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General Physics and Experimental Requirements for E160

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Abstract

The physics goal of E160 is to measure quasi-elastic $J/\psi$and ψ'photoproduction from nuclear targets in the 15 to 35 GeV energy range. A goal of over 10,000 clean (equivalent background free) counts for $J/\psi$is set for photon energies near 25 and 35 GeV for four nuclear targets, and 3000 counts at 15 GeV for two targets. A goal of 200 ψ'events is set at 25 and 35 GeV. The systematic error on relative cross sections should be below 1.5%. The requirements on luminosity, resolutions, and background levels needed to meet the physics goal are discussed. It is shown that the relative invariant mass resolution should not exceed about 4% (assuming only central decays are detected), the p_t resolution for a given decay lepton should not exceed about 0.15 GeV, that p_t^2 of the di-lepton system should be measured over a range of at least $0 < p_t^2 < 0.6$ GeV^2, and that the relative z resolution should not be worse than about 6%. Significant increases in luminosity/acceptance are required to account for increased backgrounds when resolutions are not perfect. Summaries of the general requirements for the photon beam, target, spectrometer, and detectors are given. Because the requirements are highly correlated, it is recommended that a full simulation of any specific experimental setup, including all backgrounds effects, be performed to ensure the required accuracy can be met in the time frame of the proposal.

1 Physics Goals

The first physics goal is to measure the A-dependence of quasi-elastic J/ψphotoproduction at photon beam energies of 15, 25, and 35 GeV. A goal of about 1.5% statistical and systematic errors was set for each of four targets ranging from Be to Pb for 25 and 35 GeV, with a more modest goal of 2.2% statistical error at 15 GeV, using only the Be and Pb targets. Note that measuring quasi-elastic production implies that contributions from coherent and inelastic production must also be measured and accounted for. Given the 10^{-4} duty cycle at SLAC, it can be demonstrated that this cannot be done by measuring all final state particles (for example recoil nucleus for coherent production, compared to recoil nucleon for quasi-elastic production). Therefore we require a measurement of the transverse momentum p_T of the $J/\psi$with good enough resolution to separate coherent and quasi-elastic contributions (based on the coherent contribution has a much steeper p_T dependence than quasi-elastic production does). Inelastic contributions are expected to have an even flatter P_T distribution than quasi-elastic, but as detailed below, a cut in $z = E_\psi/K$ (where E_ψ is the J/ψenergy, and k is the photon energy) is also needed. This leads to the requirement that the energy k be known, either through the coherent bremsstrahlung peaks described in the proposal, or by some other technique. It also leads to the requirement that E_ψ be measured, through full reconstruction of the J/ψdecay products. This is in contrast to the previous SLAC experiment [1], where only one of the two decay leptons was detected, and coherent and inelastic contributions were accounted for by calculations, but not measured. We require actual measurements of the coherent and inelastic production rates so that we can make a significant improvement over the previous experiment.

The second, equally important, and much more difficult goal is to measure ψ'photoproduction at 25 and 35 GeV with a statistical error of 7Due to the small cross sections involved, this places strong constraints on the product of luminosity and acceptance for the beam and spectrometer, especially when one considers the dilution of statistics that arises from a) isolation of quasi-elastic photoproduction from nuclear coherent contributions at low p_t and inelastic contributions at $z = E_\psi/k < 1$; and b) subtraction of Bethe-Heitler background and J/ψtail. This requires a sophisticated analysis to obtain optimal results, but we can get an idea of the tradeoffs in resolution and running time using someone simplified models. The results for Invariant Mass resolution, P_t resolution, and z resolution are outlined in the next sections.

1.1 Invariant Mass resolution

The requirements on reconstructed $J/\psi$and ψ'mass resolution are driven by the physics goal of cleanly separated the J/ψparticle (mass 3.097 GeV, branching ratio to two leptons 6.02%) from the ψ'(mass 3.686 GeV, branching ratio 0.85%), and from Bethe-Heitler (BH) pair production background. We assume that ψ decays to two leptons is the only useful channel for identifying these particles, given the poor duty factor at SLAC.

We first examine the resolution needed in the absence of BH background. Experiments at SLAC, HERA, and Fermilab show that the ψ'cross section is about 7 times smaller than the J/ψelastic photoproduction cross section (see Fig. 4 in [2], independent of photon energy within the statistical accuracy. This leads to approximately 50 times less lepton pairs from ψ'decay than from J/ψdecay. Table I shows values for the ratio of ψ'signal (near the 3.69 GeV mass peak) to J/ψtail as a function of Gaussian relative mass resolution (in percent)(see bosted/jpsi/resolj.f). Because the background is so much higher on the low side of the peak than on the high side, and asymmetric cut was used: one sigma on the low mass side, and 1.5 sigma on the high side. This preserves about 76for this ratio is 1 to 1, because beyond this the statistical accuracy becomes increasing limited by the background subtraction, and non-Gaussian tails can also become important. As seen in Table 1, the mass resolution required to meet this goal is 5.5%.

We now consider the additional problem arising from Bethe-Heitler pair production of lepton pairs. The SLAC experiment [3] using the small solid angle 8 GeV and 20 GeV spectrometers in coincidence measured 5 ψ'counts with no background with the incredibly

Table 1: Ratios of ψ'di-muon signal to J/ψtail only (R) and to J/ψtail plus Bethe-Heitler background with no cuts (R_{nc}) and with the cut $0.3 < R_e < 0.7$ (R_c) for 25 and 35 GeV photons as a function of invariant mass resolution in percent. A $\psi'/J/\psi$cross section ratio of 0.02 is assumed, and the Bethe-Heitler production from lead (although it is almost indistinguishable from lighter nuclei). The signal/noise is averaged from -1 sigma on the low mass side, to 1.5 sigma on the high mass side.

		20 GeV		40 GeV	
Resolution (%)	R	R_{nc}	R_c	R_{nc}	R_c
1.0	> 1000	1.29	3.02	1.19	2.71
2.0	> 1000	0.65	1.53	0.61	1.38
3.0	1000	0.45	1.08	0.42	0.96
4.0	90	0.35	0.79	0.32	0.77
5.0	3.3	0.27	0.53	0.25	0.56
6.0	0.65	0.18	0.30	0.17	0.30
7.0	0.24	0.12	0.16	0.11	0.17

good mass resolution of 0.3%, at a photon energy of 20 GeV. Going to higher energies, ψ'photoproduction experiments at 90 GeV [4] and 200 GeV [2] have found a signal to background of approximately 2 to 1 at the ψ'peak for a mass resolution of 1.1%, and 1 to 1 for 1.5% resolution, respectively. These resolutions are much tighter than than needed merely to separate the two mass peaks, and would be very difficult to achieve in an affordable large acceptance spectrometer design. The experiments all show that if the ψ'peak is visible above BH background, then the BH background under the J/ψpeak is very small, so the ψ'peak is the one that drives the experimental requirements.

Fortunately, as pointed out in [5], the BH pairs characteristically have smaller values of di-muon transverse momentum squared p_t^2 than the ψ decay, and even more importantly have a distribution in $R_e = E_1/(E_1 + E_2)$ that is more peaked near zero and 1 than the distribution form ψ decay (where E_1 and E_2 are the energies of the two muons). Thus a spectrometer that has an acceptance function peaked near $R_e = 0.5$ will have a better signal to background than one with a uniform acceptance.

To investigate this question further, we have made some detailed Bethe-Heitler calculations for the conditions of 10^{14} monochromatic 20 or 35 GeV photons impinging on a 1 b-1 (1.6 gm/cm^2) lead target. In the mass region $3.5 < M < 3.9$ GeV, the predicted BH contribution for 20 GeV photons is 1330 counts (1 nuclear elastic, 1267 quasi-elastic, and 62 inelastic). The result at 35 GeV is 3263 counts (38 elastic, 2491 quasi-elastic, and 734 inelastic). Note that the elastic contributions are essentially negligible at these photon energies in the region of the ψ'mass peak, so that the results per nucleon are essentially the same for lead and beryllium. These calculations were done using the formulas of Tsai [6], implemented in a Monte Carlo method following Ref. [7] (see bosted/jpsi/bhqe.f for elastic and quasi-elastic, and bosted/jpsi/bhwp.f for inelastic calculations). The calculations were done assuming muon pairs, because the rates are lower than for electron pairs, and also because almost all existing data comes from muon pairs. The distribution of BH events in R_e and p_t^2 for 35 GeV photons is shown in Fig. 1 by the crosses. Note the strong peaking near $R_e = 0$ and $R_e = 1$.

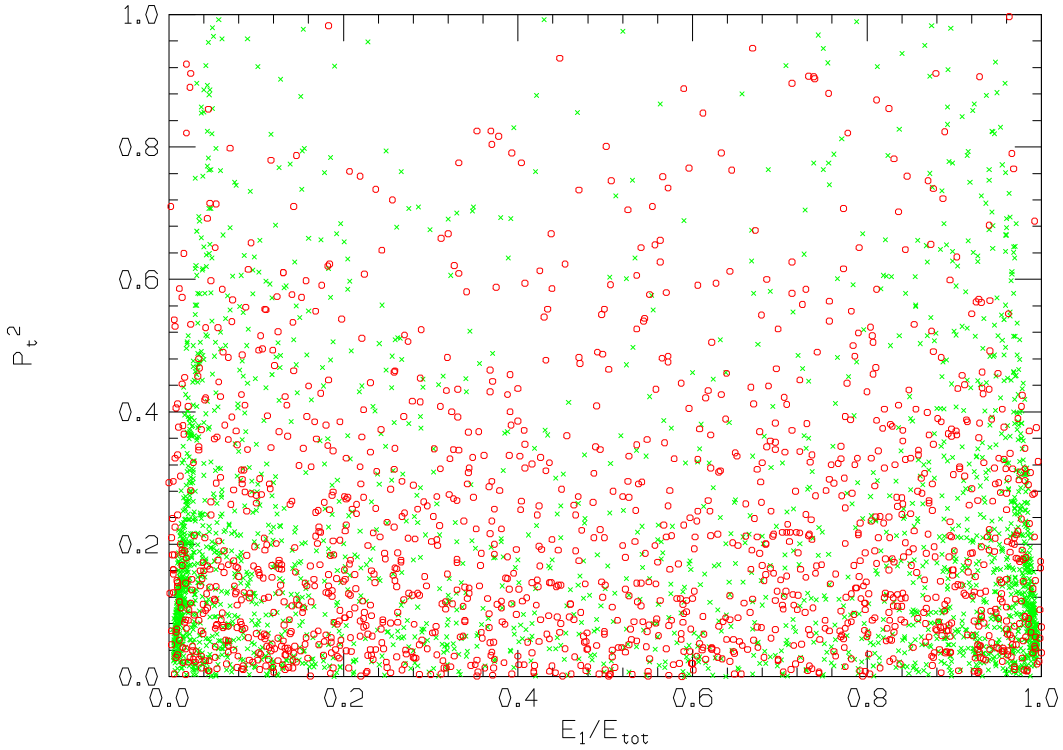

Figure 1: For a 35 GeV photon beam, distribution in R_e and p_t^2 of ψ'muons pairs (circles) and BH events (crosses) in the mass region $3.5 < M < 3.9$ GeV.

The photoproduction of $\psi'$was calculated (see bosted/jpsi/resplt.f) assuming a total J/ψcross section of 3.6 nb (8 nb) at 20 GeV (35 GeV), taken from Fig. 6 of Ref. [5], 50 times less ψ'than J/ψevents from the ratio of cross sections and branching ratios to two muons [2], a t-dependence of $e^b t$, with $b = 2.0$ GeV-2 (average from proposal), and an angular decay distribution into two muons of $[1 + \cos^2(\theta_{cm})]$ from s-channel helicity conservation [3, 5]. For the same luminosity as the BH events, we expect a total of 440 counts at 20 GeV, and 960 counts at 35 GeV, or about one third of the BH rate in the mass region $3.5 < M < 3.9$. The R_e and p_t^2 distribution is shown in Fig. 1 by the circles. Compared to BH, the distribution is more evenly distributed in R_e. Overall, the BH events are peaked at lower p_t^2, but in the central R_e region, there is not a great difference in the p_t^2 distribution. While an R_e cut is more useful than a p_t^2 cut, it turns out we will be making a p_t^2 cut anyway to reduce the coherent J/ψflux, so it is worth noting that typically the cut $p_t^2 > 0.2$ GeV^2 increases the signal to background (with R_e cut already applied) by about 50%.

Table 1 shows the $\psi'$to BH background (including the J/ψtail) at the 3.7 GeV mass peak for several values of the mass resolution, with and without a cut in R_e. As before, the ratio is the average from -1 to +1.5 sigma. The ratios would be about 50% higher with

Table 2: Increase in luminosity/acceptance f needed to compensate for the BH and J/ψtail backgrounds shown in Table 1.

	20	GeV	35	GeV
Resolution (%)	R_{nc}	R_c	R_{nc}	R_c
1.0	2.56	1.66	2.68	1.74
2.0	4.06	2.31	4.26	2.45
3.0	5.42	2.85	5.82	3.09
4.0	6.71	3.52	7.17	3.60
5.0	8.52	4.75	9.00	4.60
6.0	12.07	7.77	12.71	7.68
7.0	18.03	13.71	18.83	13.02

a cut $p_t^2 > 0.2$. The results are in good agreement with what was observed in previous experiments, lending confidence in the results. It can be seen that even with an R_e cut, the ratio decreases below unity for a mass resolutions larger than 3.5%. This would lead to a loss of statistical accuracy due to the subtraction of the BH background. We have modeled this subtraction by assuming that the BH plus J/ψtail background can be measured on the wings of the ψ'peak with a statistical accuracy equal to the number of counts under the ψ'peak. The increase in luminosity needed to achieve the same statistical error as for no BH background is approximately given by $f = 1 + 2/R$. Table 2 lists values of f for the same mass resolutions as shown in Table 1. It can be seen that as the resolution increases, a substantial increase in beam current and/or acceptance is needed to account for the increased background level. It turns out that f increases less than linearly for resolutions up to about 4%, then increases very rapidly above that value, mainly due to the J/ψtail coming in like a brick wall. This leads to the conclusion that the mass resolution should be no worse than 5%. Examples of the simulated spectra at 35 GeV are shown in Fig. 2, with a cut in R_e applied.

This calculation does not take into account the systematic error on the shape of the BH background, which will likely be of the order of 10%, dominated by the uncertainty in the spectrometer acceptance as a function of invariant mass. Although this should not depend on target material, it will still generate an uncertainty in the A-dependence through the uncertainty in background level on which the ψ'peak is sitting. A rough estimate, based on a relative acceptance uncertainty of 5%, is that $R > 0.8$ is needed to measure the A-dependence with the desired 7% accuracy (regardless of how small the statistical errors are). From Table 1, this means the mass resolution should be 4% or better, with the cut in R_e, or 1.5% with no cut in R_e.

A further consideration, based on previous experience, is that spectrometer resolution functions typically have non-Gaussian tails due to effects such as sprinkle hits in detectors, imperfect knowledge of magnetic fields, overlapping tracks, and granularity effects. This mainly affects the consideration of how big the J/ψtail will be under the ψ'peak, and what shape should be used to model the tails. It would therefore seem prudent to design for a somewhat better resolution that the above calculations show (such as 3% using the R_e cut, rather than 4%).

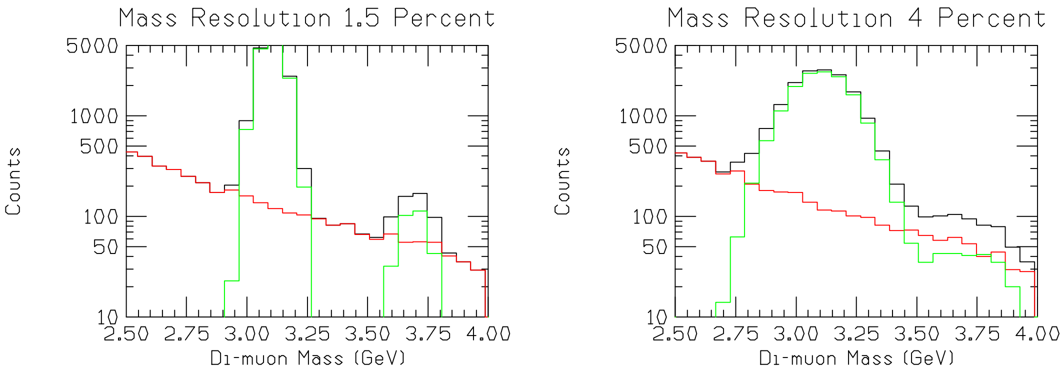

Figure 2: Simulated mass spectra for 35 GeV photon beam and mass resolution of 1.5% (left) and 4% (right), with a cut in R_e applied. The BH background is shown in red, the $J/\psi$and ψ'signals in green, and the sum in black.

2 Momentum and Angle Resolutions

Using the approximate formula $M^2 = 4p_1p_2\sin^2(\theta/2)$, where p_1 and p_2 are the momenta of the two muons, with θ the opening angle between them, we can find momentum and angle resolutions needed once the desired mass resolution is fixed. In the case where relative momentum resolution is independent of momentum, the desired value is given by $dP/P = \sqrt{2}dM/M$. As an example, a relative mass resolution of 3% implies momentum resolution of 4.2%. If, as in many tracking system, $dP/P = aP$, the desired resolution is defined for the highest values of P that contribute (typically $0.7k$, where k is the photon energy). The opening angle relative resolution (if the dominant contribution to mass resolution), is simply proportional to relative mass resolution. As an example, 3% relative mass resolution implies 3% relative opening angle resolution. In the symmetric case for J/ψdecay, $p_1 = p_2 = k/2$, and the average angle of a decay muon with respect to the beam direction ($\theta/2$) is given by $\theta/2 = 3.1/k$, or 0.2 rad (0.09 rad) for $k = 15$ GeV ($k = 35$ GeV). In the case where angular resolution is dominated by multiple scattering, which also depends on $1/k = 2/p_1$, the interesting result is that the relative angular resolution is independent of beam energy.

3 p_T resolution

The p_T resolution must be good enough to separate coherent and quasi-elastic photoproduction adequately. In the proposal, the coherent rate is modeled as $0.14A^{1.4}33e^{33t}$, where t is the momentum transfer squared (always negative), while the quasi-elastic production has a much softer t dependence of $A^{0.94}2e^{2t}$. In the worst case of lead ($A = 208$), we find the ratio of coherent to quasi-elastic production can be written as $r(t) = 27e^{31t}$, which crosses unity at $t_c = -0.1$ GeV^{-2}. In the ideal case of perfect t resolution, there is a loss of useful quasi-elastic statics approximately given by the fraction of counts between zero and t_c, or $(1 - e^{2t_c})$, or about 20% in the ideal case. However, if the resolution in t (we will call this t_r is comparable 0.1 GeV^{-2}, there will be an increase the effective value at which coherent and quasi-elastic can be separated, leading to an increased effective loss of statistics.

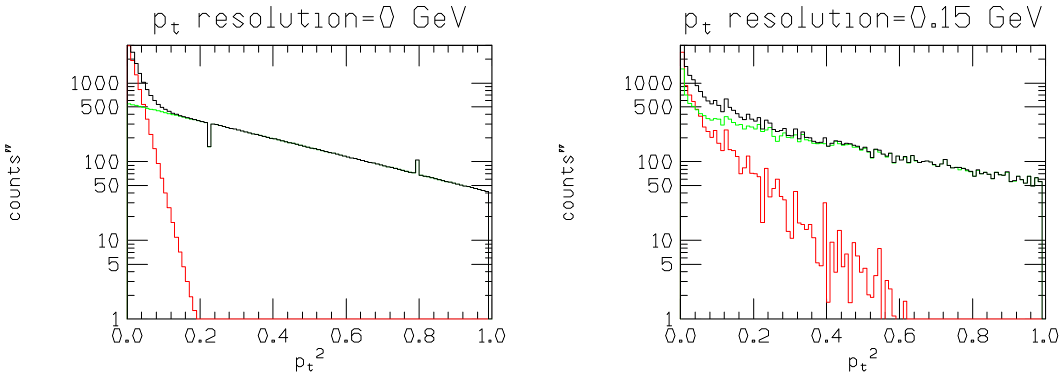

Figure 3: Simulated p_t^2 distributions for coherent (steep slope, in red) and quasi-elastic (shallow slope, green) contributions at 25 GeV, for perfect resolution (left), and p_t resolution for each muon of 0.15 GeV (right). The black curve shows the sum.

From the exact relations $t = (k - E_j)^2 - k^2 - P_j^2 + 2kP_j\cos(\theta)$ and $p_t^2 = P_j^2(1 - \cos^2(\theta)$, where θ is the lab angle between a photon of energy k and a $J/\psi$of momentum P_j and energy E_j, it can be shown that $p_t^2 \approx -t/2$ for the region of interest near $-t = 0.1$ GeV^2. Since we do not precisely know the photon energy k with a coherent bremsstrahlung beam, in the proposal we assume that p_t, rather than t, is the quantity that will be used to separate the coherent and quasi-elastic contributions. Experimentally, we assume that it is the resolution in p_t, rather than p_t^2, that is approximately independent of kinematics. We have made a Monte Carlo simulation (see bosted/jpsi/resplt.f) of the p_t^2 distribution of coherent and quasi-elastic counts with p_t resolutions of 0, 0.05, 0.1, and 0.15 GeV, and find only moderate losses of usable counts, leading to required increased luminosity factors f shown in Table 3. The table also shows the value of p_t^2 at which the coherent/quasi-elastic ratio is about 20%. Fig. 3 show the simulated distributions in the ideal case of perfect p_t resolution, and for a relatively poor resolution of 0.15 GeV for each muon, which corresponds to a relative momentum or angle resolution of about 10%, for typical muons with $p_t = 1.5$ GeV. In this case a luminosity increase of 1.8 is called for, compared to the ideal case of 1.2. A more troublesome aspect is that as the resolution gets worse, the *shape* of the coherent and quasi-elastic curves becomes more and more similar, leading to systematic errors that are difficult to evaluate.

We conclude that the p_t resolution of each muon should not be larger than 0.15 GeV, and ideally should be considerably better than this. It is also essential to have a good spectrometer acceptance over a wide range of p_t^2 (from 0 to at least 0.6 GeV^2), so that there is enough range for a simultaneous fit to both coherent and quasi-elastic contributions.

Table 3: Increase in luminosity/acceptance f needed to compensate for the p_t resolution (of each muon) shown. Also given is the value of p_t^2 at which the coherent/quasi-elastic ratio is about 0.2 (label Cross).

p_t Resolution (GeV)	Cross	f
0	0.05	1.2
0.05	0.06	1.2
0.10	0.1	1.5
0.15	0.2	1.8

4 Separation of Inelastic: z-resolution

In the proposal, the inelastic and quasi-elastic contributions are separated entirely using the difference in t distributions, and leads to an effective increase in error of about 1.5, compared to no inelastic contributions. However, this requires measured the J/ψparticles over a very large range in t (or p_t^2), which is difficult to do with most spectrometer designs, because at large p_t of the di-lepton system, one of the leptons will have very large p_t, hence a large scattering angle, making it difficult to detect if we also want to keep events with R_e close to 0.5 to minimize the BH background.

However, the inelastic and quasi-elastic contributions can also be distinguished using $z = E_\psi/k$, because quasi-elastic essentially means $z = 1$, while the inelastic production is peaked near $z = 0.5$. Detailed simulations have not been done, but a preliminary examination of inelastic data suggests that the inelastic rate can be reduced by a factor of δz, where δz is the resolution in z. Since the inelastic fraction in the region $p_t^2 < 1$ GeV^2 is about 30% with no z cut, it should be possible to reduce this to less than 3% with a z resolution of about 7% or better. This matches nicely with the E_ψ resolution that results from require a missing mass resolution of 4% or better (see above). The photon energy resolution from coherent bremsstrahlung is not Gaussian, but equivalent Gaussian widths are generally about 5% to 8% wide, depending on how tightly the beam is collimated (see proposal). It is also possible to use the endpoint region of a bremsstrahlung spectrum. In this case, z is defined relative to the endpoint energy, and the resolution depends on how far below the endpoint one places the cut, so once again there is a tradeoff in resolution, backgrounds, and statistics. This must be simulated in detail for any specific photon beam spectrum and spectrometer/detector configuration.

5 Luminosity/Acceptance

This beam flux required depends on the spectrometer acceptance and resolution. For illustration, assuming the $\psi'$is detected by the decay to two leptons in a spectrometer that accepts 10% of the decays, with mass and p_t resolution effectively resulting in a 50% loss of statistics (or $f = 2$), a 0.2 r.l. Pb target, a rate of 10^7 quasi-monochromatic photons

Table 4: Combinations of Acceptance (Acc), Background factor f, and quasi-monochromatic photons/spill (γ/spill) required to meet the physics goals for 35 GeV photons on a Lead target.

Acc	f	γ/spill
0.4	1.5	0.2×10^7
0.2	2	0.5×10^7
0.1	2	1×10^7
0.1	5	2.5×10^7
0.05	5	5×10^7
0.01	2	1×10^8

per beam spill is needed. This is based on a maximum of 3×10^7 beam spills available for the measurement, obtained by taking two months of running time at 120 Hz, a 50% beam delivery efficiency, and assuming a total of 10 measurements (3 energies and either 2 or four targets). Table 4 shows several other combinations of photons/spill, spectrometer acceptance, and values of f (background factors depending on resolution, see above) that meet the physics goals. It can be seen that even for the largest realistic acceptance figures, more than 2×10^6 photons/spill are required, corresponding to about 300 nuclear interactions per few hundred nsec long beam spill. This essentially precludes the use of an open detector system that detects all particles generated in a given beam spill.

6 Photon Beam

The photon beam must have the following characteristics, assuming that the coherent bremsstrahlung technique is chosen:

- Photon energies of 15 to 35 GeV (hence electron energies up to 48.3 GeV, the highest possible at SLC).
- Monochromatic or quasi-monochromatic component to energy spectrum, in order to distinguish elastic and inelastic production using two-body kinematics (implying that energy of ψ must also be measured).
- An intensity in the quasi-monochromatic component of the spectrum large enough to meet the statistical goals given above. For reasonable spectrometer designs, this means at least 10^7 photons per beam spill in the primary coherent peak.
- Spot size of a few mm at the target (to obtain good momentum and angle resolutions).
- As high a ratio of coherent to incoherent photons as possible.
- Equipment to dump the electron beam that produces the photons

- Equipment to measure the flux and intensity distributions of the photons.
- Equipment to measure the polarization of the photons.

7 Target

A target changer is needed that operates in vacuum and can quickly select by computer control between at least five targets, Be, Al, Cu, Pb, and a no-target position. The target foils should be at least 2 cm in diameter.

8 Spectrometer

The spectrometer must measure the momentum and angle of two decay leptons with sufficient precision to meet the mass and p_t^2 resolution requirements. The acceptance in R_e should ideally be peaked near 0.5. The p_t^2 acceptance should be large enough for good coherent/quasi-elastic separations. The acceptance must be large enough (combined with beam flux) to meet the statistics goals. The design should minimize detector backgrounds from processes like BH electron/positron pairs, hadronic punch-through, and soft photons.

9 Detectors

The detector and spectrometer design are difficult to separate. Assuming the spectrometer has a magnetic field, the detector granularity must be fine enough to active the desired momentum and angular resolutions. Because of the poor duty cycle at SLAC, the detectors should have the best possible timing characteristics. The detectors should have some particle i.d. built in: in the case of muon pairs, this implies thick material between two layers of detector to isolate muons from low energy particles such as pion, kaons, or protons. In the case of electrons, the usual complement of electron identification detectors would be needed.

10 Practical Requirements

The over-riding practical consideration is the requirement that the combination of luminosity and backgrounds allow the program of measurements to be completed in the two months of running time requested (at 120 Hz). It is also required to stay within the scope of the budget as presented in the proposal. This precludes the construction of major new facilities such as a new End Station, large dipole magnet, or very large detector array, even though these options could meet the physics goals with less running time, or allow the physics goals to not only be met, but exceeded. For example, it would really be nice to measure the ψ'cross sections with 1% accuracy, rather than the compromise of 7% mentioned in the proposal. This would change the ψ'measurements from being a first crude look, to definitive measurements.

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