FORWARD SPECTROMETERS AT THE SSC

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Abstract

Most of SSC phase space and a great deal of physics potential is in the forward/backward region ($|\Theta|<100$ mrad). Comprehensive open-geometry spectrometers are feasible and very cost effective. Examples of such devices are sketched. Because such spectrometers are very long and may operate at higher β and longer bunch spacing, they impact now on SSC interaction - region design. The data acquisition load is as heavy as for central detectors, although there may be less emphasis on speed and more emphasis on sophisticated parallel and/or distributed processing for event selection, as well as on high-capacity buffering.

I. Generalities

The appellation "4π detector," implying coverage over all of phase space, is at hadron colliders and especially the SSC, a misnomer. Phase space is better measured in rapidity units (or db), with ~ 100 db available for minimum-bias SSC physics. In e^+e^- collisions a good generic 4π detector covers, say, $|\Delta\eta| \leq 3$; i.e. ~ 25 db. The generic 4π 10^{33} SSC detector does somewhat better, reaching toward 40-50 db.

The remaining 50-75% of SSC phase space deserves to be covered in open geometry with quality detection devices both for high p_T jet/lepton studies and for low p_T work; e.g. generic top/bottom/charm production including (especially) production of leading systems. I think this can be done and is easier to do than the 10^{33} physics. Most of it requires lower luminosity.

No theorist can or should assert that the payoff physics occurs at the "TeV mass-scale" - only that this is a safe upper bound. (otherwise why build TeV I, SLC, LEP?) History goes both ways:

"Surprisingly Low" mass scale	"High" mass scale
J at ISR/FNAL	J at BNL
ψ at SPEAR	ψ at ADONE
b at CESR	T at FNAL/ISR
τ at SPEAR	Deep-inelastic at SLAC
	W,Z at CERN

Mass (or E_T) scales below the maximal one explored by the 10^{33} detector need distinct detectors; prescaling the "10^{33}" data via looser thresholds is seriously non-optimal. For example a detector designed to run only at $L_o \leq 10^{31}$ (with mass or E_T reach reduced from ≥ 1 TeV to a "mere" 500 GeV) is different. The greater bunch spacing changes collision geometry and readout rates. A lower luminosity moves back the low β quads, allowing more flexibility in design of forward/backward detection systems. Detector innards which are less radiation-resistant can now be used. Study of lower mass scales demand much longer detectors. And so on. Thus I suspect the real "special-purpose" detector may well turn out to be the 10^{33} "4π" device upon which most attention has been lavished.

In subsequent sections we sketch designs for two forward spectrometers spanning, perhaps, extrema of the kinds of coverage we have in mind. The first spectrometer is intended to study low-p_T event samples containing ~ 10^6-10^9 $b\bar{b}$ pairs, perhaps for B-$\bar{B}$ mixing studies and CP-violation physics. The second is intended to allow study of forward-produced (x_F ~ 0.3) systems of mass 200 ± 100 GeV decaying into high-p_T jets plus leptons. The physics goal is to clean up unresolved questions emergent from the great discoveries to be made at CDF and DØ, and to discover what they missed in this mass range.

These designs are far from optimized, and are meant to serve as "existence theorems," not incipient proposals. The implications for the subject matter of this workshop is that the number of data channels is as large as for the generic 10^{33} 4π detector, along with a demanding amount of on-line processing power. However, speed is probably less important, while sophistication in parallel and pipeline processing is probably paramount. In any case, from the data-acquisition point of view these experiments should not be viewed as small.

II. General Design Principles for Forward Spectrometers

1. Uniform coverage over at least 30 db ($\Delta\eta$>>6):

The systems to be studied are multiparticle or multijet, which span (at 1σ) a rapidity interval of 2 units. We should demand, in the cms of the interesting system, uniformity of coverage at least as good as Mark III, CLEO, etc.; say Θ^* from 5° to 175° (This implies $\Delta\eta$=6). Given that the cms Lorentz factor γ of the interesting system varies event-to-event by a factor π, this means adding on a few more units of η, if possible.

2. Good detection of neutral hadrons and photons

This demands calorimeter walls, whose location downstream of the collision point is dictated by physical photon and hadron shower sizes. It is hard to imagine that one calorimeter wall suffices for an η span ≥ 6 with ratio of outer diameter to inner diameter a factor $\gtrsim 10^3$. The (inevitable) alternative seems to be a sequence of walls (with central holes to pass the forward particles and the beam) each spaced a factor, say, between 2 and 10 further downstream than its predecessor (Fig. 1). If the endwall does a decent job of separating leading showers and/or hadrons of momenta 2-20 TeV and generic $p_T \lesssim 1$ GeV, then this could imply an endwall location of order a few kilometers downstream of the collision point. This endwall distance scales inversely with the relevant minimum p_T scale.

3. Microvertex tracking over all relevant phase-space intervals

This is obviously important for jet physics as well as generic charm/bottom studies. After jets and leptons, the heavy flavor tag stands out as the most promising method for isolating "new physics" signals. The planar detector geometry appropriate to forward/backward regions may be easier to implement than the barrel structures within central detectors. The detectors should reach as close to the collision axis as possible, via "Roman pot" technology already under development in colliders.

4. Good efficiency for finding and tracking, with momentum measurement, decay products of K's and hyperons within the desired η-acceptance

For the 300 GeV jet physics, this criterion is less severe than for the charm/bottom spectrometer. We guess that a coverage up to p ~ 400 GeV may be adequate for the former, with perhaps p ~ 4 TeV appropriate for the latter. If we ask for a decay path of 2 lifetimes at p = 4 TeV, the distance comes out to be of order 600 m; however the decay vertices are, for generic p_T, within 10 cm of the collision axis. For high-p_T, they are within 10 cm of the relevant jet axis.

5. Uniform acceptance and charged particle resolution as function of η:

This is important because of the spread in η of a typical multiparticle or multijet system; performance will be controlled by the weakest link. We believe it is realizable.

With multiple calorimeter walls, as in item 2, it is natural to place the momentum-analysis magnets behind them. Magnet pole faces need not and should not be exposed to neutral particles from the target. We also believe the best choice is quadrupoles, but that is a negotiable design detail.

6. Good lepton identification

This can be accomplished in a more or less standard manner.

7. Nondestructive particle identification (e.g. Cerenkov, TRD) over as much phase space as possible:

This seems the most difficult to attain and is sacrificed first; its feasibility has to be looked at case-by-case.

III. Charm-Bottom Spectrometer

1. Calorimeter walls

We choose uranium or tungsten interspersed with silicon strips for readout, for reasons of compactness. We place the endwall 2 km from the target. Additional walls are placed factors 3 closer to the target (Fig. 1). The inner hole has diameter ~ 15 cm; the outer diameter is taken to be 80 cm. With a depth of 12 ± 3 collision lengths (~2000 gm cm^{-2}), each wall weighs 1-2 tons, and is about 1-2 meters in thickness. With strip readout from either end, and with 2 mm pitch, the number of readout channels per Si plane would be ~ 10^3. With 50 ± 20 sampling layers in toto (EM plus hadronic), this gives a rough estimate of ~ 5×10^4 readout channels per calorimeter, or 3×10^5 total. Being more careful might reduce this number considerably. The closest calorimeter wall that we consider is 7 m downstream of the collision point (maximum angle ~ 50 mrad). We assume the remainder of the phase space is covered by a central detector. Certainly 2-3 more units of rapidity should (and can) be seized.

2. Magnets:

Behind each calorimeter is placed a large aperture superconducting quadrupole of diameter 20 cm, with peak field (at the coil) of 6 ± 2 T, and length 2 m. The lattice structure is chosen to be FODO. The betatron phase-advance for a beam particle is ~ 90° down the length of the spectrometer; the β^* at the collision point is $\lesssim$ 1 km.

3. Vacuum Pipe

Tracks moving at grazing incidence through vacuum-pipe walls make trouble. In such a long spectrometer, multiple scattering in air would be a disaster. Therefore evacuate the whole thing; choose a vacuum tank ~ 80 cm in diameter. Evidently the calorimeter and magnetic elements may remain at atmospheric pressure, while tracking chambers must "penetrate" the vacuum pipe but not the beam.

4. Charged particle tracking

We take, per half-cell, 4 stations of chambers each with xyuv readout. As already mentioned the chambers must penetrate the vacuum pipe but not the beam. Also, within the nominal vacuum-pipe region the chambers must present a minimum of material to the secondary tracks. It is not hard to see how this might be done; engineering details are left to the reader. The region from, say, 0.5 cm from the beam axis to 1.5 cm is covered by silicon microstrip detectors utilizing Roman-pot technology. Their on-board readout electronics can be put in the shadow of (or in front of) calorimeter walls.

The number of readout channels per half cell is less than what was assumed for the calorimeter. Even if we use MWPC's with 1 mm wire spacing, we have 4x4x80x10 =13K channels per half cell. To this must be added the contributions from the silicon microstrips. With 20μ pitch and 8 planes (4x-views; 4y-views), each (1+1)cm x (5+5)cm (top + bottom or left + right), we have 8x2x2x500 = 16K channels per half cell, giving a grand total of ~ 30K channels of tracking per half cell, to be compared with the 50K channels per calorimeter estimated previously.

What happens to a typical charged particle is conveniently summarized by viewing it in a boosted frame where it emerges at 90° to the collision axis. There is little bending until the particle is ~ 5-10 cm from the axis; it then gets a p_T kick $\gtrsim$ 2 GeV. It is again tracked until it strikes a calorimeter wall or exits the vacuum pipe; the point of destruction is typically at a transverse distance ~ 25 ± 10 cm. The spatial resolution of the tracking system is boost invariant; hence the angle measurement accuracy using the Si microstrips is $\delta\theta \sim 20$ μ/1 cm $\leq$ 0.2 mrad. Each 300 μ plane provides a δp_T of ~ 1 MeV from multiple scattering; this implies additional uncertainty of $\delta\theta \lesssim (1\ \text{MeV}/p_T)$ from this source. For 300 MeV p_T of a generic secondary, this appears a good match in accuracy to the momentum measurement. The large transverse momentum kick imparted by the last quad which is seen by the particle before destruction (or exiting), together with at least 4 stations of chambers downstream and upstream of this quad, does provide excellent momentum determination. With lever arms $\gtrsim$ 10 cm (in the coordinates transverse to the beam axis), we attain a momentum accuracy $\delta p_T/p_T \lesssim \delta\theta/\theta \sim 200$ μ/10 cm = 0.2% for (transverse) momenta $\lesssim$ 1 GeV. (The scaling law is, as usual, $\delta p/p \sim p$ for $p_T >> 1$ GeV.)

We emphasize these estimates are "boost-invariant", i.e. essentially independent of production angle, within the aperture of the spectrometer. (They are, of course, also crude, and need some realistic simulation studies.)

5. Nondestructive Particle Identification

Cerenkov counters may be placed between the calorimeter walls, but there may be problems of insufficient length. Particles of generic $p_T \leq$ 500 MeV when swept outwards by the last quads in, say, the horizontal plane are focussed in the vertical. A larger fraction (60 ± 20%??) hit the vacuum wall rather than a calorimeter face. If these regions of vacuum wall, which are a few centimeters wide at the horizontal and vertical planes, could be provided with thin windows, the exiting ribbon beam could be transported through Cerenkov counters of arbitrary length.

6. Muons:

These are identified and tracked reasonably well already by the device as described. Big toroids exterior to the vacuum pipe could be appended to supplement this coverage, if desired.

The fraction of π's which decay to μ's before being absorbed is $\lesssim$ 1%; this result is again essentially independent of production angle.

7. Jets:

High-p_T tracks will in general not remain in the horizontal or vertical planes. (This may provide a useful triggering strategy.) To see the performance of the device, again go to the frame in which the jet emerges at 90° to the beam. At p_T = 100 GeV, the two most leading particles might typically have momenta $\lesssim$ 20 and 10 GeV. At 10 cm (without bending) these are spaced by an amount

$$\delta y \sim 10 \text{ cm} \times \frac{400 \text{ MeV}}{15 \text{ GeV}} \sim 3 \text{ mm}$$

At 1 cm (in the microstrip region), they are separated by ~ 300 μ. Thus it seems credible that identification and momentum measurement of individual charged tracks in the jets should be feasible up to p_T ~ 50-100 GeV.

At the calorimeter wall, spacings of individual hits should be typically at least a centimeter; hence electromagnetic showers may also be separable.

8. Holes

An unpleasant feature of the design is the set of holes in the calorimeter walls. They create nonuniform acceptance and resolution near the edges. Most seriously, shower particles may flow down the hole and blast downstream detection elements. We discuss these in turn:

A. Acceptance and Resolution Problems: For photons, take a band of uncertainty of ~ 3 mm near the inside edge where there is trouble. This gives a $\frac{\Delta\eta}{\eta}$ loss per wall of ~ 3 mm/(7 cm) x 1.1 ~ 4%.

Hadron shower cores near the edge (≲ 2 cm?) will be messed up. However, for t/c/b spectroscopy the measurement of hadron shower energies is of marginal usefulness. But given good sampling, the hadron angles (i.e. vertex position of the shower) should be able to be located about as well as for photons. Thus for this case we take the loss factor also to be well under 10%. We note that most existing spectrometers, central collider as well as fixed-target, seem to have acceptance losses exceeding this level by a considerable amount.

B. Backgrounds: In this spectrometer, energy deposition per meter is roughly constant at ~ 10 GeV/m. On average each hole emits ~ 3 times as much energy as its upstream counterpart. But tracking devices will typically be 3 times further away, hence subtend 9 times less solid angle. Thus background problems should improve as one goes downstream to smaller angles. This should be at least true for the most insidious backgrounds, namely low energy "isotropic" sources, e.g. photons of energy $\lesssim E_{crit}$ emitted from the walls of the hole. Backgrounds from particles of energy $\geq$ 1 GeV are limited by energy conservation and should be benign, assuming the predominant source is real collisions at the target.

9. Luminosity

A simple beam-optics scheme puts "kissing" dipole magnets behind the endwall, with only one collision occuring within the spectrometer at a time. This replaces the nominal 10 m bunch spacing with a 4 km spacing, yielding $L \sim 3 \times 10^{27}$ cm^{-2} sec^{-1}. This is certain to be unpopular in neighboring collision regions. Better is a finite crossing angle. In straight line approximation, if the beams are separated by ~ 6 cm at 2 km, this means a crossing angle of ~ 30 μrad. This is head-on as far as bunch geometry is concerned. Even with no tricks, bunch separation is ~ 1 cm (adequate?) at 300 m; yielding luminosities ~ 2×10^{28}. With judicious addition of dipoles in the spectrometer, the bunch-spacing should be able to be reduced a lot more. We estimate the nominal luminosity to be expected is ~ $10^{29\pm1}$ cm^{-2} sec^{-1} if some design effort is expended in this direction. (Note the number of $b\bar{b}$ pairs produced in 10^7 sec at $L \sim 10^{29}$ is a mere 2×10^8!)

IV. Intermediate-Mass Forward Spectrometer

For a forward produced system of mass ~ 200 GeV and momentum ~ 10 TeV, we have γ ~ 50, and typical Θ's ~ $\gamma^{-1} \gtrsim 20$ mrad. We need 3 units of rapidity (factor 20) either way; hence good hadron jet coverage up into the central-calorimeter regime and down to 1 mrad. Supposing a granularity of 20 cm, this places the endwall at 200 m.

We place intermediate walls at 70 m, 20 m and 7 m, but make their apertures larger than before, 50 cm diameter, in order to lose less rapidity bite (for hadron jets) from showers originating near the aperture. This time, for variety's sake, we place dipoles and quads behind the walls. A strong transverse B-field provides double duty as "kissing" magnets and momentum analyzers.

We guess a β^* ~ 30 m and 20 m bunch spacing may work for this design. Hence a luminosity $\gtrsim 10^{31}$ cm^{-2} sec^{-1} may be attainable. A crossing angle $\lesssim$ 1 mrad matches acceptably the aspect ratio of the bunch. We may provide p_T kicks of $\gtrsim$ 3 GeV at each dipole (5T x 2m?) to straighten out the primary beams before they exit the spectrometer.

The calorimeter walls are now of more typical size, say ~ 3m x 2m. Perhaps it is worth making the coverage for the inner unit of rapidity (radius $\leq$ 3 times the hole radius) again out of uranium or tungsten; composition of the outer portion is more negotiable.

Probably, with lots of physics emphasis here on high-p_T and calorimetry, one should consider tower geometry for the calorimeters. With "standard" granularity $\Delta\eta \times \Delta\phi \sim 0.04 \times 0.04$ this adds up to $1.1 \times 2\pi \times 625 \sim$ 4K towers per wall. Whatever the criteria, they do not differ in number of channels from those of a central detector, although the planar geometry makes for some simplicity.

The layout of remaining detection elements follows the previous design, although now the detector size may create difficulty in evacuating the whole thing. The vacuum pipe design is then a pain and is left as an exercise for the reader.

Resolution and coverage follows closely the considerations of the previous section. The quality of the device should be excellent.

V. Conclusions

1. There is tremendous physics potential in the forward/backward regions ($|\Theta|<100$ mrad). Most of the phase-space is there at SSC energies.

2. Comprehensive forward/backward open-geometry spectrometers with sensitivity at least as good as collider "central detectors" are feasible.

3. Microvertex work is probably easier in the planar geometry appropriate to the forward/backward region.

4. The typical geometry is long; hundreds of meters to a few kilometers of free space are indicated.

5. These detectors impact now on SSC interaction-region design, especially in terms of the higher β lattice insertions and the long straight sections required.

6. The data acquisition load is in proportion to the $\Delta\eta\ \Delta\phi$ coverage. This is larger than central detectors; hence the data acquisition load is at least as heavy as for the "4π" generic detector.

7. Information quantity and quality per event is most important to optimize for these devices. Maximizing interaction rate may be less important. Therefore front-end rate problems may be less crucial than for the "4π" generic detector. However, pipelining, distributed and/or parallel processing, as well as high-capacity buffering, may be more demanding.

8. The natural time scale to collect data from both ends of a 2-arm spectrometer of ~ 1-3 km length is $\gtrsim$ 10 μsec. This sets a lower limit on the time scale for event-selection, e.g. for diffractive charm/bottom production. The structure of the data acquisition process in space-time becomes significant at SSC energies.

9. The cheapest rapidity intervals in terms of tonnage, physical size, etc. are the forward/backward regions. The detector cost could well be dominated there by the cost of the readout system.