PEP: The Proposed Positron-Electron-Proton Accelerator

Fourth Lecture by Owen Chamberlain
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Today I want to discuss a proposed new machine, a colliding beam accelerator, called PEP. I must emphasize that this proposal is in a very early stage of consideration. It has been under preliminary consideration for about one year by people both at Stanford (SLAC) and Berkeley (LBL). In fact, most of the work I am going to report on is in a combined publication called SLAC-146 or LBL-750. A copy of this combined SLAC-LBL report should be in the library at the new laboratory in Tsukuba.

The machine as it is now conceived would have three possible beams: positrons of 15 GeV, electrons of 15 GeV, and protons of 72 GeV. The machine would be capable of studying beam-beam collisions between positrons and electrons, positrons and protons, also electrons and protons.

The greatest physics interest would be in these four areas:

1) Inelastic scattering:

$$e^- + p \to e^- + \text{anything}$$
$$e^+ + p \to e^+ + \text{anything.}$$

2) Weak scattering:

$$e^- + p \to \nu + \text{anything.}$$

3) Photoproduction with nearly-real photons.

4) Electron-positron colliding beam reactions such as:

$$e^+ + e^- \to \text{hadrons}$$
$$e^+ + e^- \to e^+ + e^-$$
$$e^+ + e^- \to \mu^+ + \mu^- \quad .$$

The energy in the center-of-mass system for electron-proton collisions would be 65 GeV. (This would be equivalent to electrons of 2000 GeV incident on stationary protons.) The center-of-mass energy in electron-positron collisions would be 30 GeV. (This center-of-mass energy would be about the same as the center-of-mass energy at NAL when the NAL machine operates at 500 GeV.)

The purpose of inelastic electron scattering on protons would be the exploration of proton structure. The electron, by way of the photon field, can probe the proton structure in very great detail. As far as we now know, the extent of that detail is limited only by the Uncertainty Principle (deBroglie condition). SLAC experiments of the last few years on inelastic scattering have shown the property called scaling. Scaling may be said to have the following meaning: while the inelastic scattering cross section should depend upon two variables, namely Q^2 and $2M\nu$, the results obtained experimentally seem only to depend upon the ratio of these two quantities. These kinematic quantities Q^2 and $2M\nu$ will be discussed in more detail below. The proposed PEP machine would greatly expand the available limits of these quantities. For example, at SLAC the maximum value of ν is 20 GeV, while for the proposed PEP machine the maximum value of ν would be 2000 GeV. Either the experiments with the PEP machine would show that scaling could be verified into a large new region, or the failure of scaling would set a new energy scale for hadronic interactions.

The PEP machine would give very important information on weak scattering: electron incident leading to neutrino in the final state. The Fermi coupling constant is well known to have the value

$$G = \frac{10^{-5}}{M_p^2} = \frac{10^{-5}}{M^2} \quad .$$

Up to now the weak processes have been studied to center-of-mass energies E such that

$$GE^2 = 10^{-4} \quad .$$

Reactions in PEP would reach $GE^2 = 0.4$, where significant departures from Fermi theory could be expected. If no such departures were detected, then weak scattering would be giving larger cross sections than electromagnetic deep inelastic processes. Also, the W meson could be found directly if its mass is sufficiently low, about 25 GeV or less.

The photoproduction processes with nearly-real photons could allow measurements of γp total cross sections, photoproduction processes leading to π + anything, and inclusive reactions such as $\gamma + p \rightarrow p$ + anything. It is possible that γp elastic scattering (Compton scattering) could be observed.

In electron-positron colliding beam experiments, one would be using time-like virtual photons of mass up to 30 GeV. There is also the possibility of seeing the effects of 2 γ intermediate states. Heavy leptons could be produced, if they exist, up to a lepton mass of 15 GeV.

The kinematics of inelastic electron-proton scattering is shown in Fig. 1. In the derivation, shown in Fig. 1, of the kinematic relationship, the scalar products are taken to be positive if time-like. However, there is one exception: Q^2 is taken to be negative if time-like. In inelastic scattering Q^2 is positive. That corresponds to space-like momentum transfer.

Figure 2 (SLAC 2047B10) shows the kinematic region in terms of ν and Q^2 that would be available from PEP. The quantity shown as W is the same as that we have called M_x. The quantity called θ_L' is the laboratory scattering angle of the lepton, in this case the electron. The laboratory lepton energy in the final state is called E_L'.

Figure 3 (SLAC 2047A11) is a different presentation of the final lepton kinematics.

The usual expression for the scattering of electrons on stationary protons is

$$\frac{d^2\sigma}{d\Omega'' dE''} = \frac{4x^2E''^2}{Q^4}\left[2W_1(\nu,Q^2)\sin^2\frac{\theta_e''}{2} + W_2(\nu,Q^2)\cos^2\frac{\theta_e''}{2}\right]$$

There is an alternative form:

$$W_2 = \frac{1}{4\pi^2\alpha}\frac{Q^2}{\sqrt{\nu^2+Q^2}}\left[\sigma_T(\nu,Q^2) + \sigma_L(\nu,Q^2)\right]$$

$$W_1 = \frac{1}{4\pi^2\alpha}\frac{Q^2}{\sqrt{\nu^2+Q^2}}\frac{Q^2+\nu^2}{Q^2}\sigma_T(\nu,Q^2)$$

In the limit $Q^2 \to 0$,

$$\sigma_L \to 0$$

$$\sigma_T \to \sigma_\gamma(\nu)$$

where ν is the real photon energy. Up to the present time experiments show that σ_L is less than σ_T, so the authors of the SLAC-LBL report have neglected σ_L. Therefore

$$\frac{W_1}{W_2} = \frac{Q^2 + \nu^2}{Q^2} \quad .$$

Using the variables

$$x = \frac{Q^2}{2M\nu} \qquad \text{and} \qquad y = \frac{\nu}{\nu_{max}}$$

therefore

$$xy = \frac{Q^2}{s} \qquad \text{and} \qquad 2M\nu_{max} = s \ .$$

Then we have the expression

$$\frac{d^2\sigma}{dxdy} = \frac{4\pi\alpha^2}{s} \frac{\nu W_2}{x^2y^2} \left\{(1-y) \ [1 - \frac{M^2xy}{s(1-y)}] + \frac{2M^2}{s} \frac{W_1}{W_2} \right\} \quad .$$

Using

$$\frac{M^2}{s} = 2 \times 10^{-4} \qquad \text{and} \qquad W_1 \approx \frac{\nu^2}{Q^2} W_2$$

we find

$$\nu W_2 \approx \frac{1}{4} (1-x) \quad .$$

This leads to

$$\frac{d^2\sigma}{dxdy} = \frac{\pi\alpha^2}{s} (\frac{1-x}{x^2}) (\frac{1}{2} + \frac{1-y}{y^2})$$

The expected luminosity of the PEP machine is $L = 10^{32}$ cm^2 sec. With the approximations indicated above and with the assumption that practically all the final state particles can be detected, one can estimate the counting rates for inelastic scattering. These are shown in Fig. 4 (SLAC 2047B8).

The kinematics of weak scattering is very similar to that for inelastic electron scattering, except the final electron or lepton is replaced by a neutrino indicated as ν, and the structure function W_2 is replaced by the function called β. Using the Fermi theory of weak interaction one can estimate the event rate for weak scattering shown in Fig. 5 (SLAC 2047B9).

The conclusions in the SLAC-LBL report are that all of these processes could be looked at very profitably with reasonable event rates. Notice that some of the experiments will be quite demanding. For example, the numbers of weak scattering events for small values of ν are much smaller than the corresponding inelastic scattering events, therefore these events have to be looked at in the presence of a difficult background. In any case, the events with a neutrino in the final state must be detected by observing carefully practically all the hadrons in the final state, and noticing the momentum imbalance due to the momentum carried off by the neutrino. This suggests that the detector may have to look somewhat like that now being constructed for experiments at SPEAR (Stanford Positron Electron Asymmetric Rings). Such a detector is shown in Fig. 6 (SLAC 2010D3). That figure shows a partially disassembled view of the detector at SPEAR. Even the SPEAR detector has dimensions of the order of 3 m × 4 m.

There is of course great interest in the possibility of detecting the W particle. The proposers of PEP believe that the W particle could be directly observed through its decay product, providing the mass of the W particle is less than about 25 GeV. But, they also believe that if the W particle should have a mass of 37 GeV, one of the interesting values predicted by some current theories, the mass of the W could be well estimated on the basis of the weak scattering results.

I should emphasize again that the PEP proposal is a very preliminary one. As yet there has been no request for money to build PEP. In fact, it is quite sure that considerable more work must be done before a definite proposal can be made. I think the most optimistic view of the time scale on which PEP might be constructed would involve requests for financing in about 1975 with the machine to be operating no sooner than 1979. You can see then that PEP is quite a ways in the future if it is to be built at all. But there seems to be no doubt about the physics interest of the results from PEP, and those who have worked on it are very much impressed with its high potential and its great importance. It is very doubtful that comparable results could

could be achieved in any other way, since it is quite impracticable to make tremendously high energy electron beams. Thus for high energy experiments one is forced to colliding beam methods.

Figure Captions

Fig. 1. Kinematics of inelastic electron scattering on proton.

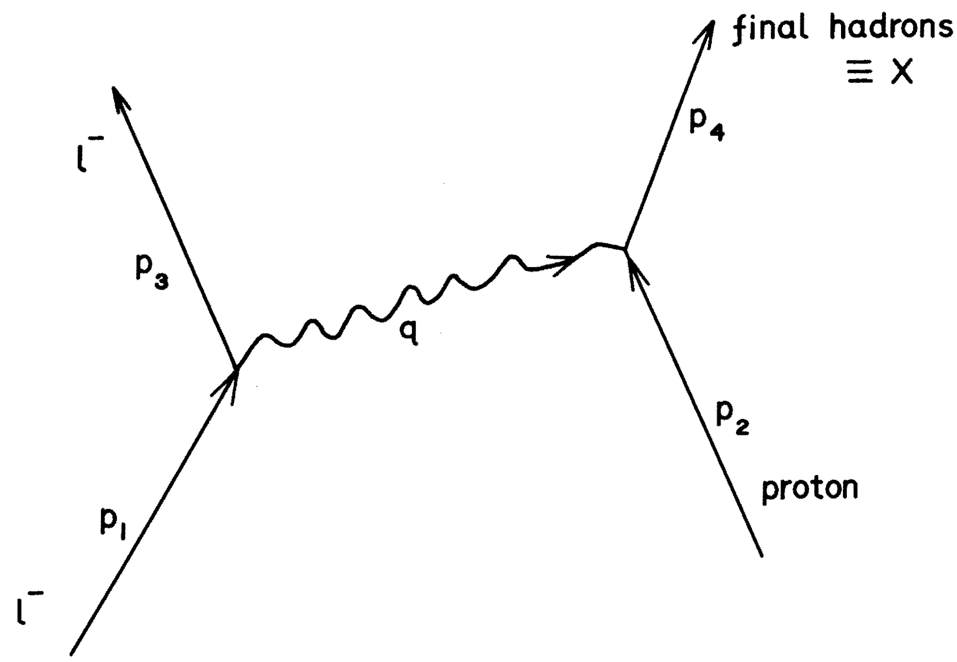
Fig. 2. Final lepton kinematics for inelastic lepton scattering of 15 GeV leptons incident on 70 GeV protons.

Fig. 3. Final lepton kinematics for inelastic lepton scattering of 15 GeV leptons incident on 70 GeV protons.

Fig. 4. Estimated inelastic electron scattering event rate from PEP.

Fig. 5. Estimated weak scattering event rate for PEP.

Fig. 6. Detector for final state particles being constructed for SPEAR.



4 - momento : $p_1 + p_2 = p_3 + p_4$

$$q = p_1 - p_3 = p_4 - p_2$$

Scolar products : positive if time — like
negative if space — like

$$t \equiv q \cdot q = (p_4 - p_2) \cdot (p_4 - p_2) = p_4^2 - 2p_2 \cdot p_4 + p_2^2$$

$$= p_4^2 - 2p_2 (p_4 - p_2) - p_2^2 = p_4^2 - 2p_2 \cdot q - p_2^2$$

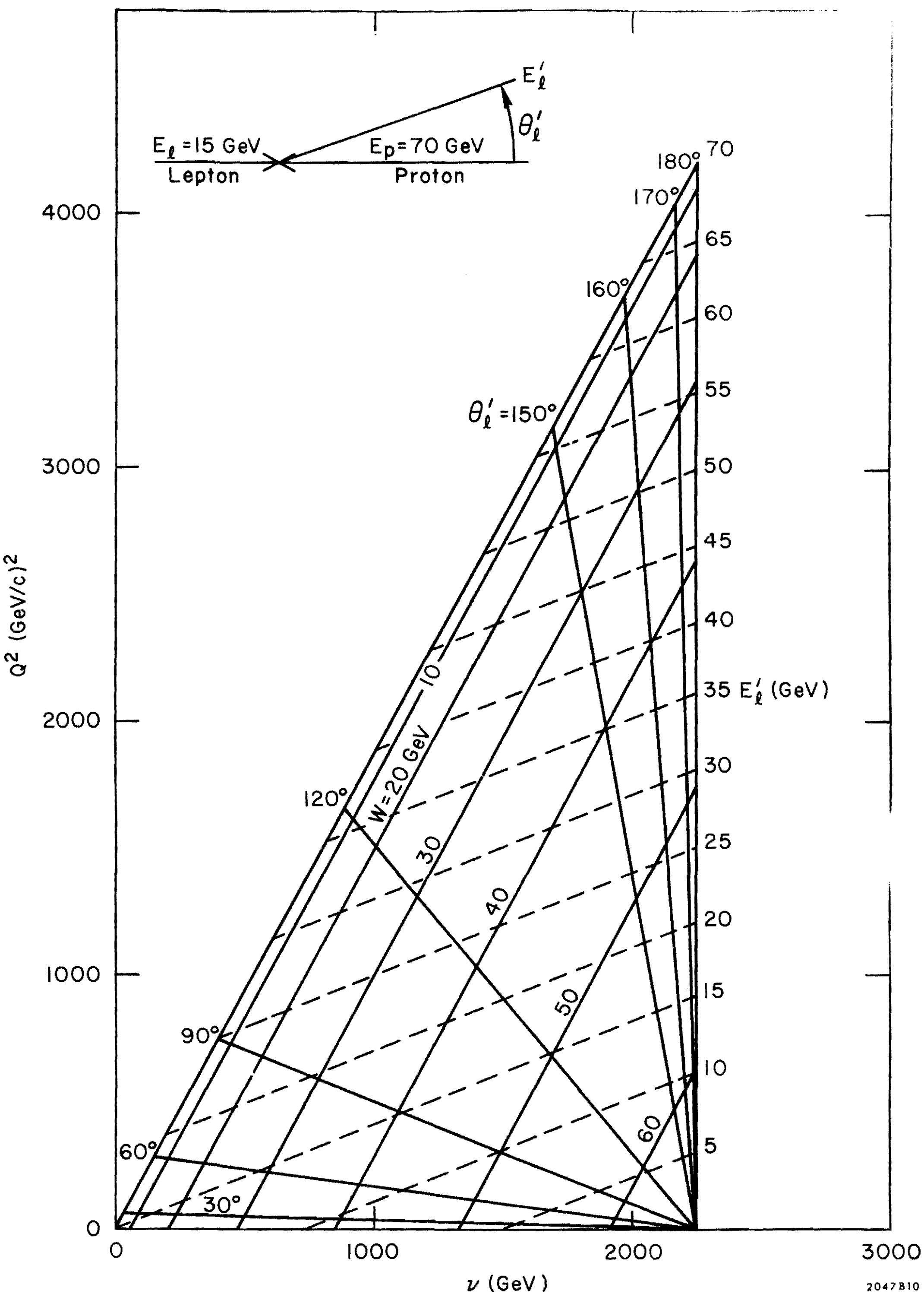
$$= m_X^2 - 2p_2 \cdot q - M^2 \qquad p_2 \cdot q \equiv M_V$$

$$= m_X^2 - 2M_V - M^2$$

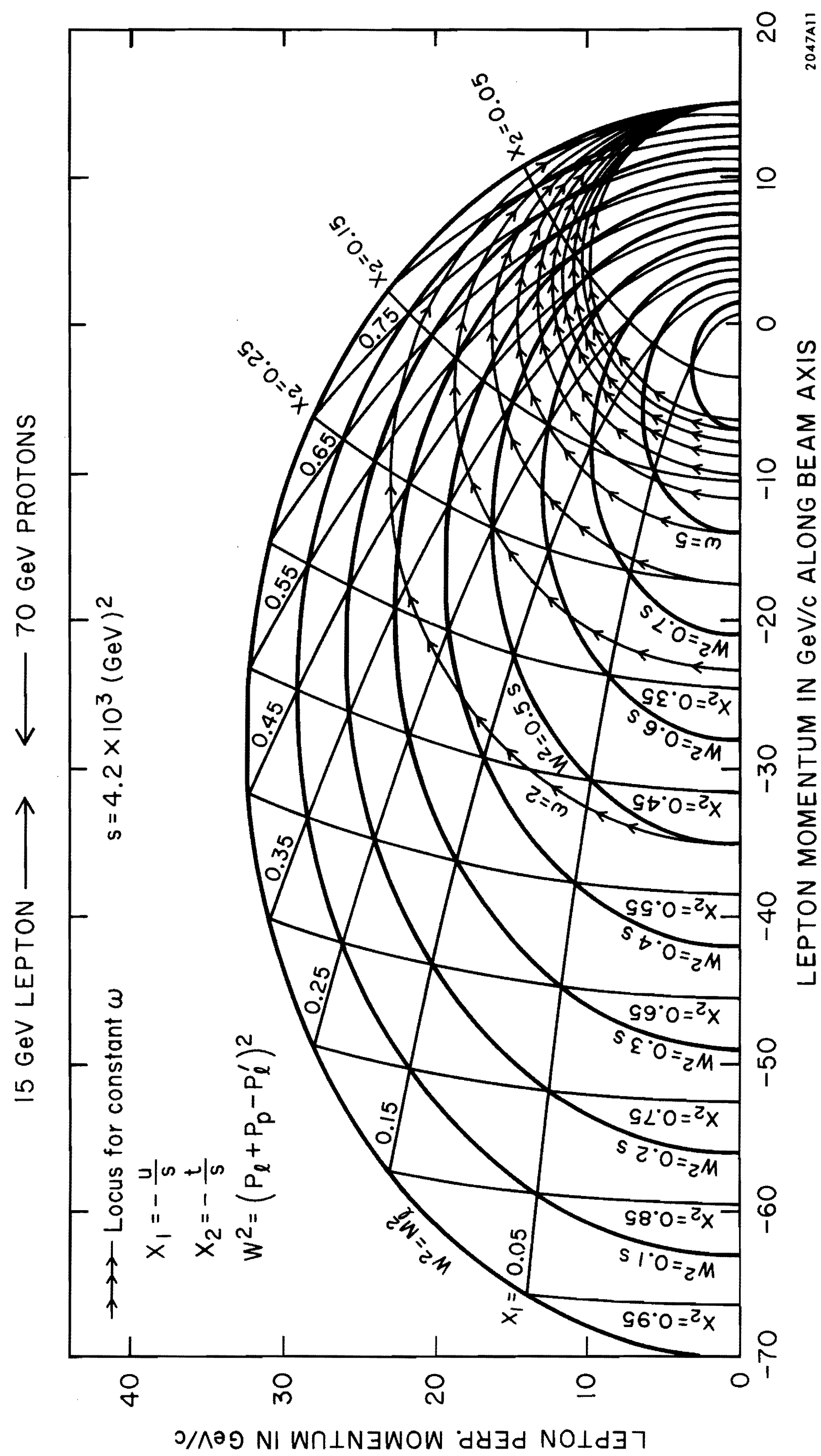
Hence :

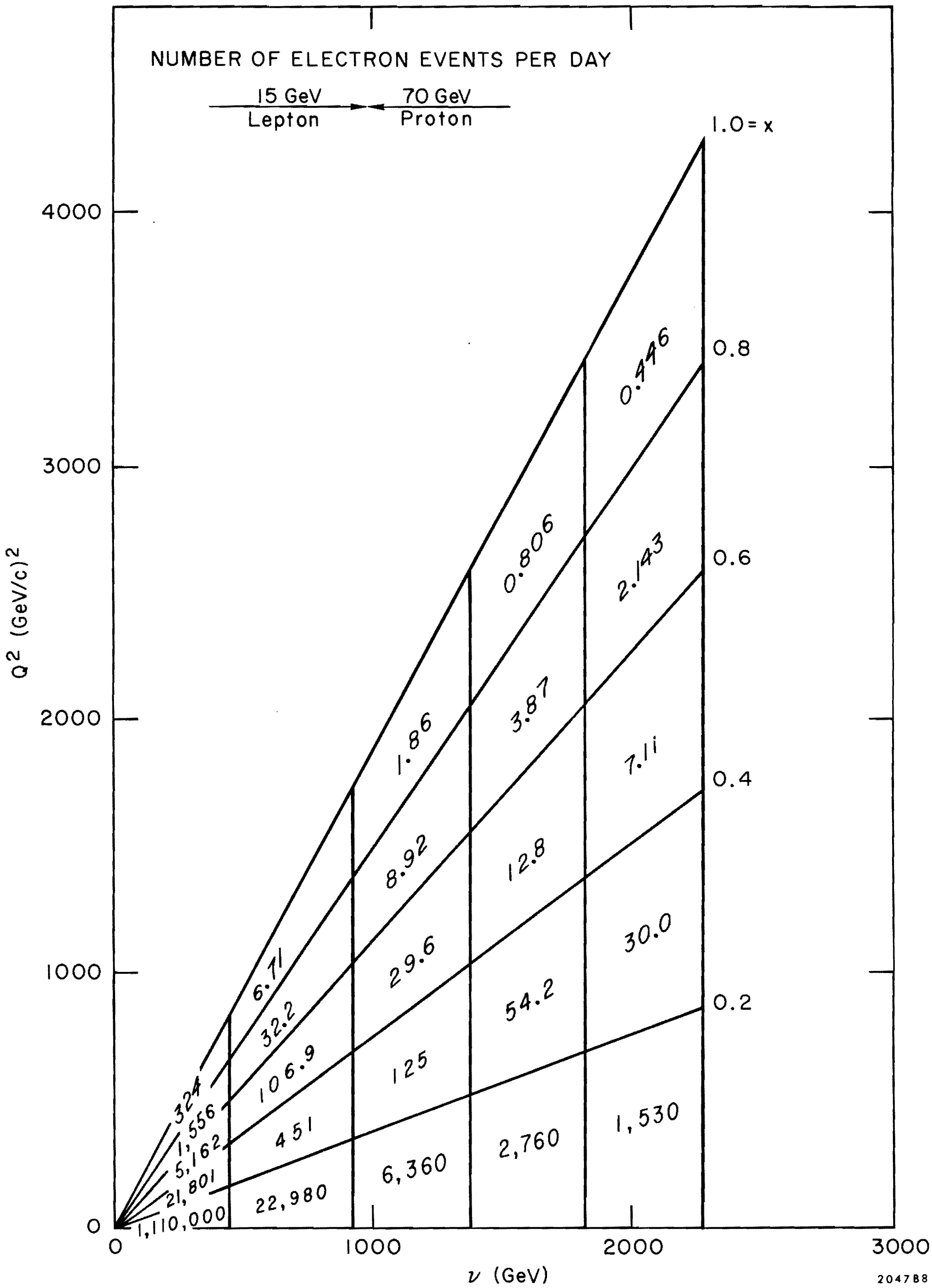
$$\boxed{-t_X \equiv Q^2 = 2M_V + M^2 - m_X^2}$$

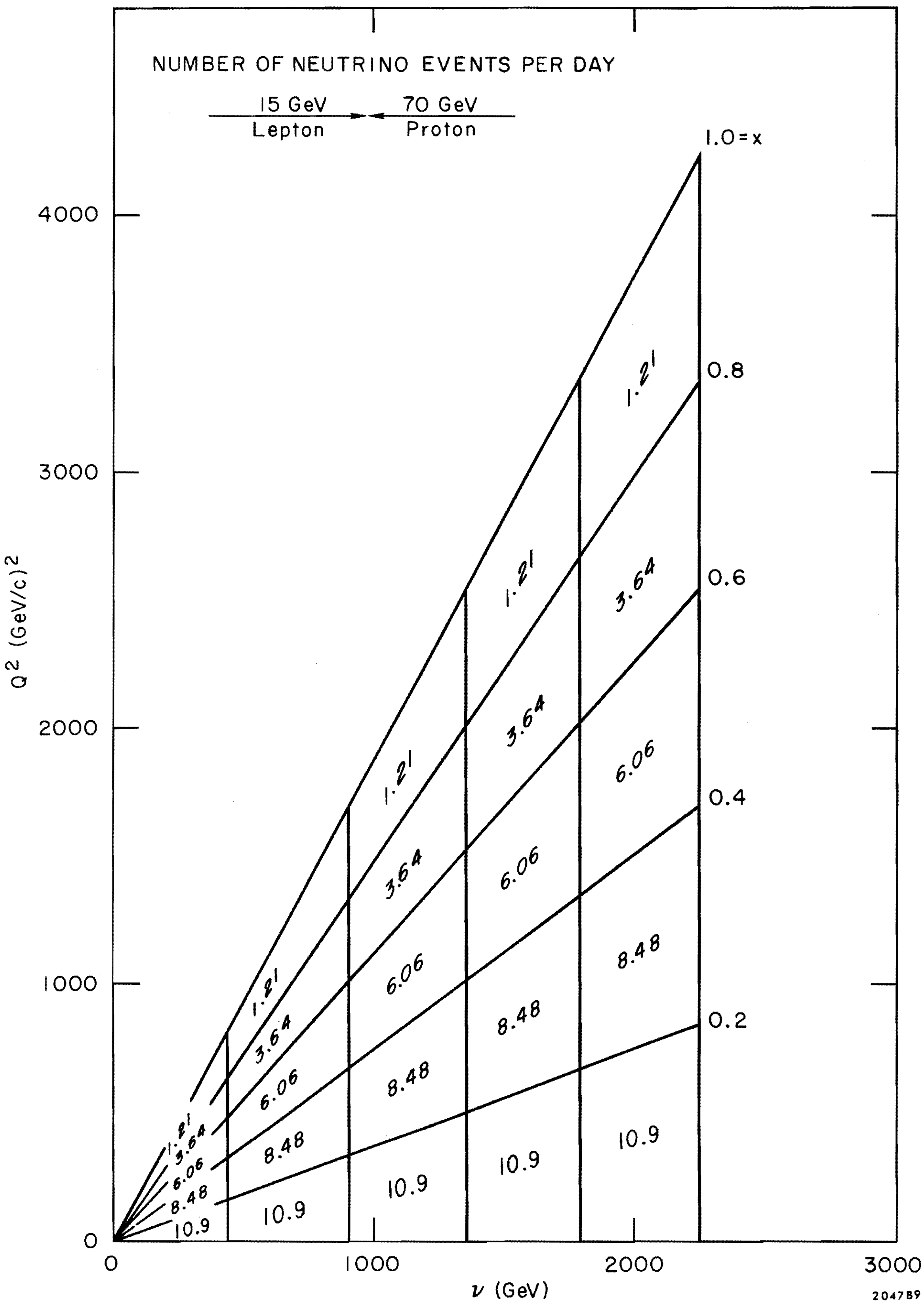
Fig. I Kinematics of inelastic electron scattering on proton.

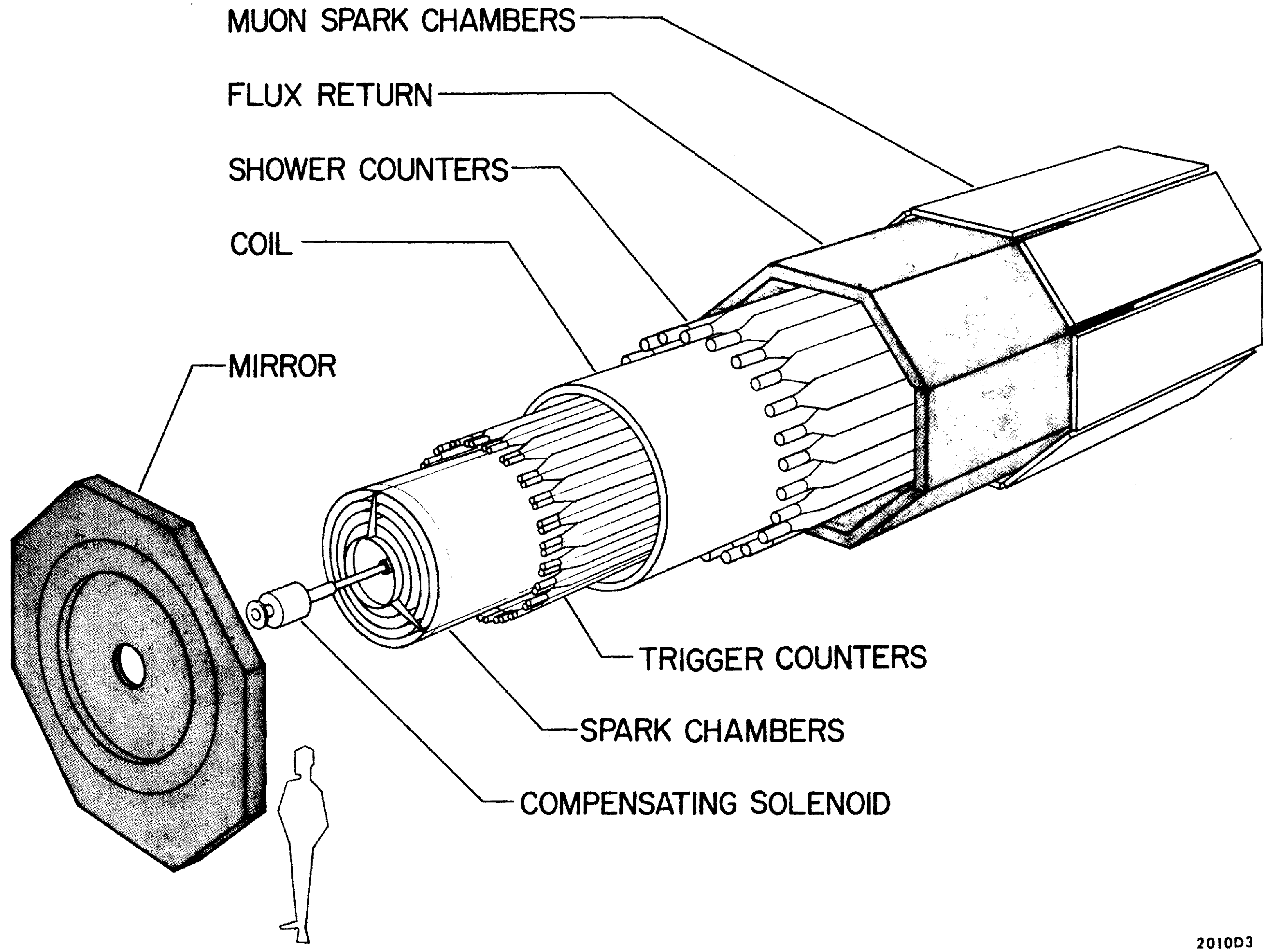


E_ℓ = 15 GeV
Lepton
E_p = 70 GeV
Proton
E'_ℓ
θ'_ℓ
Q^2 (GeV/c)^2
ν (GeV)
0
1000
2000
3000
4000
180°
170°
160°
θ'_ℓ = 150°
120°
90°
60°
30°
W = 20 GeV
10
30
40
50
60
70
65
60
55
50
45
40
35 E'_ℓ (GeV)
30
25
20
15
10
5
2047B10


15 GeV LEPTON ——→ ←—— 70 GeV PROTONS
s = 4.2 × 10^3 (GeV)^2
Locus for constant ω
X1 = − u/s
X2 = − t/s
W^2 = (Pℓ + Pp − P'ℓ)^2
W^2 = Mp^2
X1 = 0.05
0.15
0.25
0.35
0.45
0.55
0.65
0.75
X2 = 0.05
X2 = 0.15
X2 = 0.25
X2 = 0.35
X2 = 0.45
X2 = 0.55
X2 = 0.65
X2 = 0.75
X2 = 0.85
X2 = 0.95
W^2 = 0.1 s
W^2 = 0.2 s
W^2 = 0.3 s
W^2 = 0.4 s
W^2 = 0.5 s
W^2 = 0.6 s
W^2 = 0.7 s
ω = 2
ω = 5
LEPTON MOMENTUM IN GeV/c ALONG BEAM AXIS
LEPTON PERP. MOMENTUM IN GeV/c
2047A11


NUMBER OF ELECTRON EVENTS PER DAY
15 GeV Lepton
70 GeV Proton
1.0 = x
0.8
0.6
0.4
0.2
Q^2 (GeV/c)^2
ν (GeV)
0
1000
2000
3000
4000
324
1,556
5,162
21,801
1,110,000
6.71
32.2
106.9
451
22,980
1.86
8.92
29.6
125
6,360
0.806
3.87
12.8
54.2
2,760
0.446
2.143
7.11
30.0
1,530
204788


NUMBER OF NEUTRINO EVENTS PER DAY
15 GeV Lepton
70 GeV Proton
1.0=x
0.8
0.6
0.4
0.2
1.21
3.64
6.06
8.48
10.9
4000
3000
2000
1000
0
Q2 (GeV/c)2
0
1000
2000
3000
ν (GeV)
204789


MUON SPARK CHAMBERS
FLUX RETURN
SHOWER COUNTERS
COIL
MIRROR
TRIGGER COUNTERS
SPARK CHAMBERS
COMPENSATING SOLENOID
2010D3