DETECTORS AND LUMINOSITY FOR HADRON COLLIDERS

ANL-HEP-CP--83-01

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DE83 010707

ABSTRACT

Three types of very high energy hadron-hadron colliders are discussed in terms of the trade-off between energy and luminosity. The useable luminosity depends both on the physics under study and the rate capabilities of the detector.

INTRODUCTION

In designing new hadron colliders for very high energies, one must consider whether for a fixed overall cost it is better to emphasize energy or luminosity. In particular, the single ring of magnets allowed by a $\bar{p}p$ scheme would give an energy about 1.5 times higher than could be afforded with a higher luminosity pp scheme requiring a second ring. A related question in the pp case is whether the better duty factor of unbunched ("DC") beams is worth the complications caused by the larger number of protons required.

MASTER

The answers to these questions depend on the interplay of many factors:

1. Accelerator possibilities - the luminosity and time structure of collisions depend on the various machine options.
2. Detector rate capabilities - could the detectors handle high luminosity even if available?
3. Physics signature and backgrounds - some signatures are easy to pick out in a flood of random events, while others are very sensitive to rate problems.
4. Cross sections for the processes of interest - the luminosity/energy trade-off depends on both the absolute values and energy dependences.

These factors were considered in varying detail by groups at the Snowmass Summer Study. The Conventional $p\bar{p}$ Collider Accelerator Group, which I coordinated under Maury Tigner's direction, considered the performance of different types of colliders.¹ The Hadron-Hadron Collider Group, chaired by R. Palmer and J. Peoples, investigated the trade-off between luminosity and energy for several "bellwether" experiments.² While some thought was given to detector rate capabilities^{3,4}, no consensus was reached and this topic will be further studied in a one-week DPF Workshop at Berkeley this winter.

In the following I will draw heavily from the work at Snowmass,

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but will somewhat expand and interpret the results.

ACCELERATOR OPTIONS

We first consider bunched beams. For a total cross section of $100 \text{ mb} = 10^{-25} \text{ cm}^2$, the luminosity per bunch collision is

$$L = 10^{25} \langle n \rangle \text{ cm}^{-2},$$

where $\langle n \rangle$ is the average number of interactions per bunch collision. If the bunches are separated by $d = c\Delta t$, the luminosity is simply

$$\mathcal{L} = 10^{25} \langle n \rangle / \Delta t \text{ cm}^{-2} \text{ sec}^{-1}.$$

The constraint on luminosity from accelerator technology comes mainly from the minimum bunch separation that can be tolerated. Beam instabilities require that the bunches collide at only a few points around the ring, and sufficient space must be left such that the orbits of the two beams are well separated before the bunches next pass one another after the experimental interaction region. For pp bunched beams, this is easily done with dipole magnets on either side of the interaction region. Allowing ± 10 -meters free space for the detector, Fig. 1 shows that the minimal bunch separation is approximately 30 m (100 nsec), giving

$$\mathcal{L}(\text{pp bunched}) = 1 \times 10^{32} \langle n \rangle \text{ cm}^{-2} \text{ sec}^{-1}.$$

Fig. 1. Sketch of pp beam separation (from Ref. 1). Bunches (solid circles) can be spaced by ~ 30 m and still be separated when they next pass one another (indicated by the open circles).

The separation of $\bar{p}p$ orbits is considerably harder and requires the use of electrostatic separators. For maximum effectiveness, these must be placed some distance from the interaction region, at a position where the beam is large and relatively parallel (large machine parameter β). The 20-TeV example taken at Snowmass, and sketched in Fig. 2, used separators of length 7 meters operating at 65 KV/cm. This gave an orbit separation of up to ± 2.5 mm, sufficient to allow four bunches per betatron wavelength, so that $d = 240$ m (800 nsec), and

$$\mathcal{L}(\bar{p}p \text{ bunched}) = 1.25 \times 10^{31} \langle n \rangle \text{ cm}^{-2} \text{ sec}^{-1}.$$

For both the pp and $\bar{p}p$ cases, a normalized emittance of $\epsilon_N = 10\pi \times 10^{-6}$ meters was assumed for each transverse dimension. This is two or three times smaller than existing machines, but can probably be obtained with sufficient care. For a 2-meter β function at the interaction point, the number of particles per bunch for beams of equal intensity is

$$N = 1.4 \times 10^{10} \sqrt{\langle n \rangle}.$$

For the canonically allowed beam-beam tune shift, $\Delta\nu = 0.005$, values of $\langle n \rangle$ up to 25 are allowed. Higher interaction rates could, in principle, be achieved by enlarging the emittance, in which case the scaling goes as

Fig. 2. Sketch of $\bar{p}p$ beam separation (from Ref. 1). In order for the bunches to be well separated by their next meeting (open circles), they must be spaced apart by ≥ 240 m.

$$N = 7 \times 10^{10} \ (\langle n \rangle / 25).$$

The tune shift limit used above may be pessimistic, in which case the square-root scaling could be extended to higher values of $\langle n \rangle$ before having to switch over to linear scaling.

For the unbunched, "DC," pp case, the interactions occur randomly, and the comparison to the bunched cases depends on the detector rate capability. The luminosity can be expressed in terms of the average time between interactions as

$$\mathcal{L} = 10^{34} / \langle \Delta t \rangle \text{ cm}^{-2} \text{ sec}^{-1},$$

where $\langle \Delta t \rangle$ is in nsec. If we had a detector with components all having memory times ≥ 100 nsec, bunched pp beams would be preferred to unbunched; not only would the events be easier to unscramble, but fewer protons would be needed and cosmic ray background would be reduced.

Table I summarizes some typical parameters that might be expected for 20-TeV, 10-Tesla colliders. At Snowmass it was assumed⁵ that an extrapolation of Tevatron I technology could increase the $\bar{p}$ collection and cooling rate from 10^{11} /hour to 10^{12} /hour; this would result in a collection time of 4 (20) hours for $\langle n \rangle = 1$ (25). The unbunched pp option is shown for $\langle \Delta t \rangle = 50$ and 2 nsec. Above 10^{14} particles per beam, increased sophistication will be required for protection, beam dumps, etc., as well as for prevention of synchrotron radiation overloading the magnet refrigeration system.⁶

DETECTOR RATE REQUIREMENTS AND CAPABILITIES

The rate requirements of a detector depends on the physics and type of event being examined, but typically we need

1. the ability to identify two overlapping events;
2. short live time and/or sufficient segmentation to avoid pile-up and deadtime;
3. triggers and data-collection systems that can record events without excessive deadtime;
4. hardware that gives information in a form allowing rapid analysis (computer time will often be the ultimate limit in our ability to find rare events); and
5. detector systems that can withstand high rates over a long period of time.

Over the past decade, the trend has actually been to slower detectors, especially for e^+e^- detectors where the event rates are

Table I. Typical time structure, luminosity ($\text{cm}^{-2} \text{sec}^{-1}$), and number of particles per beam for three modes of operation (Ref. 1). For bunched beams, Δt is the time between bunch collisions; in the unbunched case, Δt is the memory time of the detector, taken to be 50 nsec as an example for this table.

	Δt (nsec)	$\langle n \rangle = 1$ N $\mathcal{L}$ ($10^{14}/\text{beam}$)		$\langle n \rangle = 25$ N $\mathcal{L}$ ($10^{14}/\text{beam}$)	
Bunched $\bar{p}p$	800	0.12	0.04	3	0.2
Bunched pp	100	1.0	0.3	25	1.4
Unbunched pp	(50)	2.0	2	50	9

inherently low. For example, drift chambers giving higher resolution with fewer electronics channels have largely replaced the faster multiwire proportional chambers. Time projection chambers have excellent pattern recognition properties but long memory times. For calorimeters, fast directly-viewed scintillator has been largely replaced with slower wave-length-shifter readout or wire chambers with pad readout.

Some typical live times are given in Table II. With today's technology, one may be able to do better with small-scale devices, but, in general, colliding beam detectors require large-scale systems. In most cases, it is at least possible to distinguish two events on a much shorter time scale, though at some cost for multihit electronics. With some fast elements (for example, scintillation hodoscopes), one can define roads and sort out the event of interest even if the other subsystems are slower; the amount of computer time necessary to unscramble all this may still be prohibitive. With several different subsystems in a large detector, the ultimate rate capability will, to some extent, be limited by the slowest component.

Table II. Typical memory times for detector subsystems.

Tracking (BNL-MPS 3-mm drift)	55 nsec
Particle ID (Imaging Cerenkov, dE/dx , TRD)	~ 300
Calorimetry	
Lead glass	30
Scintillator with wavelength shifter (CDF)	100
Liquid argon	200
Pad chambers (CDF)	300

Some indication of the rate capacity of "4 π " solid angle colliding beam detectors can be obtained by looking at the rates allowed by the large aperture multiparticle spectrometers used for fixed target work. The MPS's at Fermilab and Brookhaven³ typically run at $\leq 3 \times 10^6$ beam per sec of spill. For a 1-meter long liquid hydrogen target ($\sim 10\%$ of an interaction length), this works out to $\leq 10^{31}$ cm⁻² sec⁻¹ during the spill. With some improvements one could run these spectrometers at a higher rate. On the other hand, at collider energies, the cross sections are larger, the multiplicities are up, and there is no interspill period to write tape, etc.

Experience with high luminosity running at hadron colliders is somewhat limited. In a recent paper⁷, the Axial Field Spectrometer group at the ISR describes a run at 1.4×10^{31} cm⁻² sec⁻¹ which gave a pile-up background of 9% (21%) when looking at events with $E_T = 6$ (14) GeV. A brief run has been made at ten times this luminosity and the results are being analyzed.

OPTIMAL $\langle n \rangle$

The optimal number of interactions per bunch crossing (or per detector resolution time) depends not only on the detector, but, even more importantly, on the physics being examined. Some examples are listed here.

1. Multiplicity Tail. $\langle n \rangle \sim 10^{-4}$

In this case one must avoid a second interaction with vertex within position resolution of the first. Even for $\bar{p}p$ one could still look at up to 10^7 interactions per day.

2. Exploration. $\langle n \rangle \sim 1/2$

This value of $\langle n \rangle$ would give one and only one interaction for 30% of the bunch collisions, compared with maximum $1/e = 37\%$ for $\langle n \rangle = 1$, and would give some suppression of multiple interactions. One would use such a rate to look for gross features of events, search for Centauros, etc.

3. Heavy Quarks. $\langle n \rangle \sim 2$

Here one needs tracking for lepton and hadron identification, as well as possible high resolution vertex detection, so the situation cannot be allowed to get too confused, both because of possible backgrounds and finite computing resources. We might expect to have in the central tracker

$$\langle n_{\text{chg}} \rangle = \langle n \rangle \frac{dN_{\text{chg}}}{dy} \Delta y = 2 \times 5 \times 4 = 40$$

charged tracks (plus secondary interactions, albedo from calorimeters, etc.).

Fig. 3. False trigger rate for the ($\Delta y = 1$, $\Delta\phi = 90^\circ$) interval having the largest $\Sigma|p_T|$ for $\langle n \rangle = 1$ (triangles) and $\langle n \rangle = 10$ (solid circles), where only calorimeter towers with $p_T > 1$ GeV/c were used in the sum (from Ref. 3). For comparison, the open circles show the rate expected from ISAJET for inclusive jet production.

4. High Momentum Transfers. $\langle n \rangle \sim 10$ to 30

One would give up on tracking and simply look at energy flow in the calorimetry. The minimum bias events would just give a faint glow throughout the calorimeters, and one would look for hot spots of P_T into a limited region of phase space. Gordon et al.³ looked at this with the ISAJET Monte Carlo program for $\sqrt{s} = 800$ GeV and $\langle n \rangle = 10$. As shown in Fig. 3, the random background from minimum bias events is calculated to be negligible for $p_T > 10$ GeV/c.

5. Muon Pairs. $\langle n \rangle \sim 100$

The decay space would be minimized and the detectors hidden behind lots of absorber. Each beam crossing (or detector sensitive time) would give ~ 2000 charged mesons in the central region. Even with 10 interaction lengths of absorber, punch-throughs would be reduced by only $e^{10} = 2 \times 10^4$.

ENERGY DEPENDENCE OF CROSS SECTIONS

Hard collisions are thought to occur between point-like partons - quarks and gluons within the protons and antiprotons. Each parton has a fraction, x_1 , of the beam momentum, and the incident beams may be thought of as unseparated, broad-band parton beams. The subenergy squared in the parton-parton system is given by

$$s = x_1 x_2 s = \tau s \quad ,$$

where s is the overall pp (or $\bar{p}p$) center-of-mass energy squared. The structure functions giving the parton distributions in x_1 have been deduced from various experiments and a folding operation gives the probability distributions or effective luminosity for each parton-parton combination. Examples are shown in Fig. 4. As expected, the effective luminosity falls rapidly as τ increases, with gluon-gluon luminosity having the largest value at small τ and valence quarks becoming dominant at large τ .

The gluon-gluon effective luminosity for fixed $\sqrt{s}$ is plotted in Fig. 5 as a function of $\sqrt{s}$. The slope of these curves directly gives the tradeoff between luminosity and energy. Near threshold a small increase in energy can give orders of magnitude increase in the effective luminosity; well above threshold, the curves flatten such that it takes a factor of 2 or 3 in energy to boost the effective luminosity by an order of magnitude.

For hard scatters with typical $\sqrt{s} \sim p_T \sim \Lambda$, the theoretical scaling goes roughly as²

$$\sigma = \alpha_1^2 \frac{4\pi}{\Lambda^2} = \frac{\alpha_1^2 10^{-32} \text{ cm}^2 \text{ TeV}^2}{\Lambda^2} \quad ,$$

where α_1 is the coupling constant appropriate to the interaction.

Fig. 4. Differential parton-parton luminosities per $\bar{p}p$ collision as a function of $\sqrt{s}/s$ (from Ref. 8).

Fig. 5. Differential gluon-gluon luminosity as a function of $\sqrt{s}$ for various $\sqrt{s}$ (from Ref. 8).

An example of this is the well-known relation

$$\sigma(e^+e^- \rightarrow \mu^+\mu^-) \propto 1/s$$

For color interactions $\sigma \sim 10^{-34} \text{ cm}^2$ for $\Lambda = 1 \text{ TeV}$, and it is clear that substantial luminosity will be needed to explore such processes. If there turns out to be structure within the quark, we could get the "geometric" cross section, i.e., $\alpha \sim 1$ and $\sigma \sim 10^{-32} \text{ cm}^2$ for $\Lambda = 1 \text{ TeV}$.

Diffractive processes, in which there is coherence of the proton as a whole, are not bound by the above relations and can have large cross sections, even at high energies. There have been reports⁹ of substantial diffractive production of charm at the ISR, and one explanation of the Centauro events seen in cosmic rays would be diffractive dissociation (with $\sigma \sim 1 \text{ mb}$) of an incident proton into an object of mass $\sim 200 \text{ GeV}$.

Seven "bellwether" reactions were used by the "Hadron-Hadron Collider" group at Snowmass to study the luminosity-energy tradeoff.² In general, the group concentrated on event rates rather than examining in detail event selection, backgrounds, detector rate capabilities, etc. For each reaction the value of M or p_T was found for which 100 events would be expected in 10^7 seconds (approximately a year of running). This was done at several values of $\sqrt{s}$ for average luminosities of 10^{30} , 10^{32} , and $10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$.

Although some of these events will have spectacular signatures, the 100 events must be pulled out of an enormous background (10^{12} , 10^{14} , or 10^{16} events for the three levels of luminosity). There is a "Catch 22" at work here - as the luminosity is increased, the rate-dependent backgrounds become worse, while at the same time we need ever better background rejection.

The results of these calculations are shown in Fig. 6 for jet production, techni-etats, and Drell-Yan muon pairs. For the n_T , an efficiency of 10% was assumed after applying cuts. In the region near $\sqrt{s} = 20 \text{ TeV}$ and $\mathcal{L} = 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, the slopes of the curves give an order of magnitude in luminosity being roughly equivalent to a factor of 1.5 in $\sqrt{s}$ for jets or a factor of 2 for techni-etats. For muon pairs, the relatively low electromagnetic cross section results in luminosity playing the dominant role. Table III summarizes the mass and p_T limits obtained from this study for $\sqrt{s} = 40 \text{ TeV}$. For $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, these limits range from 0.4 TeV for muon pairs to 8 TeV for jets; the latter corresponds to probing distances of approximately $5 \times 10^{-18} \text{ cm}$.

Some words of caution are in order. First, as discussed above, the detectors may not be able to tolerate high luminosity; this may be a particular problem for the techni-etats if their selection requires particle identification. Second, the cross sections were

Fig. 6. Contours of M or $2p_T$ giving 100 vents in 10^7 sec (from Ref. 2).

Table III. Values of $\sqrt{s}$ (M or $2p_T$) in TeV giving 100 events in a year's time (10^7 sec) for $\sqrt{s} = 40$ TeV at various luminosities (Ref. 2).

$(\text{cm}^{-2} \text{ sec}^{-1})$	Jets ($2p_T$)	n_T (M)	$\mu^+\mu^-$ (M)
10^{30}	2.4	1.5	0.10
10^{32}	8	5	0.4
10^{34}	14	12	1.7

obtained via long extrapolations. Past experience has shown that other mechanisms often come into play and the cross sections may be larger, in which case it may be possible to reach these regions of $\sqrt{s}$ with lower luminosity. Third, entirely new physics may open up and could have larger cross sections than those calculated here; new effects induced by diffractive dissociation or quark constituents are examples. In this case having a high energy which crosses a threshold may be more important than luminosity.

pp OR $\bar{p}p$?

Would one build two rings for pp at higher luminosity, or a single ring for $\bar{p}p$ at higher energy? For the "bellwether" experiments studied at Snowmass, the relatively low cross sections indicate that the factor of 10-30 increase in luminosity of a pp machine more than compensates for the factor of ~ 1.5 loss in $\sqrt{s}$. The matter is by no means clear, however, as suggested by the above set of cautions on detector rate capabilities, long extrapolations of cross sections, and the possibilities of new thresholds to be crossed. Note that even at the "low" $\bar{p}p$ luminosity of $10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ ($\langle n \rangle \sim 0.8$), there would be $\sim 10^{13}$ interactions per year; quite rare processes would produce substantial numbers of events, and the limit may already be set by backgrounds and signature, rather than rate.

At present day energies, the instincts of the community are to go for higher energy at the sacrifice of luminosity. This is typified by the Tevatron 2 project in which a gain of a factor of ~ 1.5 in $\sqrt{s}$ is being bought at the cost of 5-10 in luminosity. Clearly, the experimenters at PEP would trade a factor of 10 or more in luminosity if they could gain a factor of three in $\sqrt{s}$. While our eagerness for higher energies, even at the expense of luminosity, may dampen as the cross sections fade as $1/\Lambda^2$, our instincts are based on past experience showing that advances in our field usually come more from increased energy than increased luminosity. Some of

this is due to the fact that as the energy gets well above threshold, the signal to background improves sufficiently that processes of interest can be picked out.

CONCLUSIONS

There are many very interesting physics topics which can be explored at very high energy hadron colliders, even with today's detector technology. New colliders, both pp and $p\bar{p}$, should be able to deliver high luminosities, and there is a clear incentive to improve detector rate capabilities. R and D funds spent on this over the next few years could have enormous cost benefits in the long term.

The main advantage to the more costly pp option is the better duty cycle. The significance of this advantage depends, in large measure, on the rate capabilities of the detector subsystems. With the technology being built into today's collider detector, the advantage is relatively slight, perhaps a factor of 2 or 3. The question remains as to the ultimate advantage one might hope to achieve in the future. The answer will not be clear cut, but will depend strongly on the physics being studied.

With no specific landmark (such as the Z^0), one possible strategy for a new, very high energy machine would be to initially go for the highest energy possible with a single ring $p\bar{p}$ system. Later one could add a second ring to gain the factor of 10 to 30 possible with pp , if warranted by experience at the lower luminosity.

The Snowmass study uncovered no fundamental problems in constructing and using a hadron collider of 10 to 20 TeV per beam. Both accelerator and detector R&D are needed if such a project is to be carried out in an optimal fashion. Given the long lead times inherent in such a project, it is important that this R&D be vigorously mounted now. We, of all people, should understand the long range benefits of R&D and be prepared to invest in the future.

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