4/4/84

(To appear in the Proceedings)

BNL-34614
OG 777

CONF-840154--1

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BNL--34614

DE84 010799

Invited Talk Presented at the SSC Fixed Target Workshop

The Woodlands, Texas
January 27-29, 1984

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A HIGH ENERGY HIGH INTENSITY COHERENT PHOTON BEAM FOR THE SSC

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Requirements on the Accelerator

I assume the acceleration of 5 x 10^{14} protons with a 200 second ramp up, 200 second flattop, and 200 second ramp down. This gives a repetition rate of 600 seconds, with a duty cycle of 1/3. In this case the proton rate on a "target" is 5x10^{14} protons/200 seconds = 2.5 x 10^{12} p/sec instantaneous rate. With the above duty factor, the average rate of protons is 8.3 x 10^{11} per second or 3 x 10^{15} protons/hour. In what will be described later, the duty cycle will not be the limiting factor, it could be a factor of $\sqrt{3}$ worse. However, the average number of protons accelerated per hour should not be reduced.

What I propose to do with the 20 TeV protons hitting a fixed target is to make a tertiary electron beam similar to that which is the basis of the tagged photon beam at Fermilab.[1] Briefly, a zero degree neutral beam is formed by sweeping out the primary proton beam and any secondary charged particles. Then the photons, from the decay of π° in the neutral beam, are converted to e^+e^- pairs in a lead converter and a high quality electron beam is formed. This beam is brought to the target area where it is converted to a photon beam by Bremsstrahlung in a radiator.

I don't believe that there are any difficult requirements on the primary proton target. A hydrogen jet inside the main ring would be suitable provided that the interaction rate were high enough. However, good beam optics for the 10 TeV electron beam transport are critical so that the beam can be useful to produce a high energy photon beam via coherent Bremsstrahlung in a diamond radiator.[2] I don't think that this will be a major problem. Extrapolation from the tagged photon beam at Fermilab seems rather straightforward.

The principal requirements on the electron beam are intensity, angular divergence and spot size. The angular divergence and spot size achieved at Fermilab compared to the maximum values desired for this beam at the SSC are shown in Table I.

Requirements on Electron Beam

	Angular Divergence (m rad)	Spot Size (mm)
FNAL TPL (150 GeV)	±0.14 x ±0.44	6 x 25
SSC (10 TeV)	±0.01 x ±0.10	5 x 5

TABLE I

It should not be difficult to achieve these required values. The angular divergence of the beam at the SSC should be 14 times smaller than at Fermilab, but the energy is larger by a factor of 60. The spot size is set by the desire to use a diamond with edge dimension 8.5 mm as a radiator. For coherent Bremsstrahlung, only one angular divergence of the beam is required to be small. It would not be worth too much effort to make the angular divergence smaller than the 10^{-5} radian value given in the table because then it would become smaller than the natural mosaic spread of the crystal planes in diamond.

The spectrum of equivalent photons to be expected from a 10 TeV electron beam incident on a suitably oriented diamond is shown in Figure 1. Except for the value of the smallest tilt angle, which is indicated on the figure, the other parameters are as given in reference 2. The left hand scale is roughly equal to the coherent enhancement over an amorphous radiator of the same thickness. The coherent peak is at 9.48 TeV.

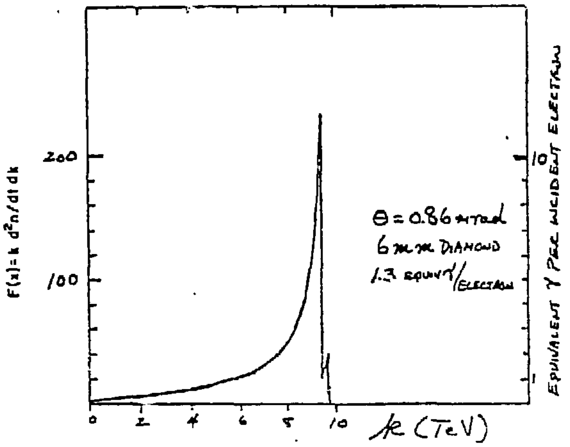


FIGURE 1

For a 6 mm thick diamond, which is 5% of an amorphous radiation length of carbon, the integral of Figure 1 is 1.3 equivalent quanta per electron! It is clear that it will not be particularly difficult to make a photon beam with a huge coherent peak near the endpoint and a ratio of equivalent photons/electron of order unity. What is not clear is how multiple photon emission in the "thick" radiator and reabsorbtion by coherent pair production in the radiator will distort the spectrum. These effects are not expected to be large[2] but remain to be investigated in detail.

The Photon Beam

For the intensity of the electron beam, I have taken the bench mark value e/p = 10^{-5}, at electron energy equal to half the primary proton energy. This is only a factor of 4 higher than the flux estimated for the TPL tagged beam at Fermilab using 1 TeV protons.[3] The electron flux in the FNAL beam, at a constant fraction of the proton energy, is predicted to increase a factor of 6 in going from 400 GeV to 1 TeV protons.[3] Thus, an extra factor of 4 enhancement in going up to 20 TeV doesn't seem outlandish. Experts in beam design are encouraged to try their hands!

Using all of the available protons/hour to make electrons gives

$$3 \times 10^{10} \text{ 10 TeV electrons/hour average}$$

or approximately 10^7 electrons/second on the average. Since the number of equivalent photons per electron is ~ 1, this results in a photon beam with intensity $\sim 10^7$ photons/second on the average. The spectrum of the photons is effectively "monochromatic" at 9 ± 0.5 TeV. This beam is 50 times higher in photon flux than any beam envisioned at FNAL, and the spectrum is much better as well. The flux of actual photons expected is shown in Figure 2.

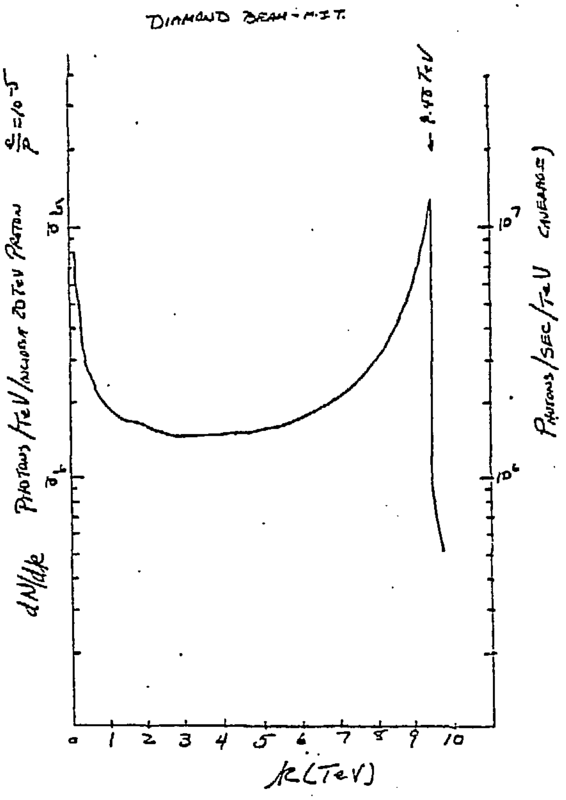


FIGURE 2

Photon beams for fixed target physics have already been discussed[4] by Reibel and Ruchti in Snowmass 1982. Their beam was derived from Λ° and K° decay, and had a decent spectrum shape and a relatively small low energy tail, but was nothing nearly as neat as the spectrum shown in Figure 2. Their flux was down by a factor of 50 as well, for similar assumptions about number of protons and duty factor.

For the purposes of estimating counting rates, I will use 10^7 photons/second, on the average, with energy of 10 TeV. Most experiments will involve final state hadrons so I assume a 1.5 meter long liquid hydrogen target for the photoproduction experiments. This gives a luminosity of

$$6.3 \times 10^{24} \quad \text{cm}^{-2}\text{/photon}$$

$$6.3 \times 10^{31} \quad \text{cm}^{-2}\text{s}^{-1}$$

$$1.9 \times 10^{35} \quad \text{cm}^{-2}\text{/hour}$$

and $\quad 0.6 \times 10^{39} \quad \text{cm}^{-2}\text{/year } (10^7 \text{ sec})$.

This compares nicely to Stu Loken's nominal HERA year of 1.0×10^{39} cm^{-2}. Of course the shape of the photon spectrum has some enormous advantages over HERA which will be presently discussed.

Possible Physics Program

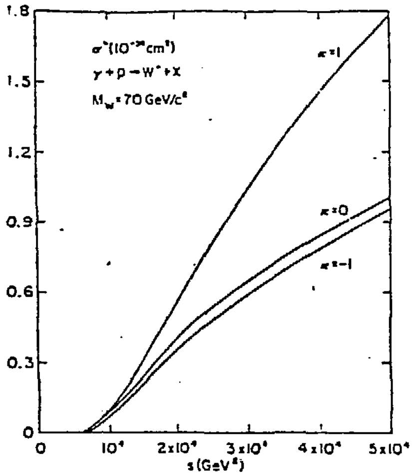
It seems reasonable, to me at least, that a golden fixed target facility at the SSC, including all the experiments (most of which would just be stretched out arrangements of equipment from the Tevatron), couldn't possibly cost as much as one typical collider experiment. Nevertheless, I will also attempt to make quantitative physics arguments for such a fixed target facility, in particular the photon beam just described. I persist in using 10 TeV as the nominal photon energy for the 9 TeV facility just described because the center-of-mass energy for the collision of a 10 TeV γ ray with a proton at rest is $\sqrt{s} = 137$ GeV. Even without the elegant formulation of Glashow, Weinberg and Salam, I would have guessed that some interesting physics would occur at that particular energy.

Single $W^\pm$ Photoproduction and the Tri-Linear Gauge Coupling

Of course in the year 1984, we all know that 137 GeV is above the threshold for $W^\pm$ and Z° production. The real question is: Why try to produce them with photons? The answer is simple. Single W photoproduction can directly probe the $\gamma W^+ W^-$ tri-linear gauge boson coupling. This is one of the main arguments for building LEP Phase II. It is amusing that this physics can also be studied as sort of a side line at the SSC. The cross section for single W^+ photoproduction

$$\gamma + p \rightarrow W^+ + \text{anything}$$

has been calculated[5] and is shown in Figure 3.



For $M_W = 70$ GeV/c^2, the total cross section for $\gamma + p \rightarrow W^+ + X$, in units of 10^{-35} cm^2, as a function of s in units of GeV^2. The three curves correspond to $\kappa = 1$, $\kappa = 0$, and $\kappa = -1$ as indicated.

FIGURE 3

The value $M_W = 70$ GeV was used in the figure whereas we now know the mass of the W is ~ 83 GeV.[6] The prediction[5] scales like s/M_W^2, so that we find the single W^+ photoproduction cross section at $\sqrt{s} = 137$ GeV as follows:

$$\sigma_{W^+} = 1.9 \times 10^{-36}\ \text{cm}^2 \text{ if } K = -1$$

$$\sigma_{W^+} = 3.1 \times 10^{-36}\ \text{cm}^2 \text{ if } K = +1.$$

The W^- cross section is supposed to be roughly equal to that of the W^+. The parameter K is the anomalous magnetic moment of the W, which is predicted to be equal to +1 in the standard model. Historically, the anomalous magnetic moment has revealed a great deal about particles. It clearly indicated that the proton and neutron are fundamentally different from the electron and muon, and may prove to be equally revealing about "compositeness" of the W as well.

Using the above luminosities yields a W^+ production rate in hydrogen, for the standard model, of

0.7 W^+/hour and an equal number of W^-.

This is roughly 3500 of both charge W's per year (10^7 seconds). The rate of W production is a factor of 10 lower than expected at LEPII, with a luminosity of 10^{32} cm^{-2}s^{-1}, but is certainly adequate to give a statistically precise measurement of K even if the $W^\pm$ can only be detected via the leptonic branching ratios. Of course the signature of the W in photoproduction may prove to be so spectacular that it could be detected inclusively as well.

Elastic W^+ Photoproduction, W Photoproduction in Deuterium

For reference, the diagrams for W photoproduction are given in Figure 4 below.

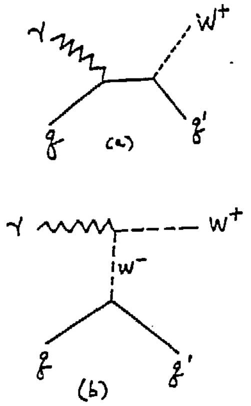


FIGURE 4

Diagram (a) is the "Compton" process, and diagram (b) the γWW process. No attempt has been made to illustrate all the "crossed" channels. In the diagram the W^+ is shown as being photoproduced off quarks. However W^+ can also be photoproduced "elastically" from protons. The reactions are

$$\gamma + p \rightarrow W^+ + n$$

$$\gamma + n \rightarrow W^- + p.$$

The cross sections for this process are also given by Mikaelian.[5] Incredibly, in the standard model, the cross section for the elastic process is energy independent and equal to the huge value of 4.6×10^{-35} cm^2. I would urge some more theorists to take this problem seriously and reevaluate these cross sections using the best present knowledge.

Although I can't tell from the paper,[5] I feel certain that the nucleon form factor has not been taken into account in the above calculation. If the effect is similar to what occurs in ρ° photoproduction, with a t dependence of roughly e^{8t}, then the effect will be a suppression of a factor of $\sim$2.5, since t_{min} for W production at 10 TeV is simply

$$-t_{min} = \left(\frac{M_W^2}{2E_\gamma}\right)^2 = 0.12\ \text{GeV}^2 .$$

If these considerations are at all correct, one can envision a "missing mass" experiment to detect W^- photoproduction in deuterium, measuring only the recoil protons.[7] The photon beam becomes in effect a tagged 10 TeV W^- beam with a respectable counting rate of 3 tagged W^- per hour. This now becomes possibly an order of magnitude better than LEPII for tagged W studies, since they may have to pay an 8% leptonic branching ratio in order to make precision studies of W decays.

"Coherent" $W^\pm$ Photoproduction in Nucleii

Another possibility that suggests itself from the above considerations is "coherent" $W^\pm$ photoproduction in nucleii. The diagram is the same as Figure 4 except now the q + q' represent nucleii. I have no idea whether such physics is interesting, or worth the effort. I only wish to point out that it would be possible. The benefit in using nuclear targets, in addition to the obvious one of studying the interactions of $W^\pm$ with nucleii, is that the effective center-of-mass energy of the collision is increased. This is summarized in Table II. Theorists, HELP!

Center-of-Mass Energies and Elastic Form
Factor Suppression for $W^\pm$ Production by 10 TeV
Photons in Nucleii.

Nucleus	Pb	Cu	C
$\sqrt{s}$ (GeV)	1980	1093	475
Suppression	3×10^{-4}	2.3×10^{-3}	1/25

TABLE II

Searches for Toponium and Higgs, etc.

Photon beams are old favorites for producing vector mesons.[7,8] Rather than estimate toponium production, I estimate

$$\gamma + p \rightarrow t\bar{t} + x$$

where t will combine with sea quarks to produce real "top" particles. I use the SLAC hybrid results of 50 nb for

$$\gamma + p \rightarrow c\bar{c} + x \quad \text{at } \sqrt{s} = 6.2\ \text{GeV}$$

as reported by Nash,[7] and the scaling law

$$\sigma \sim \frac{1}{m^2} F(m/\sqrt{s}) .$$

This corresponds to a t-quark mass of roughly 44 GeV at $\sqrt{s}$ = 137 GeV and a cross section of approximately 10^{-34} cm^2. This would be 20 events an hour for the standard conditions described above.

As emphasized by De Rujula at this meeting, the $t\bar{t}$ might decide to materialize as a neutral higgs plus a photon.[9] This could happen if $\sqrt{s}$ = 137 GeV were above the real $t\bar{t}$ threshold. It could also happen via all sorts of virtual heavy fermion loops which would induce the $H^\circ\gamma\gamma$ coupling.[9] In this case we could imagine H° photoproduction via the Primakoff effect.

I'm sure that the possibilities of photoproducing gauge bosons, scalar quarks, and all sorts of other good things, are endless. Let this be a plea to theorists to start thinking in this area.

Traditional Photon Physics

Even in ultra-high-energy physics, photons are still the best particles for diffraction phenomena. In both the leptonic and hadronic sector there are major processes in which the photon converts into one or two particles with the full beam energy. The classical process is of course photo-pair production. Any charged particle, particularly leptons, are produced at a rate equal to roughly

$$\frac{7}{9}\left(\frac{m_e}{m}\right)^2$$

per radiation length where m_e is the masa of an electron and m is the mass of the particle. Values of m up to $\sim M_W/2$ are possible in the beam just described.

Precision Lifetime Measurements

For the more traditional leptons, $\mu^+\mu^-$ pairs are produced at a rate 10^{-4} per radiation length and $\tau^+\tau^-$ pairs at a rate of $\sim 10^{-7}$ per radiation length. For the beam and target described above (or any other 15% of a radiation length thick target) the production rate of $\tau^+\tau^-$ pairs is 10^{-1} per second or 360 per hour. The higher energy lepton in the pair has energy between 5 and 10 TeV, which means that its mean flight path is between 25 and 50 centimeters. In addition, the direction of the τ leptons is also very well defined. This dramatically improves the possibilities for precision lifetime and decay property measurements.

In a similar fashion, beams of charming and beautiful particles can be produced except with much higher cross section. Taking the charm cross section as 500 nb and the beauty cross section as 50 nb gives the production rate for

real $c\bar{c}$ as 100,000/hour

real $b\bar{b}$ 10,000/hour.

The charm particles have $\gamma \gtrsim 2000$ with mean flight paths of $\sim$20 cm and the beauty particles have $\gamma \gtrsim 450$ with mean flight paths of $\sim$10 cm. The experiments will probably be vastly easier than the present versions at Tevatron II and PEP.

It should be noted here that for charm, beauty and τ production, 10 TeV might be too large a photon energy. In principle, the energy of the coherent peak in Figure 1 can be reduced, say to 7.7 TeV, and the beam will become $\sim$30% linearly polarized. The intensity would also increase by a factor of 6, but since it is already $\sim$1 photon/electron, this means that a thinner diamond, or perhaps even silicon, could be used. The practicality of such a polarized beam must still be further investigated.

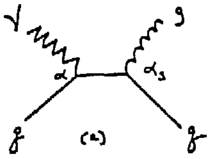
Hard Photon Physics

By hard, I refer to point-like scattering where the photon interacts directly with a quark in the target proton. The experiments are also difficult, and results have remained elusive in the present generation. There are two basic but similar hard processes (see Figure 5)

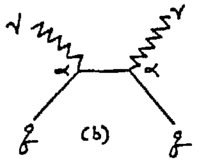
$\gamma + q \rightarrow g + q$ QCD-Compton.

$\gamma + q \rightarrow \gamma + q$ QED-inelastic Compton.

The kinematics and structure functions are identical for these two processes.



QCD-COMPTON



QED-COMPTON

FIGURE 5

Photons have one major advantage over hadrons for the study of QCD effects in a hadron target. The photon is a direct participant at the constituent level so its full momentum is available to be absorbed by a constituent in the target. This means that in a hard scattering induced by a photon, there are 2 large transverse momentum jets representing the scattered constituents, and a jet from the target fragments. There is no beam jet since the beam was a full participant in the hard scattering.

In addition to probably curing the NA-5 disease[10] since the beam hemisphere will contain only the high P_T jets, jet production by photons is also very attractive since the kinematics are over constrained.

Once a jet is detected with transverse momentum P_T and rapidity, y, there will be another jet with equal and opposite P_T at rapidity y' where

$$y' = \ln\left(\frac{2}{X_T} - e^y\right)$$

and $X_T = 2P_T/\sqrt{s}$. The rapidities are measured in the γp center of mass system. The kinematics of the struck quark are also determined:

$$x = e^{-(y+y')} = \frac{e^{-y}}{\frac{2}{X_T} - e^y}$$

This has the additional implication that coincidence experiments, in which the two high P_T jets are detected, are both desirable and conceptually simple.

The inelastic QED-Compton process[11] is particularly beautiful because the scattering constituents are directly accessible in both the initial and final states, and in addition, the cross section can be calculated analytically with a simple formula. Ignoring d and sea quarks, the formula for photoproduction of a prompt photon with P_T,y (with a quark jet balancing P_T at y' as given above) is

$$E\,\frac{d^3\sigma}{dP^3} = \left(\frac{2}{3}\right)^4 \frac{\alpha^2 X_T^2}{2P_T^4}\, u(x)\, \left(1+\left(\frac{X_T e^y}{2}\right)^2\right).$$

A simple numerical formula is

$$\frac{d^3\sigma}{dP_T dy d\phi} = 2.05 \times 10^{-33}\ \mathrm{cm}^2/\mathrm{GeV}\ u(x)\ \frac{\left[1+\left(\frac{X_T e^y}{2}\right)^2\right]}{X_T\left(\frac{\sqrt{s(\mathrm{GeV})}}{2}\right)^3}.$$

It is worth reiterating that the rapidities are measured in the Y-P center of mass system. The latter formula clearly illustrates the separation of the structure function effects from the subprocess effects. The factor in the square brackets is just the Compton subprocess angular distribution in the constituent-scattering center-of-mass system. The factor u(x) is the "number structure function" or probability that a u quark has fractional momentum x. Of course, this cross section is sensitive to the mean 4th power of the quark charges of the proton, whereas muon or electron scattering is sensitive to the mean square charge of the quarks. The standard value has been assumed in the above formula.

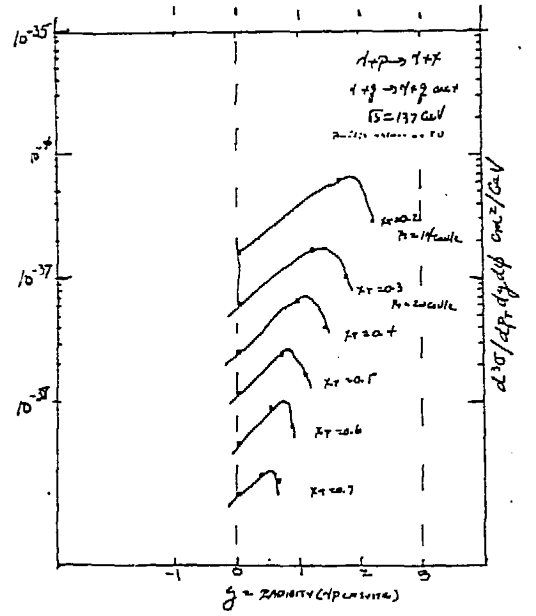


FIGURE 6

A sketch of the rapidity distribution of both the emitted γ and jet is shown in Figure 6. The lowest value of rapidity plotted is y = 0, 90° in the γP cm system. In the Y-quark cm system, this corresponds to photon emission at an angle

$$\cos\hat{\theta} = -(1-X_T),$$

with the quark (jet) 180° opposite. The highest value in rapidity shown in Figure 6 at each X_T is when the quark (jet) comes out at the above angle and the photon is at the complementary angle. The central point on each distribution is the symmetric case: $\cos\hat{\theta} = 0$, $y = y' = -\ln X_T$. A detector with acceptance between rapidity 0 and 3 in the γP cm system is quite adequate to detect both the γ and the jet in all cases. The background to the inelastic Compton γ-jet events from π^0-jet events should be very small compared to experience in hadron-hadron collisions since these two processes will have comparable photoproduction rates.[12]

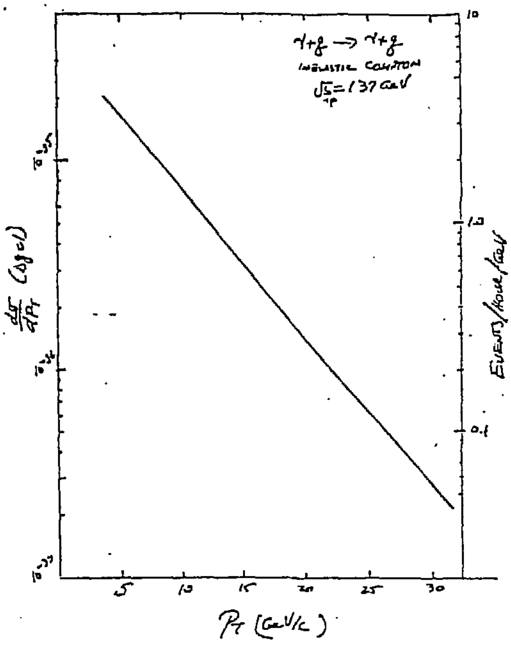


FIGURE 7

The integrated cross section and event rate for inelastic Compton scattering are shown in Figure 7. At each value of P_T the cross section has been integrated over a rapidity interval Δy = ±0.5 about the maximum cross section (Fig. 6.). Nice clean measurements can be made up to X_T values of 0.4 to 0.5. It will be interesting to see whether any clean measurements of this process can be made at the present generation of accelerators. If not, then fixed target at the SSC will be the only hope.

Comparison with HERA

HERA will be an eP collider with 30 GeV electrons colliding with 820 GeV protons with a luminosity of $6 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. The center-of-mass energy for the eP collisions is $\sqrt{s}$ = 314 GeV. The virtual photon luminosity is related to the eP luminosity by approximately

$$\frac{\alpha}{\pi}\ln\frac{s}{m_e^2} = \frac{2\alpha}{\pi}\ln\frac{\sqrt{s}}{m_e} = 6.2 \times 10^{-2}$$

for an equivalent γP luminosity of

$$3.7 \times 10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}.$$

However these virtual photons cover all energies up to the maximum, with a divergent $d\nu/\nu$ spectrum. For lab photon energy >100 GeV, $\sqrt{s} = 13.7$, the flux is

$$\frac{2\alpha}{\pi} \ln \frac{\sqrt{s}}{13.7} = 1.5 \times 10^{-2}$$

for a luminosity of

$$8.7 \times 10^{29}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \quad E_\gamma > 100\ \mathrm{GeV}.$$

The flux of virtual photons with $\sqrt{s} > M_W$ is

$$6.2 \times 10^{-3}$$

or a luminosity of

$$3.7 \times 10^{29}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}.$$

This is more than two orders of magnitude lower than the real photon beam possible at the SSC, without having addressed the question of the efficiency of tagging the virtual photons. Also, the virtual photon spectrum has the typical Brems shape, so one must cope with at least an order of magnitude more low energy photons per high energy photon than shown in the nicely shaped spectrum of Figure 2.

It is also clear that the flux of virtual photons will not increase much with increasing $\sqrt{s}$, if the luminosity is held fixed. For the "large" scale eP project at the SSC discussed by Prescott, 70 GeV e on 20 TeV p, the $\sqrt{s}$ is 2366 GeV. This increases the flux of virtual photons with $\sqrt{s} > M_W$ to

$$1.6 \times 10^{-2}$$

or a factor of 2.5 larger than HERA. The luminosity of this eP machine would have to be 4×10^{33} $\mathrm{cm}^{-1}\mathrm{s}^{-1}$ to improve on the real photon facility just described, for cases where the virtual photon-proton center-of-mass energy, $w = \sqrt{s}$, were important, rather than Q^2.

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