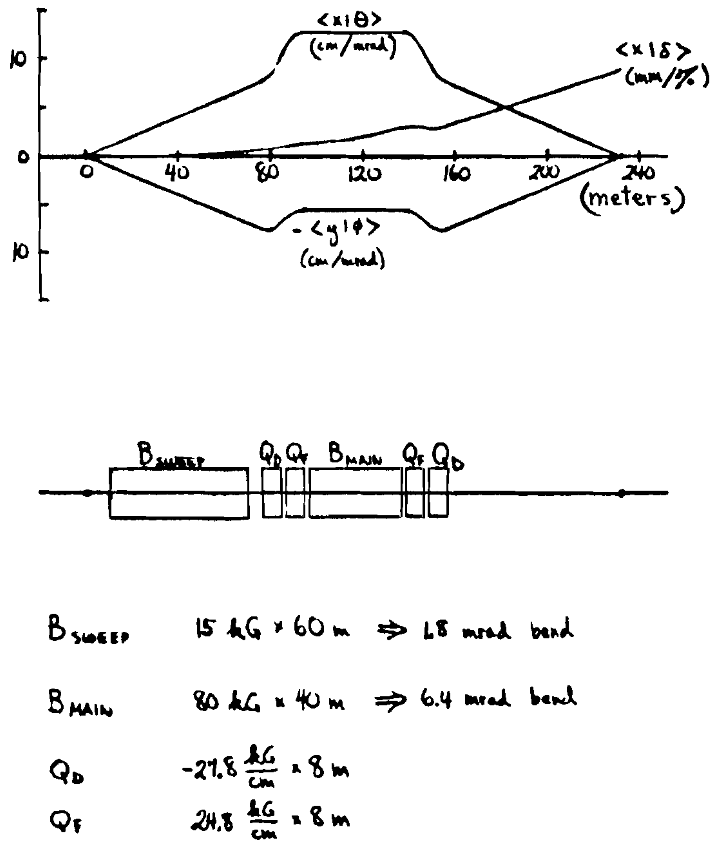

Fig. 4. 15-TeV hyperon beam.

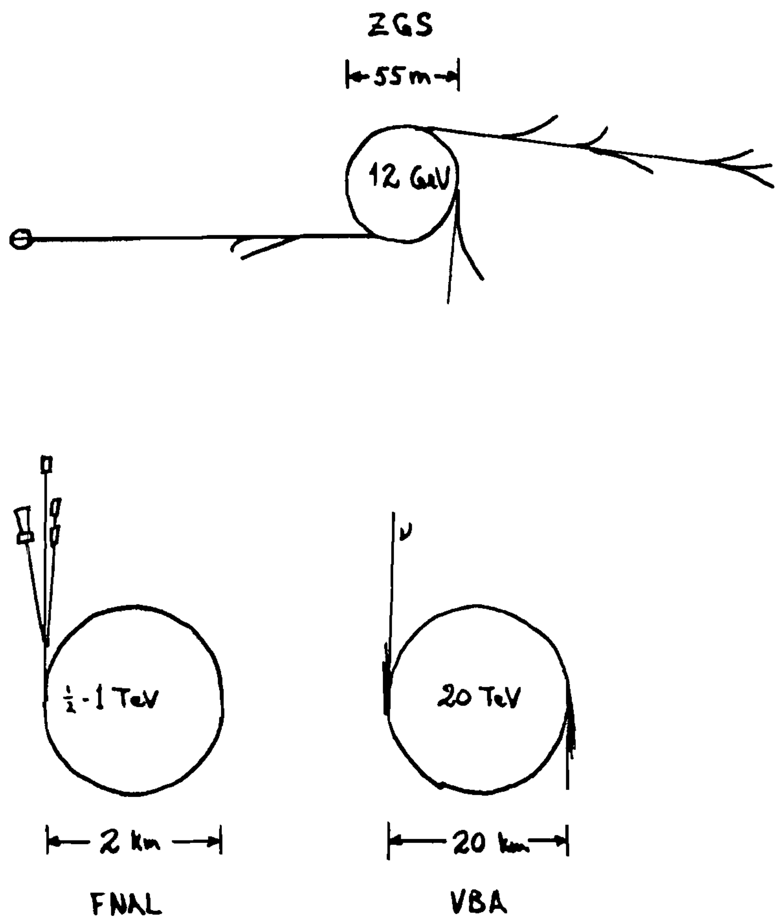

Fig. 5. Site plans for three laboratories, showing that the external beam lines become a relatively smaller part of the laboratory as the energy increases.

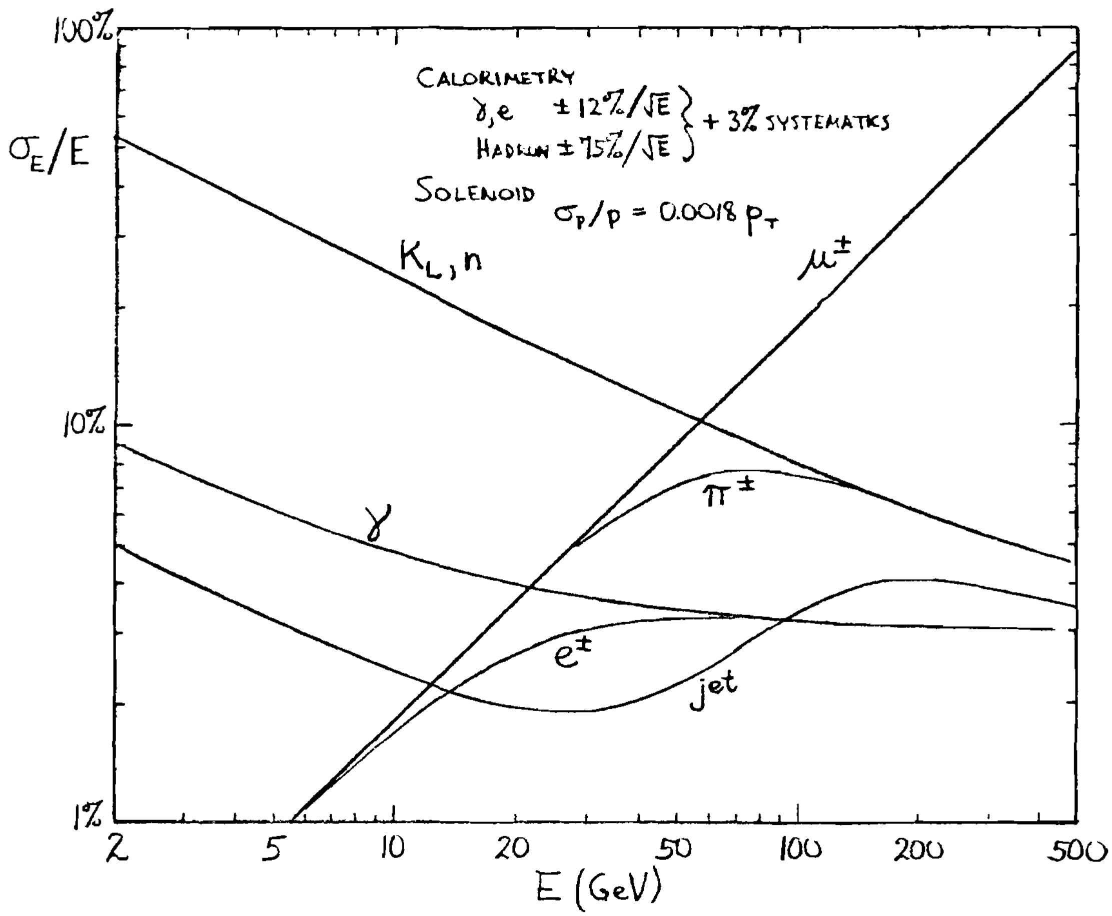

Fig. 6. Energy resolution calculated for various types of particles to be detected in a large solenoid detector system (Ref. 4).

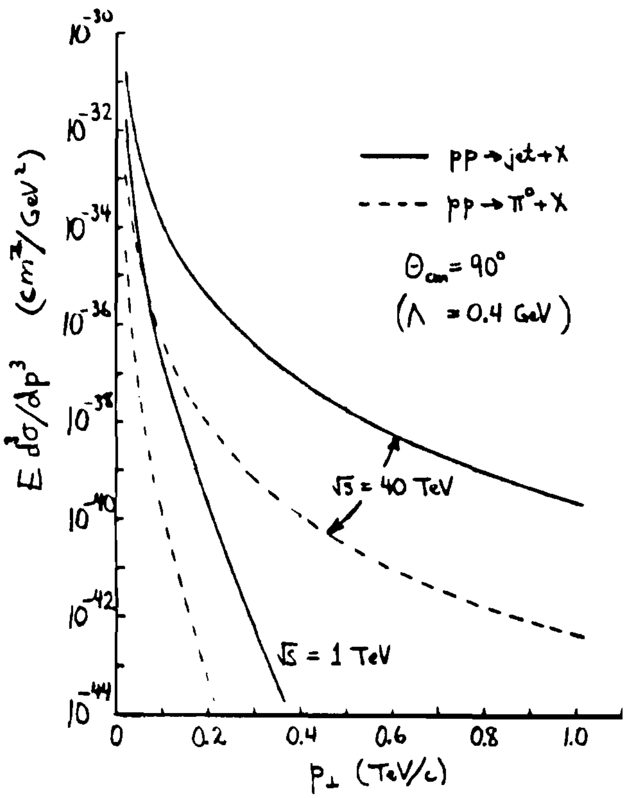

Fig. 7. QCD calculations by R. D. Field