WEAK-INTERACTION EXPERIMENTS WITH 1000-BEV ACCELERATOR

N. P. Samios
Brookhaven National Laboratory

I should like to discuss briefly some of the theoretical interest in doing weak-interaction experiments, mainly the obvious ones, the neutrino experiments.

It was demonstrated here, a year or so ago, that there are two types of neutrinos. If you take neutrinos from π-meson decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

and let the μ neutrinos interact with some material, it is found that you do not observe the reaction

$$\nu_\mu + (\text{material}) \rightarrow (\text{material}) + e^-$$

but do observe the reaction

$$\nu_\mu + (\text{material}) \rightarrow (\text{material}) + \mu^- \ .$$

There are other topics which would be interesting to investigate. I shall list them:

1) Are there neutral currents? One investigates this by scattering neutrinos from hydrogen,

$$\nu_\mu + p \rightarrow \nu_\mu + p \ .$$

2) Do you allow the current $\frac{\Delta Q}{\Delta S} = -1$? This can be done quite nicely with neutrino type of experiments; for example,

$$\nu_\mu + n \rightarrow \Sigma^+ + \mu^- \quad ,$$

which is just the inverse μ decay of the Σ^+.

3) Are there currents with $\Delta Q = 0$ and $\Delta S \geq 2$? The reaction to study this would be

$$\nu_\mu + n \rightarrow \nu_\mu + \Sigma^+ + K^- \quad .$$

4) The question of $\Delta Q \neq 0$ and $\Delta S \geq 2$. The reaction here is again with a neutron

$$\bar{\nu}_\mu + n \rightarrow \Xi^- + \mu^+ \quad .$$

I should also mention that events of all these types are analyzable in a deuterium bubble chamber, in that you see enough of the particles so that the event is either determined or over-determined.

5) There is the general class of neutrino experiments such as

$$\nu_\mu + n \rightarrow p + \mu^-$$

$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$

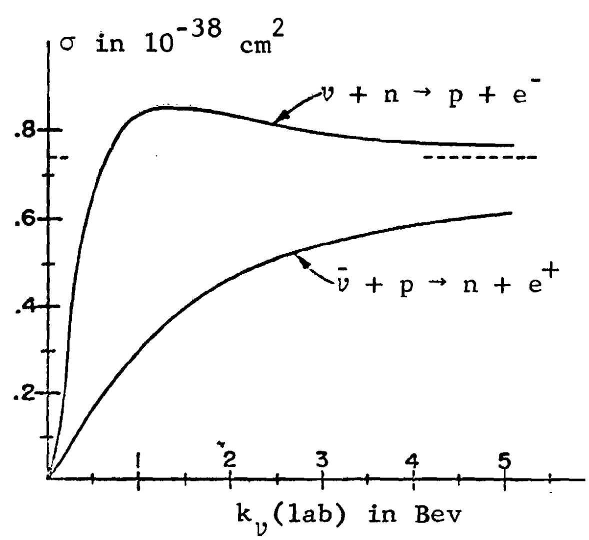


Fig. 1 - "Elastic" neutrino cross sections. The dashed line represents the limit of σ as $k_\nu \rightarrow \infty$.

One notes that if one were going to perform an experiment which depends on low-energy neutrinos, you would prefer working with neutrinos instead of antineutrinos. Therefore, one would try to optimize on π^+ decays, which is precisely what was done at CERN. With these reactions one can investigate the weak-interaction form factors at higher momentum transfer.

6) Finally, there is the question of the intermediate boson. This can be produced in the reactions

$$\nu_\mu + p \rightarrow \mu^- + W^+ + p\,.$$
$$W^+ \rightarrow e^+ + \bar{\nu}_e$$
$$W^+ \rightarrow \mu^+ + \bar{\nu}_\mu$$

The cross sections here have been estimated by Lee for various masses of the boson (Fig. 2). Thus one can get quite an increase in cross section if this boson exists. All of these results depend on having reasonably high neutrino flux and momenta. To conclude, one can possibly do μ-scattering experiments, at very high energy, as a by-product.

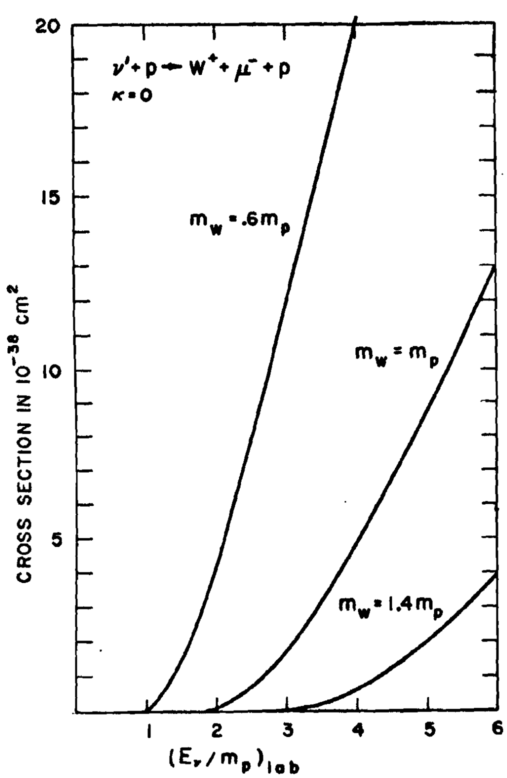


Fig. 2 - Estimated cross sections for bosons of various masses.
$(\nu' + p \rightarrow W^+ + \mu^- + p)$
$k = 0$

I would now like to discuss some rules of thumb in designing neutrino experiments. Consider the case where you have a target, a shield and a detector (Fig. 3).

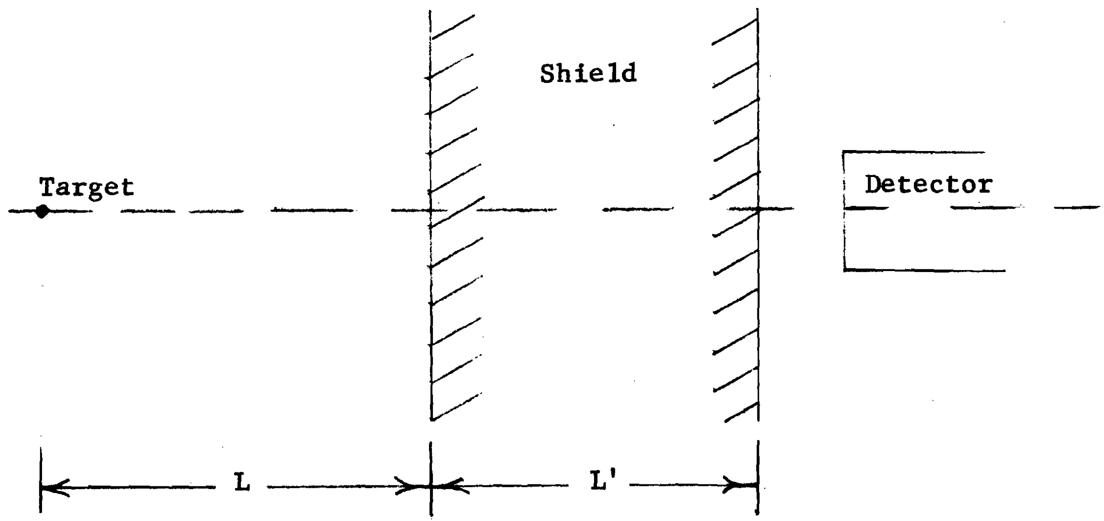


Fig. 3

The two distances L and L' are the flight path and shield thickness respectively. The flux entering the detector can be estimated if one knows the number of particles produced per unit energy and per unit solid angle at the detector. One has to multiply this factor by (1) the solid angle subtended by the detector at the target, (2) the decay solid angle, since the π's decay into a certain cone and (3) the lifetime factor for the π decays. This gives

$$\text{Flux} \approx \frac{d^2N}{dE_\pi d\Omega} \times d\Omega^{\text{det.}} \cdot \Delta\Omega^{\text{decay}} \times \text{lifetime} .$$

On what do these factors depend? $\frac{d^2N}{dE_\pi d\Omega}$ is a number that is given. The "$d\Omega$ detector" is proportional to $\frac{1}{(L + L')^2}$. The decay solid angle is proportional to $1/p_\pi^2$ and the lifetime is proportional to L/p.

In order to maximize the flux for a given π momentum and given L', one would maximize the expression $\frac{L}{(L + L')^2}$, yielding the condition L = L', (i.e., the decay path and the shield length are the same). The above is true if the detector is small compared to the production and decay angles. In the case where this is not true, the production and decay angles are small compared to detector size. The flux entering the detector then depends only on

$$\frac{d^2N}{dE_\pi d\Omega} \times \left(\frac{L}{p} \right)$$

Therefore, one gains linearly with the flight path so that one increases L until it equals L' .

To be more specific, let me discuss the case for a 30-Bev AGS-type accelerator. Consider again the case of the detector and the shield. The mean angle for the neutrino is the sum of the squares in quadrature of the production angle and the decay angle.

$$\bar{\theta}_\nu = \sqrt{\theta^2_{prod.} + \theta^2_{decay}}$$

If one considers production and decay angles at which the flux drops to one-half its maximum value, one attains the relationship that the neutrino angle varies as a constant divided by the π energy, i.e.,

$$\bar{\theta}_\nu \simeq 0.12/E_\pi \quad .$$

We shall take as a starting point an iron shield of 25 meters, which will stop μ's with energies of the order of 30 Bev, and a detector, such as the freon chamber which exists at CERN, (effective radius = 0.3 meter). Then the angle subtended by the detector is

$$\theta_{det.} = \frac{0.3}{(L + L')} \ .$$

The neutrino cone angle is $\bar{\theta}_\nu \simeq 0.12/E_\pi$. Let us take two cases:

1) Consider 10-Bev pions. This gives $\bar{\theta}_\nu = .012$ radians, and for 25 meters of iron and an equal decay length,

$$\theta_{det.} = 0.3/(50) = 0.006 < .012 \ .$$

2) If one now considers 20-Bev π's, one now has a solid angle $\bar{\theta}_\nu = 0.006$ and the detector is also 0.006, so they are exactly matched at 20 Bev. This means that for 20-Bev π's, the neutrinos come exactly into the chamber. The ones that have a higher momentum have a smaller solid angle, and vice versa.

The CERN drawings of the latest ν experimental setup indicates a 25-meter iron shield and a 25-meter flight path, so that the decay angle is always larger than the detector for most of the spectrum, the matching point being 20 Bev. One should further note that in the case where the detector is small compared to the neutrino cone, one gains roughly linearly with the thickness of the shield. That is to say, if one employs a material K times denser than iron, then L' and L are reduced by the same factor. One increases the flux by K^2 due to the solid angle and decreases it by K due to the reduced flight path, so that there is a net gain of K. (The above assumes that the energy loss per gm/cm^2 for both materials is the same.)

I would now like to present some spectra and flux estimates of neutrinos obtained from the 1000-Bev machine. I will first do this for the present AGS (or PS), compare them with the new CERN experimental results and then scale the spectra and flux estimates for the higher-energy machine. Since the experimental pion spectra are known at 4.75°, 9° and larger angles, there arises the question of how one estimates the flux at 0° and other small angles. For these regions I have used the Cocconi, Koester and Perkins distribution, namely

$$\frac{d^2N_\pi}{dE_\pi d\Omega}(E_\pi,\theta) = \text{Const. } E^2 e^{-E(a + b\theta)}$$

where E is the proton energy and θ is the pion production angle. This formula was derived assuming that the transverse momentum and energy of the produced pions are uncorrelated. It also fits the experimental data as obtained by Baker et al. at the AGS quite well.

If one then takes the experimental arrangement as shown in Fig. 3, with L = L' = 25 meters and a target efficiency of 40%, one gets the pion spectrum, i.e. the number of π's per Bev/c per steradian plotted as a function of energy as shown in Fig. 4. This is for 30-Bev incoming protons.

The pions are seen to have a broad spectrum peaking at ~ 8 Bev with a full width at half maximum of ≈ 13 Bev. If one then takes into account the lifetime effect for the 25-meter path, one gets the dotted curve. The net effect is to shift the peak to a lower energy of about 4 Bev and reduce the integrated flux by about one order of magnitude. The

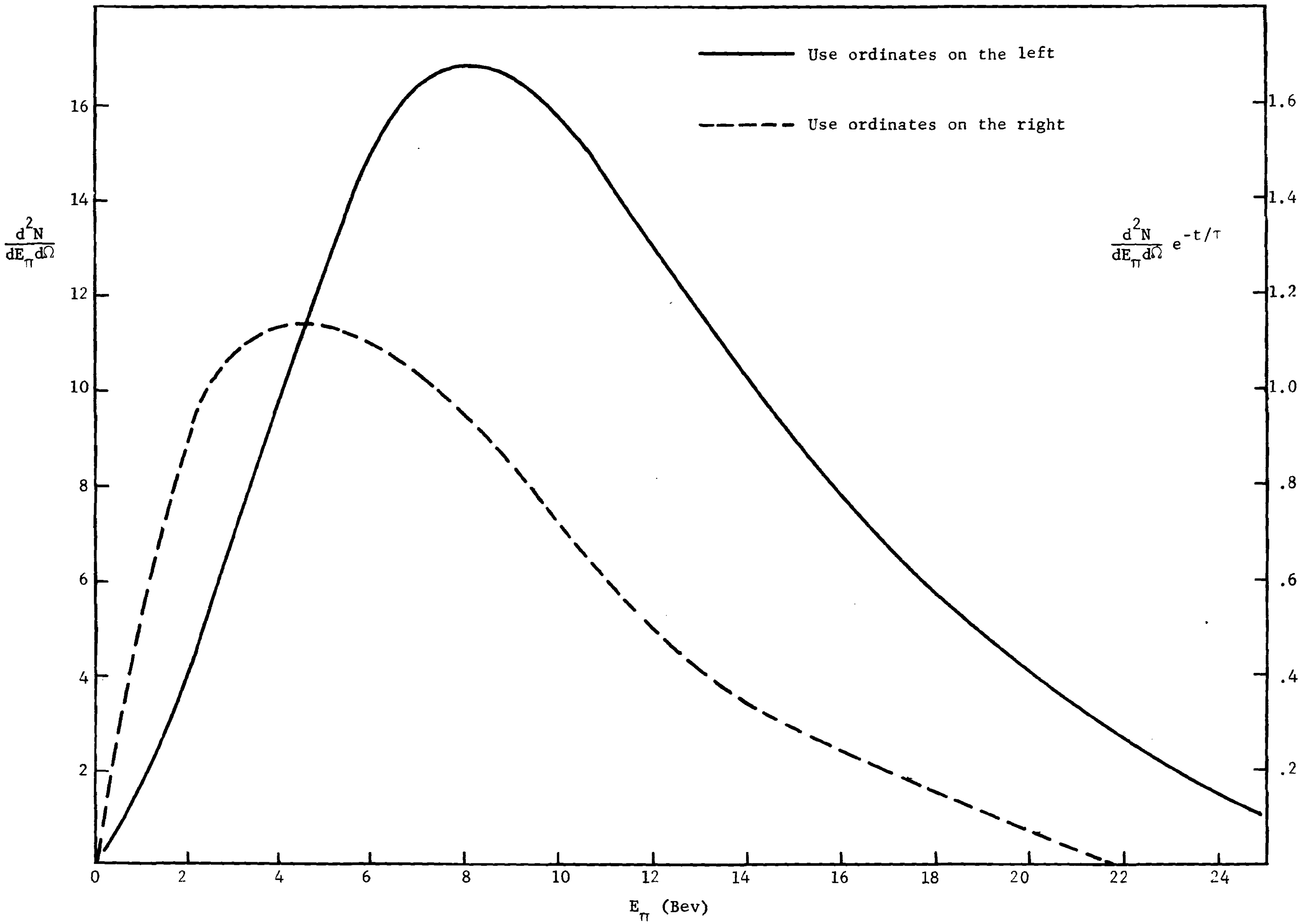


Fig. 4 - Pion spectrum with L = L' = 25 meters and a target efficiency of 40%

corresponding neutrino spectrum is shown in Fig. 5. This peaks at $E_\nu = 1.5$ Bev and the total integrated flux is $\approx 10\ \nu$/Bev/steradian.

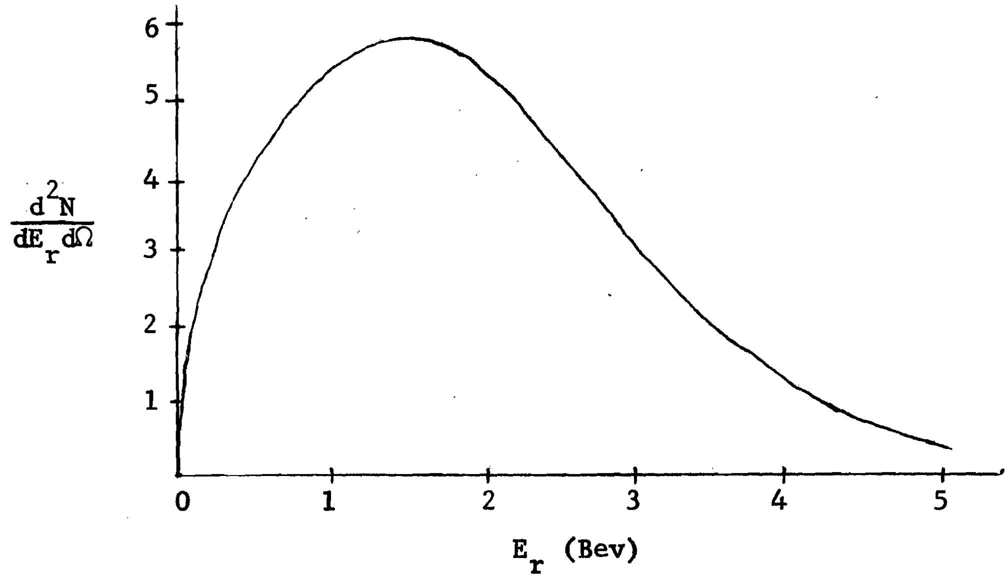


Fig. 5 - Neutrino spectrum

If one then takes the spectrum I have calculated and calculates the number of events that should have been seen at CERN in the freon bubble chamber, assuming a chamber of 500 liters and a target efficiency of 40%, one gets $N = 10^{38}\sigma$, (for 5000 pictures), where σ is the cross section for these neutrino reactions.

L.M. Lederman (Columbia): You forgot about the horn.

N.P. Samios: I'll put a factor of 2 to 3, whatever it does.

Therefore, one sees that this extrapolated spectrum gives the correct order of magnitude for the yield of neutrino events.

I would now like to proceed to a discussion of the 1000-Bev machine. The first point to be made is that, if the flux spectra are distributed as predicted by the "Cocconi et al." formula, then the particles emerging from the target are extremely collimated in the forward direction. This is shown in Fig. 6, where the various curves correspond to the integrated yield of pions per Bev expected for various angles. Therefore, one must be able to arrange experiments so that the detectors sit essentially at 0^o to the target, i.e. external beams.

How do the angles and energies scale? If the transverse momentum $P_\perp$ is a constant and the multiplicity $n \approx E_o^{1/4}$ where E_o is the incident proton energy, then

$$\theta \approx E_o^{-3/4}$$

$$E_\pi = E_o^{3/4}$$

and

$$\left.\frac{d^2N}{dE_\pi d\Omega}\right|_{1000} = \left[\frac{E_o(1000)}{E_o(30)}\right] \left.\frac{d^2N}{dE_\pi d\Omega}\right|_{30} = \left(\frac{1000}{30}\right) \left.\frac{d^2N}{dE_\pi d\Omega}\right|_{30} ,$$

i.e., the number of π's per Bev per steradian goes linearly with proton energy, and

$$\left.\left(\frac{dN}{dA}\right)\right|_{1000} = \left[\frac{E_o(1000)}{E_o(30)}\right]^{1/4} \left.\left(\frac{dN}{dA}\right)\right|_{30} = \left(\frac{1000}{30}\right)^{1/4} \left.\left(\frac{dN}{dA}\right)\right|_{30} .$$

For a fixed detector size dA, the increase in flux is proportional to

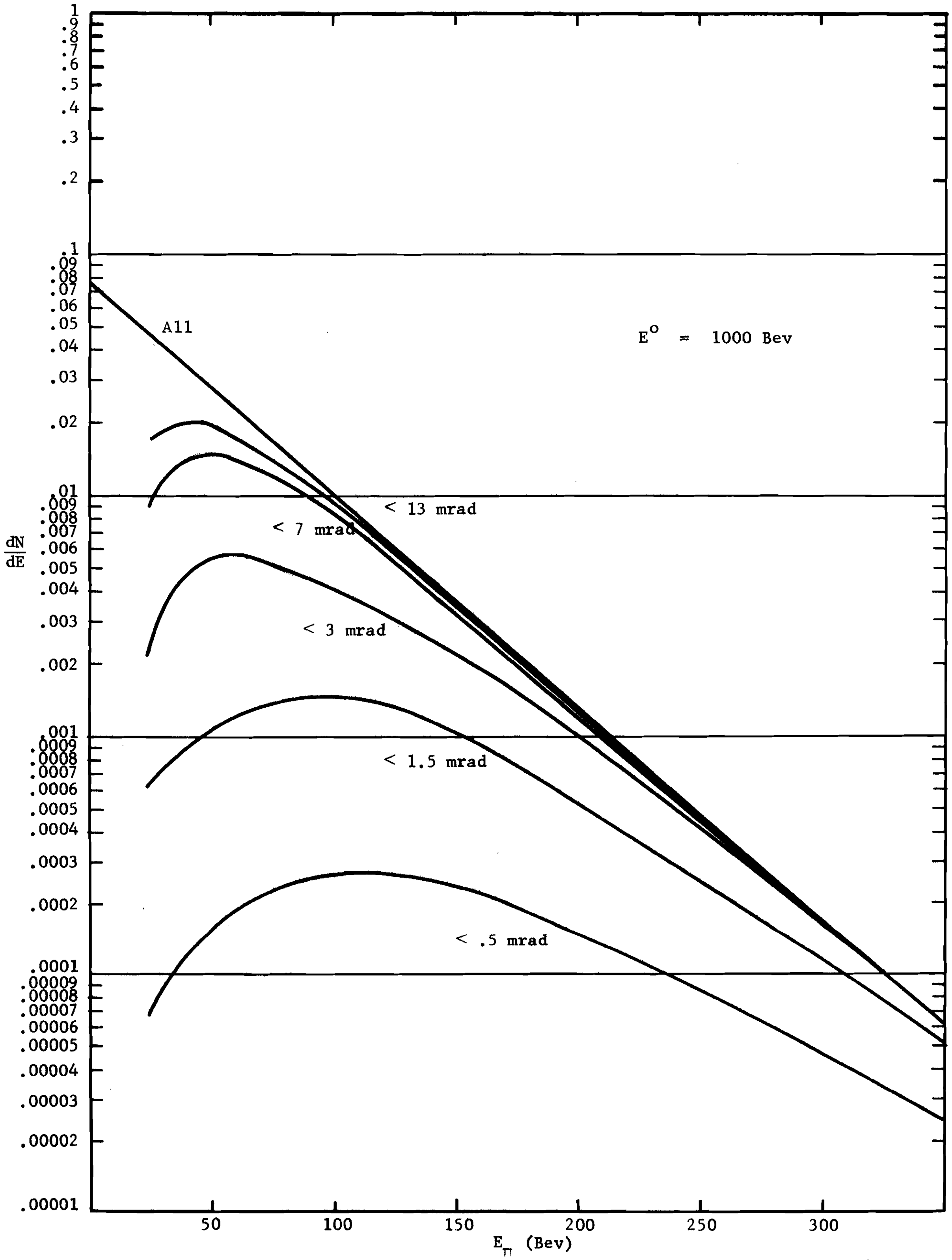


Fig. 6 - Integrated pion yield per Bev expected at various angles

the one-quarter power of the ratio of machine energies, i.e., one gains very slowly with machine energy. Therefore, we can scale the ordinates of all previous curves by $\left(\frac{1000}{30}\right) \approx 30$ and the abscissa by $\left(\frac{1000}{30}\right)^{3/4} \approx 13$.

E.H.S. Burhop (CERN): Are you scaling the length as the energy or as the 3/4 power?

N.P. Samios: The 3/4 power.

E.H.S. Burhop: I think this is very dubious because of the straggling of the μ mesons. I think it is assumed that one should scale the length as the machine energy and not as the 3/4 power. So you want $E^{\frac{1}{4}}$ here and thus no gain. I asked Perkins about this.

N.P. Samios: That may be correct; I hadn't considered the straggling, but it has very little effect on the flux since one only gains by the 1/4 power anyway. The big gains are to be achieved elsewhere.

L.M. Lederman: You no longer have the matching condition. At 300 Bev, the conditions don't hold. The detector is no longer small compared to the spray.

N.P. Samios: No, everything scales - angles, momenta and distances.

L.M. Lederman: You're not doing any focusing?

N.P. Samios: No, I'm not focusing.

L.M. Lederman: How are you scaling the detector?

N.P. Samios: I'm not scaling the detector. If I scale the detector, I'd gain linearly; but if I keep the detector fixed, I gain by nothing or the 1/4 power. That's where I lose enormously. The 1/4 power is just a factor of 2 or so that you gain between the energies.

Let us see what sort of fluxes one can expect to get in the 80" hydrogen or deuterium bubble chamber. On the recent CERN run with the 500-liter CF_3Br chamber with density 1.5 gm/cm^3, they achieved roughly one event every 5000 pictures. The density of liquid deuterium is 0.12 gm/cm^3 and the volume of the 80" BNL chamber is 1000 liter. So we lose a factor of 12 in density and gain a factor of 2 in volume, so that the net change is 1/6 if we try to use deuterium. In other words, we would get 1/6 as many events as they do at CERN, just by scaling everything. The other thing one can possibly do instead of using this arrangement would be to try to decrease L'.

L.M. Lederman: That optimization is based on the fact that you have a certain thickness shield and you always gain by moving the detector closer to the target so you are even better off by making the shield thinner.

N.P. Samios: That's right, and in fact you gain linearly with the shield thickness.

Instead of using 300 meters of iron, one can probably shorten it to something on the order of ~ 150 meters and then match it with a 150-meter flight path. This can probably be done by the use of magnetized iron as well as regular deflecting magnets in an arrangement as shown in Fig. 7.

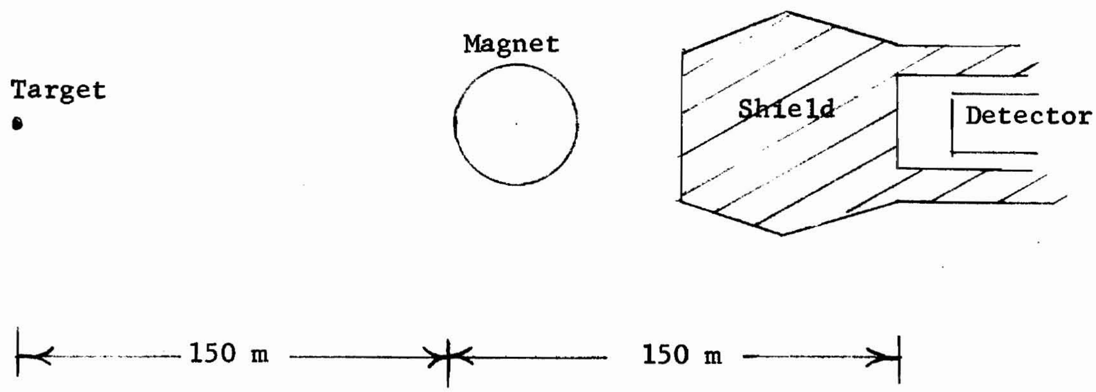


Fig. 7

From the way in which the energies and flux scale (energies as the 3/4 power of the machine energy E_o and $[d^2N/dEd\Omega]$ linearly with E_o), one notes that the energy region, in which one stops particles by just using absorbers, decreases with increasing machine energy. This is shown in Fig. 8. One has the further advantage that the high-energy μ's are well collimated and have small coulomb-scattering angles. They are susceptible to manipulation by magnetic fields. The lower-energy μ's, which arise from larger angles, multiply scatter through larger angles and are more easily stopped by suitably arranged absorbers. It therefore appears that, by being a bit clever, one may gain a further factor of 2 in flux over the CERN results.

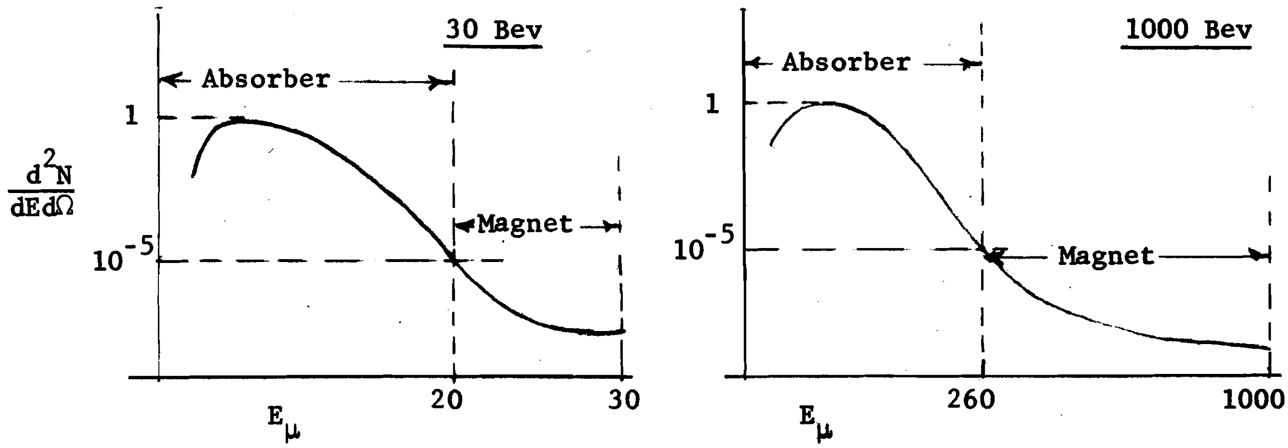


Fig. 8

Further increases can come only from a more intense proton beam in the accelerator or from higher neutrino cross sections due to the higher neutrino energies. It is estimated that proton fluxes of about (1-2) X 10^{13} protons per pulse or higher are achievable with a 1000-Bev machine. This is 20 times the flux of the CERN PS (i.e., 6 X 10^{11} protons per pulse). Finally, T.D. Lee estimates that the cross section per channel is $\approx 10^{-38}$ cm^2 and $\sigma_{total} \approx (p_{\nu_{CM}})^{\frac{1}{2}}$, which is about 2.5 times as high for a 1000-Bev accelerator as for a 30-Bev accelerator. By combining all the factors, one gets for the number of events, per 5000 pictures in the 80" deuterium chamber with 2 X 10^{13} protons per pulse,

$$N = 1 \times 1/6 \times 2 \times 20 \times 2.5 \approx 15 \text{ events/5000 pictures or 60 events/day.}$$

Therefore, one can accumulate hundreds of events in a relatively short length of time, at a rate one obtains strange particle events nowadays.

With these rates one can investigate all the neutrino interactions noted earlier in this talk. Furthermore, there is some evidence, from the recent exposures here and at CERN, for the existence of the intermediate boson. If this is verified, then the production of bosons in the chamber, by such a beam, would be one or two orders of magnitude larger than the 60/day estimated for the other neutrino reactions.

In order to do μ-scattering experiments, one has to shorten the shield and substitute an elaborate spark chamber for the 80" bubble chamber and solve any of the problems arising from the high flux of muons that will impinge on the detector.

The final conclusion I would draw is that neutrino experiments are easily feasible with a 1000-Bev machine, the main gains being due to increased internal proton flux and higher neutrino energies. This necessitates an external beam but no increase in the size of detection equipment.

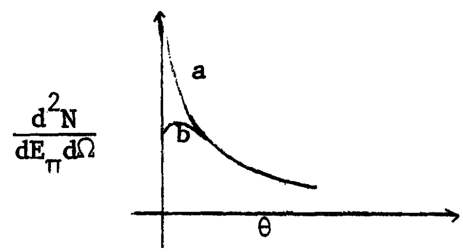
Discussion

L.M. Lederman: I'd like to comment on the Cocconi-Koester-Perkins spectrum. Quite a bit is known about what happens at 30 Bev and we can check the predicted spectrum which looks something like this

$$\frac{d^2\sigma}{dE_\pi d\Omega} \sim \exp - \frac{E_\pi}{T} \left[1 + \frac{\theta T}{P_o} \right]$$

where T and P_o are parameters.

This is a very simple formula which was deduced by some intuition and some experience on cosmic-ray data and what data there was in accelerators. Nobody took it enormously seriously, except that it was an easy one to use, especially when trying to compute intensities which you would expect for neutrino experiments or to try to evaluate the qualities of various focusing devices. Also, it was used by us in predicting the muon beam we'd get in our muon-proton scattering experiment. However, if you plot this equation, it doesn't look very sensible. If you compare the plot with the data available as a function of angle, when last seen, the data came down to 2 or 3 degrees and one didn't know how to extrapolate to zero.



If you use curve (a), an exponential, you get a very high value at 0^o. It didn't look realistic to try to convince a scheduling committee of this, so people just extended the points something like curve (b). The difference between the two results is enormous if you try to evaluate the properties of, for example, the Van de Meer horn, or when you try to estimate how many muons we get.

There are three somewhat independent experimental results. When we designed our muon beam, we used the extrapolation (b). We were getting π mesons produced by the AGS at approximately 0^o and, when we turned on the beam, we, in fact, found an intensity which was quite a bit higher than expected. We went back to our old calculations and found a point closer to curve (a). This was for (6-10)-Bev π mesons.

Then Fitch, looking at 20-Bev pions from the same target (G9), was also pleasantly surprised by a factor of 10 more intensity than he expected. Again, he had also used this formula and then reduced it by a factor of 10. And then he found a high point experimentally.

The third indication is that we've heard rumors second or third hand that a new beam survey, done by a group at CERN, has succeeded in extending these points to smaller angles, very close to 0^o, using a diffracted proton beam. The report is that the 0^o point is in good agreement with the Cocconi-Koester-Perkins spectrum. This handy formula for the pion at 0^o seems to be surprisingly valid.

People point out that angular distributions never approach the axis exponentially, but where it turns over may be small, $\sim$ 1/10 milliradian.

W.L. Willis (BNL): I would like someone to comment on the usefulness of focusing devices.

N.P. Samios: They probably work very well for low momenta. The high-momentum π's go straight forward, so there is nothing you can do except increase the flight path.

W.L. Willis: What is the E_π for the 1000-Bev situation where the chamber sits in the beam?

N.P. Samios: You take $0.12/E_\pi$ and scale by the 3/4 power. It's $E_\pi \times 13$, and at CERN, it's matched at 20 Bev. Here it would be $20 \times 13 = 260$ Bev.

W.L. Willis: That would be about 40-Bev neutrinos.

N.P. Samios: Yes, 40-50 Bev.

W.L. Willis: So for 10-Bev neutrinos, which might be a decent energy, you would still gain with the horn.

N.P. Samios: Yes, in fact, with the higher-energy machines, you'd want to peak up on the low end as much as you can, and that's where the horn pays off. The same is not true at the AGS. If one is interested in producing bosons, here one may try to peak up the high end of the spectrum by increasing the flight path.

One thing I didn't consider at all is that you also get contributions from K decays, and they're higher momenta.

L.M. Lederman: Magnetizing the iron shield to decrease the required thickness is not trivial. The difference between muons and neutrinos is that the neutrinos have a wider spray -- the muons are really at 0^o, i.e., there is no angle between the π and the μ. You might take advantage of this by moving the detector off the central axis of the beam. In this case, you may very well be in a place that the muons can't reach unless they are very low energy and can be stopped by a moderate shield, whereas you'd get neutrinos, especially those from K mesons. Of course, you sacrifice some neutrino energy, but if you're at 1000 Bev, you can afford it.

L.C.L. Yuan (BNL): Isn't it true that at higher energies you get more advantage from the K neutrinos, with higher neutrino energies, so your cross sections would go much higher?

N.P. Samios: The point is that the π's from a 1000-Bev machine yield neutrinos whose energy is above the region where the cross section flattens off, so you don't gain much from higher-energy neutrinos which come from K's. You gain much more at 30 Bev if you use K's.

L.C.L. Yuan: That depends on the mass of the intermediate boson.

N.P. Samios: Yes, the energy value for the lowest-energy neutrinos which will yield boson events depends on the boson mass.