Colliding γ Beams

(2-Photon Processes and Tagging)

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Abstract

The two-photon process is reviewed and the nature of forward tagging investigated for the proposed PeP, 15-Gev e^+e^-, configuration. Problems associated with working close to the beam are discussed. Tagging low energy electrons appears possible at the 50% level, useful in suppressing background for single photon studies. A prototype experiment for two-photon studies is presented with reasonable rates possible for many channels.

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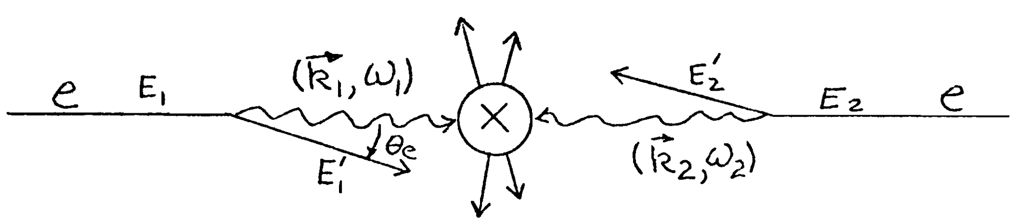
1. Basics

The two-photon process can be split into two regions, almost real photons and heavy virtual ones. The latter with one or both heavy is called deep inelastic. The case of photons nearly real is treated in the equivalent photon approximation.



Rates are easy to calculate in the approximation:

$$d^2\sigma = \sigma^{(s)}_{\gamma\gamma \to X} N_1(\omega_1)\, N_2(\omega_2)\, \Delta^2$$

$$\text{where} \qquad \Delta^2 = \frac{d\omega_1}{\omega_1}\,\frac{d\omega_2}{\omega_2} \qquad \text{a)}$$

$$\text{or} \qquad = \frac{ds}{s}\,\frac{d\beta}{1-\beta^2} \qquad \text{b)}$$

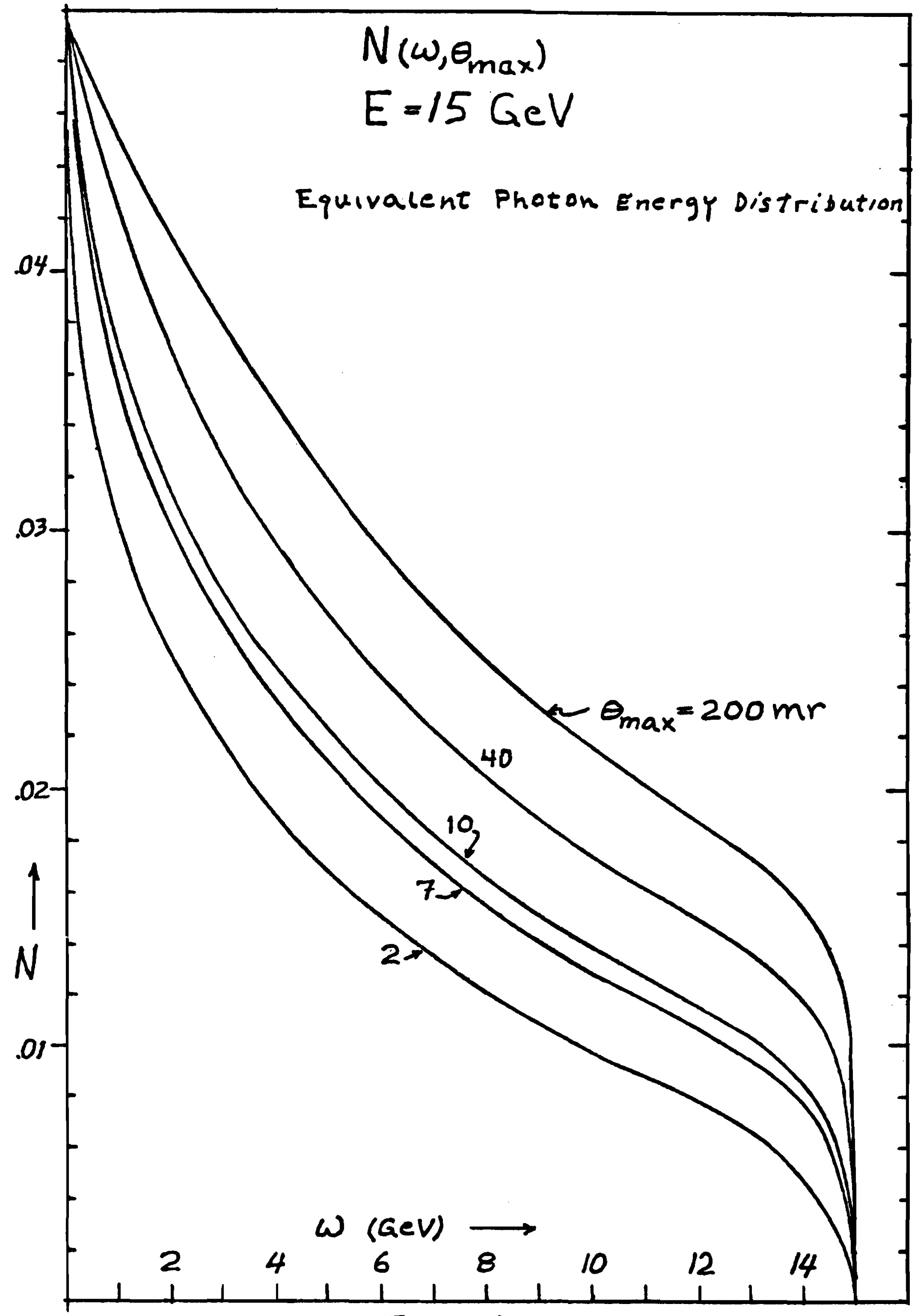

N(ω, θmax)
E = 15 GeV
Equivalent Photon Energy Distribution
.04
.03
.02
.01
N
θmax = 200 mr
40
10
7
2
ω (GeV)
2
4
6
8
10
12
14

FIG. 1

or $$\Delta^2 = \frac{ds}{s} \frac{dp}{\sqrt{p^2+s}} \qquad c)$$

and $\omega = E - E'$, $s = 4\,\omega_1\omega_2 = m_x$, $p = \omega_2 - \omega_1$ $(\omega_2 > \omega_1)$, $\beta = \frac{\omega_2 - \omega_1}{\omega_2 + \omega_1}$ is velocity of X, $\sigma_{\gamma\gamma\to x} \sim \frac{4\pi\alpha^2}{s}$ for a final state X with momentum p from two virtual photons labeled 1 and 2. Photon energy distribution, $\dot{N}$, is plotted in Fig. 1, integrated over ϕ_e and θ_e up to θ_{max}.

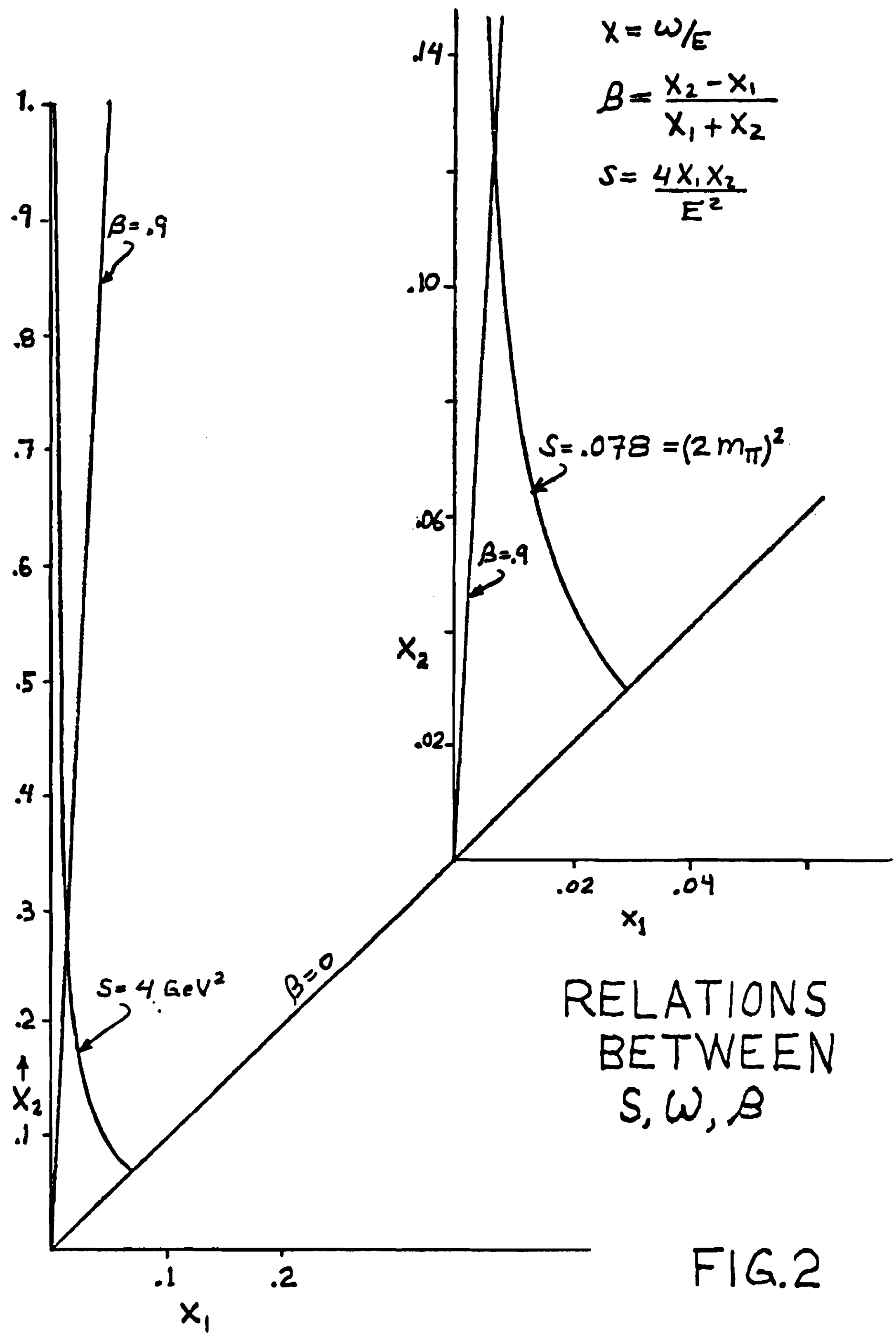
A tagging system to identify the 2-photon process will require operating between θ_{min} and θ_{max} so that N is obtained at a given ω by taking the difference between two curves. The double differential cross section may be visualized as a double radiator, (a); or as a moving object with mass $s \pm ds$, (b); or as a mass with a production momentum distribution, (c).

Note that most of the rate comes from $\omega_2 >> \omega_1$ and p can be large with m_x moving very forward in the lab frame. This can be seen more exactly in a plot such as Fig. 2 where the curve is a line of constant s $(= 4E^2x_1x_2)$. Regions which contribute most to a given ds are obviously for $x_2 >> x_1$, also indicated by expression (b).

One immediate observation to be made is that double $(\theta>0)$ tagging is very inefficient for low m_x. In particular

$$\omega_1 = \frac{m_x^2}{4\omega_2} \sim \frac{m_x^2}{4p} = 0.1 \text{ GeV for } m_x = 1 \text{ GeV}$$
$$p = 2.5 \text{ GeV/c}$$

and a look at Fig. 1 shows that all the flux for this low ω region comes from small θ (< 2 mrad). As we will see below, there appears



RELATIONS BETWEEN S, ω, β

FIG. 2

to be no hope of small angle (< 3 mrad) tagging due to beam-beam Bremsstrahlung at PeP.

A second observation is that good tagging efficiency can be achieved by going to large angles. Covering the range from 10 to 200 mrad provides 30% efficiency while decreasing θ to 7 mrad only improves it to 33% in the middle energy region. In other words, the angular dependence is not so steep as to require heroic efforts. Also, at large energy loss (high ω) the low energy electron can be detected with 50% efficiency for the 10 to 200 mrad case. If single tagging, double ended, is used to monitor 2γ vs 1γ processes where $s > 750$ GeV^2, then one or the other of the electrons can be seen with 75% efficiency.

2. Prototype Detector

In order to investigate noise problems and possible 2γ physics, we have sketched a detector, Fig. 3, which (a) looks at forward m_x states with single tagging from 10 to 40 mrad and, (b) performs double tagging for high q^2 (deep inelastic) by having a small angle tag on one side and large angle plus small angle on the other side. The small angle tag is done with NaI to obtain maximum event constraint. The inherent resolution of the tag is limited by $\delta E/E$ of the machine ($\sim$3/4%) and radiative effects (1-3%). Large angle tagging is accomplished with a magnet very close to the beam pipe and with narrow septum. It covers an angular range of 50 to 300 mrad with 5% momentum resolution up to 5 GeV/c.

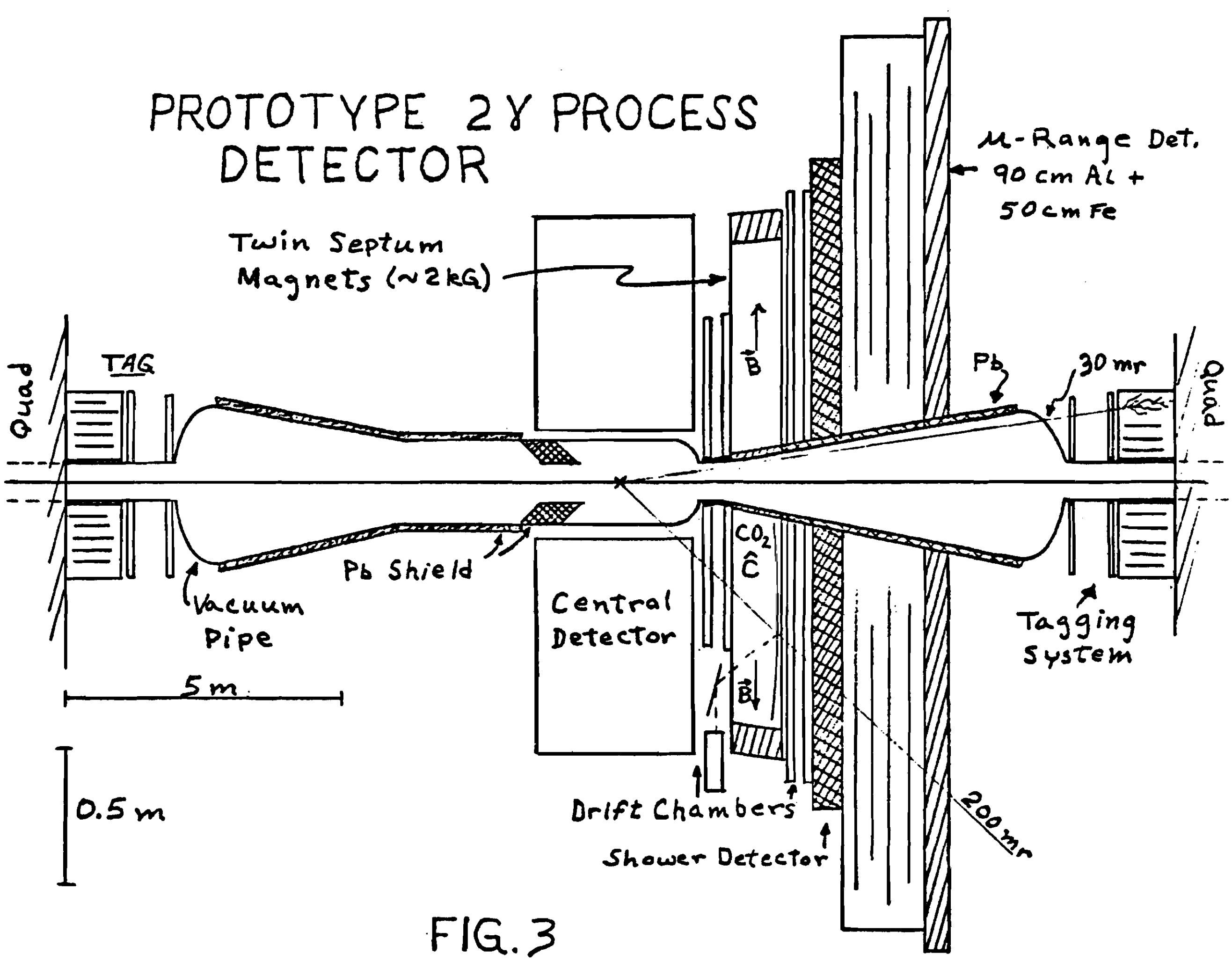

PROTOTYPE 2γ PROCESS DETECTOR
μ-Range Det.
90 cm Al +
50 cm Fe
Twin Septum
Magnets (~2 kG)
B
TAG
Quad
Pb
30 mr
Quad
CO2
Ĉ
Pb Shield
Vacuum
Pipe
Central
Detector
Tagging
System
5 m
B
0.5 m
Drift Chambers
200 mr
Shower Detector

FIG. 3

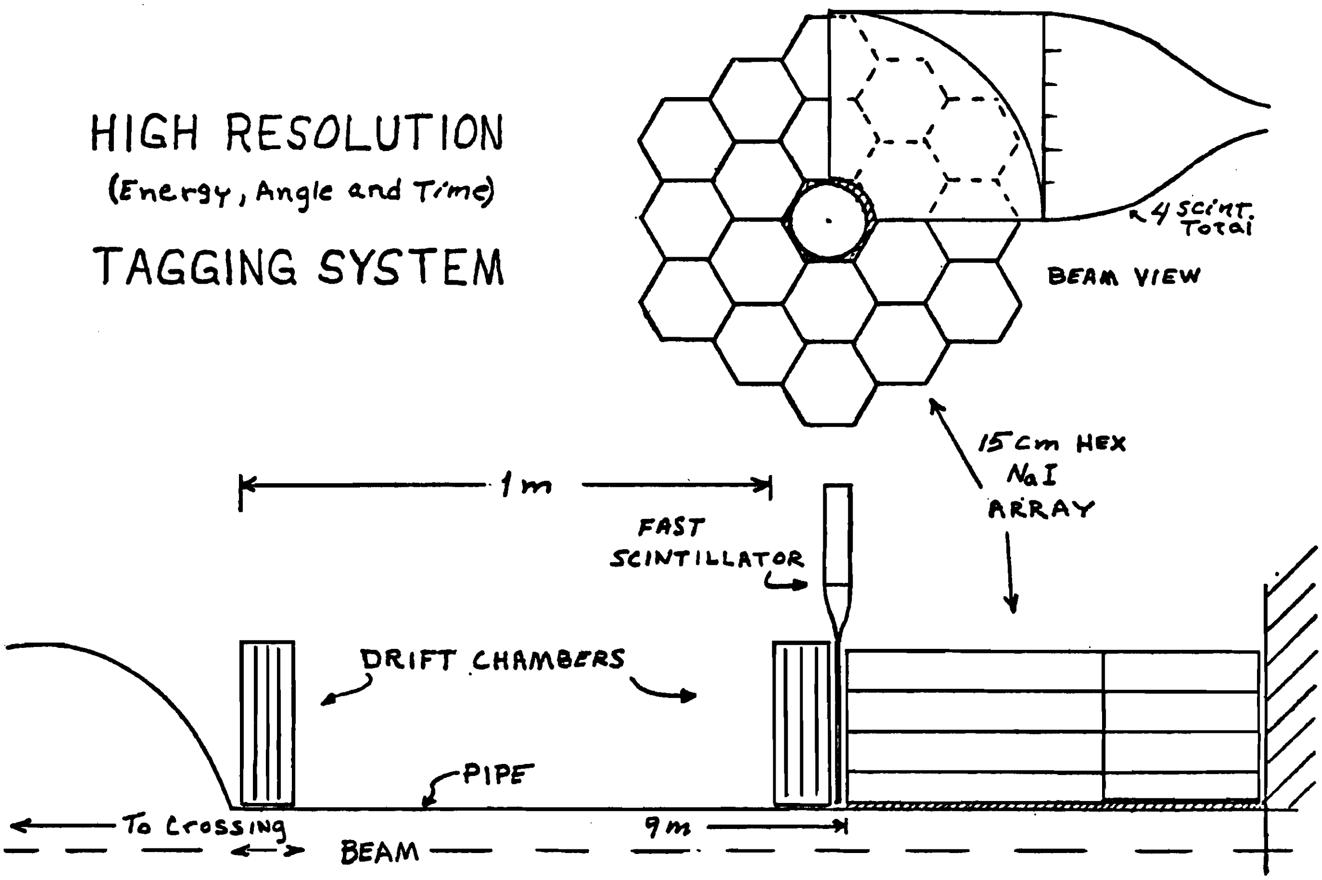

HIGH RESOLUTION
(Energy, Angle and Time)
TAGGING SYSTEM
4 Scint. Total
BEAM VIEW
15 cm HEX NaI ARRAY
1 m
FAST SCINTILLATOR
DRIFT CHAMBERS
PIPE
To Crossing
9 m
BEAM

FIG. 4

Small angle tagging is assumed to take place at the ends of the intersection region. A possible combination of elements is shown in Fig. 4 in which hexagonal cross section NaI crystals are used for electron (or γ) energy analysis. The front face of the NaI is 9m from the beam intersection point. Drift chambers with 1m spacing are incorporated to provide angle measurements for the electrons with 0.2 mrad accuracy so that correlation with the interaction region is optimized. Fast scintillation counters are used to distinguish e and γ in the trigger and provide timing information, largely for suppression of "backporch" noise. Good energy resolution ($\sigma \sim 1\%$) is obtained over an angular range of 12 to 35 mrad. Allowing worse resolution extends the range to 9-40 mrad. The NaI is 7.6 cm from the beam center at the closest point and probably should have $\sim$ 1 cm Pb between it and the beam.

The magnet aperture, shown in Fig. 5, is fairly good for detection of low m_x, exclusive, or higher masses, inclusive. The magnet gap is filled with atmospheric pressure CO_2 $\check{C}$ medium to separate π and e with high π rejection (or electron anti), necessary for background suppression. Shower counters behind the magnet will aid in electron identification, γ detection and π-μ separation at low energy. Higher energy π, μ, p separation will be done in the range chamber following the shower counter. A central detector, as yet unspecified, would be tailored to specific wide-angle requirements such as the large ν, high q^2 deep inelastic process.

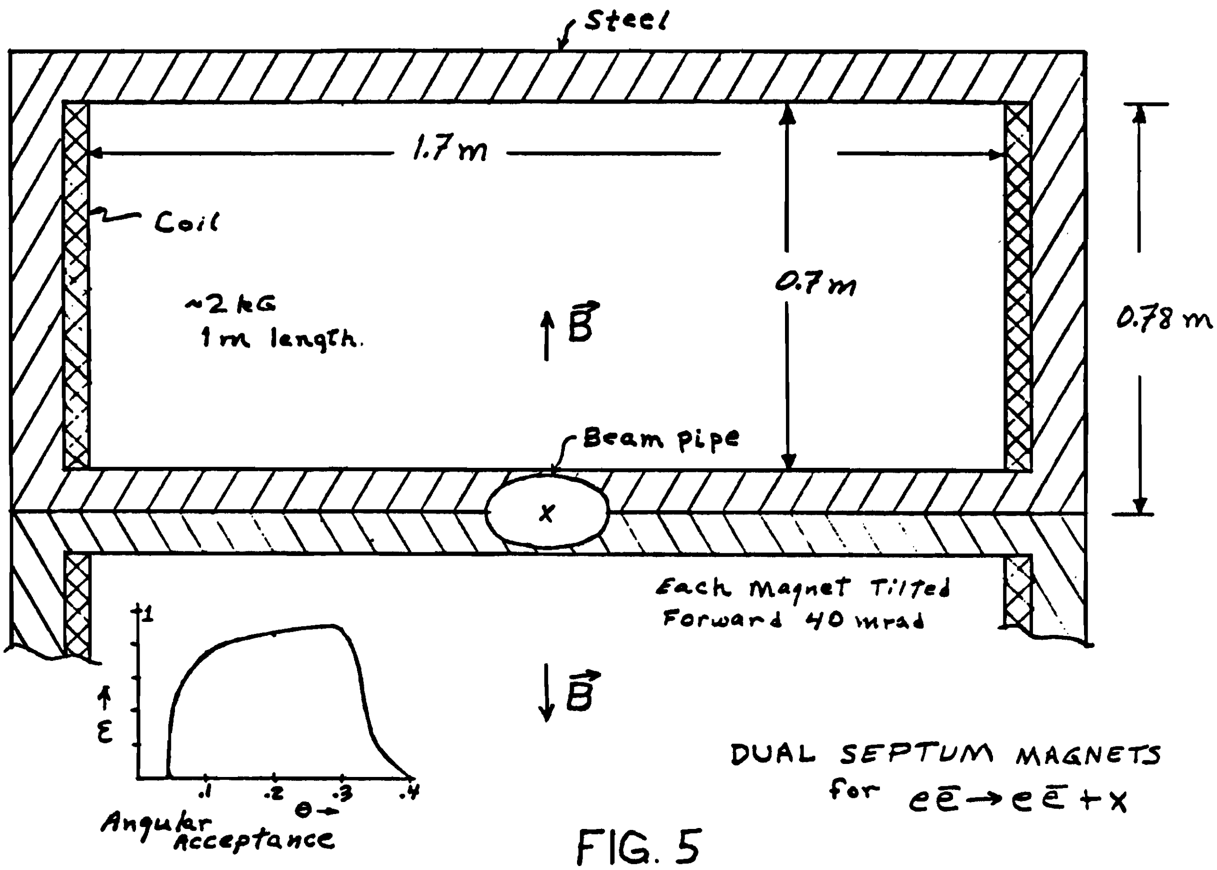

Steel
1.7 m
Coil
~2 kG
1 m length.
B
0.7 m
0.78 m
Beam pipe
x
Each Magnet Tilted
Forward 40 mrad
B
ε
.1
.2
.3
.4
θ→
Angular Acceptance
DUAL SEPTUM MAGNETS
for eē→eē+x

FIG. 5

3. Noise Problems

We have looked at several processes that feed particles into the intersection region at low angles such that the close-in detectors are most affected. Note that the problem in the prototype setup is shared between the magnet entrance (wire chambers) and the tagging counters. We have assumed $\mathcal{L} = 10^{32}$ $(cm^2\ sec)^{-1}$ and 10^{12} particles/bunch.

Class 1. Beam-Beam

a) ee Bremsstrahlung. This process is a high energy loss mechanism at PeP and leads to high "occupancy" because of the low bunch frequency. It causes no problems with the detector, but does seem to eliminate the possibility of looking at zero angle for electrons which have lost energy from the 2γ process. We estimate that there is unity occupancy (once for every beam crossing) for one electron in the bunch to lose between 40 and 50% of its energy (i.e., $\frac{\Delta E}{E} = 10\%$). Any forward direction ($\theta < 3$ mrad) detector would appear to be doomed in a rate like that, for any choice of energy loss.

b) Bhabha. There will be a rate of about 50/sec into each of the hexagonal NaI counters near the beam pipe ($d\Omega = 1.7 \times 10^{-4}$ sr at $\theta \sim 15$ mrad). This is a nice rate for luminosity monitoring but does contribute to accidental problems at some level.

Class 2. Beam-Gas

a) Coulomb scattering. This is small for scattering off the nucleus (10^{-4} occupancy) principally because the quads focus the low angle back to the center for events from the LSS (Long Straight Section, 60 meters preceding the interaction region). The ee scattering, however, is a much larger effect because the soft electron comes out at a large angle, 20^{o} for a 5 MeV electron. Occupany of 0.2 is possible for 10^{-8} Torr, E_e > 5 MeV, 10 m path length. This will produce some noise in wire chambers but no severe tagging problems because of the NaI energy scale.

b) Bremsstrahlung, γ. The LSS is a potential serious source of high rate, high energy noise in the intersection region. There is a 4-meter segment between QF and Q1 located on a line of sight 65 meters from the intersection point where gas pressure is high (say 5×10^{-9} Torr partial pressure of CO) and β is large (large angular dispersion). The γ flux from this source corresponds to $\sim$ 0.3 GeV/meter for each beam. Some fraction of these γ's will strike the walls in the interaction region, depending on beam alignment, angle dispersion, and proximity to the beam. The apparatus we have sketched has several apertues at 7 cm from the beam, so that a 1 mrad electron angle in the segment at the start of the LSS illuminates that small aperture part of the apparatus.

If 5% of each bunch (for example, $\sigma_\theta \sim \frac{1}{2}$ mrad) contributes for the 4m path, then 0.25 GeV/crossing is deposited in the apparatus. This can cause fairly high noise levels, worsening NaI resolution, and produce high energy events with about 1% occupancy. We suggest that scraping the beam upstream of the insertion quads may improve the situation. This would amount to restricting machine aperture to $\sim$ 6 cm radius, 15m from the crossing point. Another way of reducing this noise rate would be to build the ring in the form suggested for the eP configuration. The alternating vertical sectors reduce gas scattering effects by an order of magnitude.

c) Bremsstrahlung, electron. Here, the problem described in (b) manifests itself as beam electrons being bent into the apparatus by the quads because of severe energy loss. Once again the rates are high due to the LSS. Furthermore, the electron may have significant angle, appearing to come from the center of the quads, and will still have > 1 GeV energy. Estimates of this rate appear in the machine background group report and may be as high as 50% occupancy. The deflected electrons may be constrained to a narrow horizontal swath so that we would have to give up some of the tagging solid angle to reduce noise rate. Reduced gas pressure in the LSS and magnetic deflection at the entry to the insertion, as mentioned in (b) would help this problem considerably. This appears to be the most serious noise problem investigated in our study.

d) Electroproduction. This is a problem only at the level of event reconstruction for single tagged events. Rates at the low mass, multiple pion region are comparable to the 2γ process but the baryon will take enough momentum to distinguish the process most of the time. The correlation of longitudinal position with beam crossing allows remaining backgrounds to be subtracted.

4. Two-Photon Physics

In order to illustrate some possible channels that may still be interesting in 6 years, the table of rates has been made up assuming the apparatus in Fig. 3. For the lower mass processes only single tagging is assumed. The low mass $\pi\pi$ will be very clean at PeP because of good

TABLES OF RATES FOR $\gamma\gamma$ Processes

$$e^+e^- \to ee + \gamma^*\gamma^* \to ee + \quad (1 \text{ hour} \equiv \int \mathcal{L} = 10^{35}/cm^2)$$

X	m_x (GeV)	No./hour detected	⟨P⟩ GeV/c	Conditions
		Single Tagging		
$\pi\pi$	0.4	1	1.5	$\delta m = 50$ MeV
$\omega\omega$	2	1	10	$\delta m = 0.1$ GeV
$\rho\rho$	2	0.3	10	$\delta m = 0.1$ GeV
η	0.5	0.1	2	
η'	0.96	0.2	6	$\Gamma_{\eta'\to\gamma\gamma} = 5$ KeV
$e\pi$		1		$q^2 > 1(GeV/c)^2$
$e\mu$		50		$q^2 > 1(GeV/c)^2$
		Double Tagging		
$\pi + x'$		10		inclusive
$\Lambda\bar{\Lambda}$,pp	> 2	< 0.01		
DEEP INELASTIC (ν > 1 GeV/c)		1		$q^2 > .25\ (GeV/c)^2$
		0.1		$q^2 > 1.0\ (GeV/c)^2$

π-μ separation and convenient forward detection. This will resolve the soft pion problem if it hasn't been done by 1980. Electromagnetic resonance states such as η and η' will be produced and widths measured to 10% or better, and higher mass states with larger widths can be seen clearly. Production of kaons (including $K_s^o K_s^o$) will lead to interesting effects in s dependence of the $\sigma_{\gamma\gamma \to \text{hadron}}$ cross section and may yield information on kaon form factors.

The intermediate mass region or diffraction region can be investigated, at least for gross rate checks, up to s values which overlap electroproduction studies at the Fermilab. Processes such as $\rho\rho$ and $\omega\omega$ production characterize this region.

The most interesting 2γ process is likely to be the deep inelastic region where predictions for rates are uncertain within an order of magnitude. What is striking at PeP energies is the large ν range available, $\nu \leqslant 500$ $(GeV/c)^2$; even if q^2 is small. This may also be a region where information about the hadronic structure of the virtual photon will help in the understanding of the single photon annihilation channel. A central detector and double tagging are required to extract maximum information from the events.

Another interesting process can be seen as a re-arrangement of the normal 2-photon diagram so that one electron effectively scatters from one of a low mass pair, say $\mu\mu$ or $\pi\pi$. The result is a single tag, high energy electron and $e\mu$ or $e\pi$ at wide angle in the lab. The remaining μ or π may be missed because of its low transverse momentum. The calculation of rates for the process requires knowledge of $e\mu$ or $e\pi$

scattering at high q^2, off the mass shell, but provides a clue as to electromagnetic form factors at much higher q^2 than can be achieved with direct πe or μe scattering.

Forward tagging has another feature which can be exploited to search for heavy leptons, etc., which show up as deviations in virtual Compton scattering, $ee \to ee\gamma$. All three must be detected and rates are approximately 1/sec. The kinematics makes it a nice energy-angle calibration channel for the detector.

Inclusive cross sections , such as $e\bar{e} \to e\bar{e}\pi + X$ can be studied when double tagging is used in conjunction with particle label properties of the detector. Additional $\check{C}$ counters for π,K,P separation may be required, but they would not be large area devices such as 4π detectors require.

5. An Aside on $2\gamma/1\gamma$ Interference

The apparent high rates of hadron production in the 2γ process cause some consternation among single photon explorers. The rates shown in Fig. 6 should put the problem in perspective. When $\sqrt{s}$ ($=m_x$) is required to be larger than some value, as the curves indicate, the rate drops rapidly. Forcing $m_x > 15$ GeV keeps the total rate below any expected one-photon annihilation rate. Obviously crude total energy measurement is the single best thing to incorporate into one-photon experiments if one wishes to avoid the two-photon background. Further suppression is available by electron tagging and momentum summing, both transverse and longitudinal.

6. Conclusions

Physics using the two-photon process at PeP appears to be possible with a relatively simple detector. Several interesting channels can be

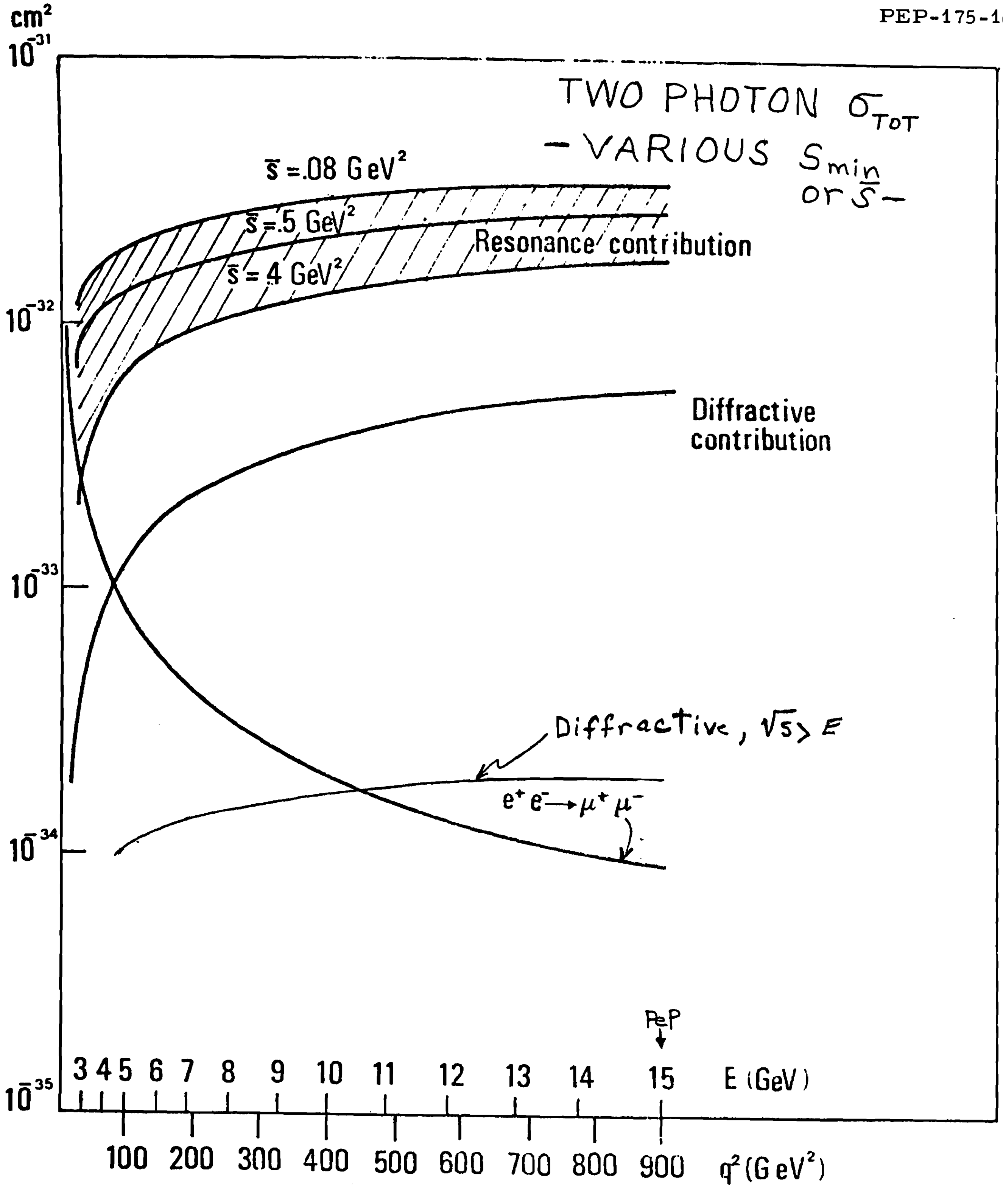

cm²
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
TWO PHOTON σ_{TOT}
- VARIOUS S_{min} or $\bar{S}$ -
$\bar{s}$ = .08 GeV²
$\bar{s}$ = .5 GeV²
$\bar{s}$ = 4 GeV²
Resonance contribution
Diffractive contribution
Diffractive, $\sqrt{s} > E$
$e^+e^- \to \mu^+\mu^-$
PeP
3 4 5 6 7 8 9 10 11 12 13 14 15 E (GeV)
100 200 300 400 500 600 700 800 900 q² (GeV²)

FIG.6

seen simultaneously which compensates for relatively low rates in particular channels. Observation of masses from $2m_\pi$ up to 20 GeV is possible but the low mass region will have to be done with single tagging. The long (20m) intersection region is desirable for tagging, but appears to be even more useful for the forward m_x detector. Problems arising from working close to the beam appear to be exaggerated at PeP due to the long straight sections collinear with the intersection region. We feel we benefit significantly from a ring which looks like the electron ring in the eP configuration.

It appears that tagging of low energy electrons becomes 50% efficient with angular acceptance going out to 15^o but not having to go below 10 mrad. This is important for one γ contamination problems where the two γ may be produced as indistinguishable events when the electrons both drop below ~ 2 GeV ($\omega \gtrsim 13$ GeV in Fig. 1).

References:

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2. H. Terazawa, Rev. Mod. Phys. 45, 615 (1973).
3. Journal de Physique, C-2 (1974).