SLAC-PROPOSAL-E159

Proposal to Measure $\Delta\sigma^{\gamma N}(k)$ and the High Energy Contribution to the Gerasimov-Drell-Hearn Sum Rule

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OUTLINE

- Introduction
- The GDH Sum Rule
- High energy behavior of $\Delta\sigma^{\gamma N}(k)$
- Connection of virtual photon results
- Experimental Overview
- Beam and Compton Polarimeter
- Target and Detectors
- Backgrounds
- Anticipated Results

INTRODUCTION

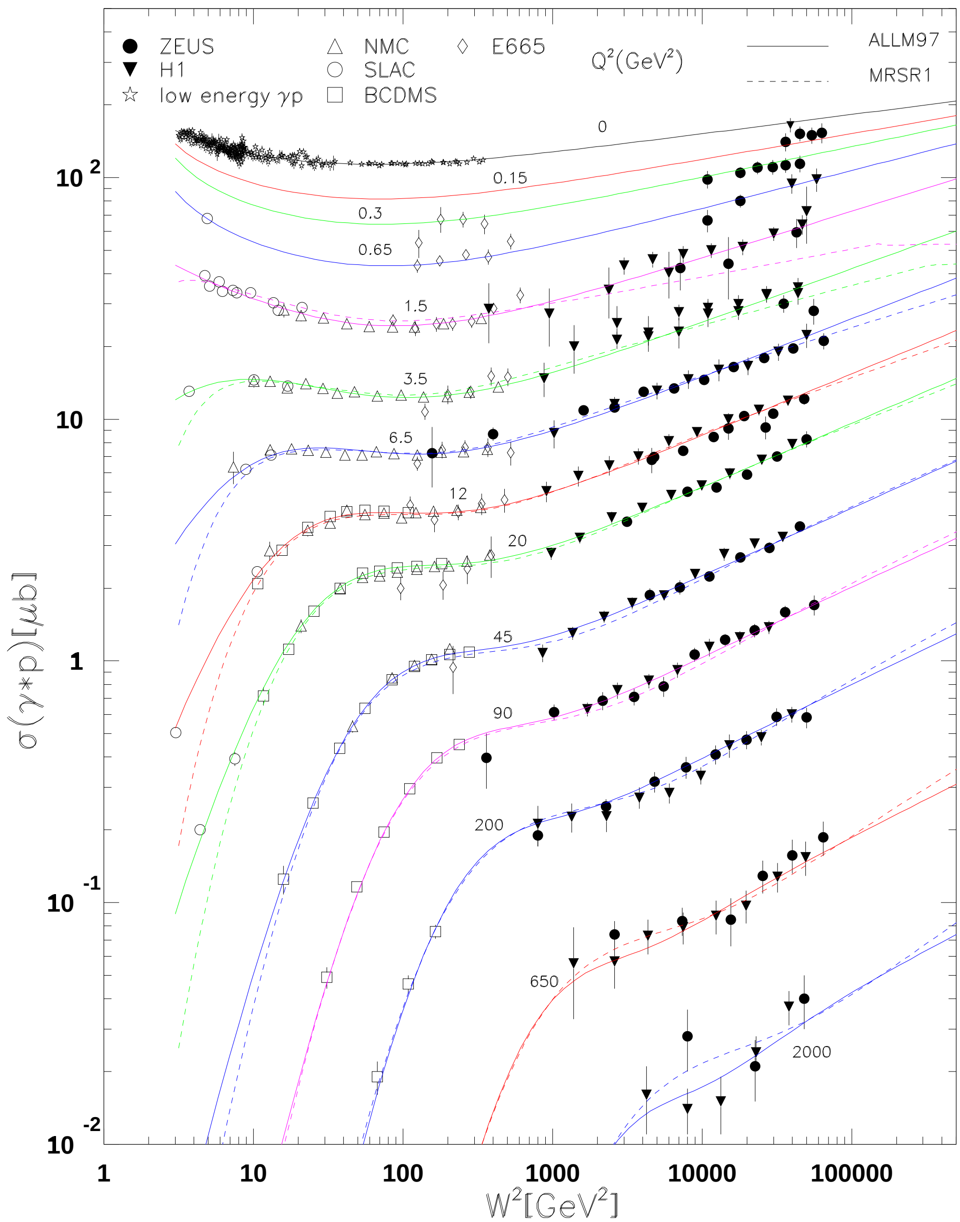
- Total photoabsoption cross section $\sigma^{\gamma N}(k)$ depends only on photon energy k for real photons.
- Can be decomposed into spin 1/2 and 3/2 final states $\sigma_{3/2}$ and $\sigma_{1/2}$, corresponding to helicity of photon aligned or anti-aligned with spin of nucleon.
- Spin-averaged $\sigma^{\gamma N}(k) = (\sigma_{1/2} + \sigma_{3/2})/2$ well-measured (including SLAC early 1970's). Roughly constant at 120 μb.
- We propose to measure

$$\Delta\sigma^{\gamma N}(k) = \sigma_{3/2} - \sigma_{1/2}$$

using circularly polarized photons and longitudinally polarized nucleons.

SPIN-AVERAGED $\sigma^{\gamma N}(k, Q^2)$

Large body of data: explore connection perturbative and non-perturbative regimes of QCD.



The GDH SUM RULE

- Relates integral over $\Delta\sigma(k)$ to anomalous magnetic moment κ of target with spin S (composite or elementary).

$$\int_{k_\pi}^{\infty} \frac{dk}{k} \Delta\sigma^{\gamma N}(k) = \frac{2\pi^2 \alpha \kappa^2}{M^2}$$

- Follows from general principles of causality, universality, Lorentz and electromagnetic gauge invariance.
- One assumption: that unsubtracted dispersion relation can be used for $f_2(\nu)$ (the spin-dependent part of the forward Compton amplitude).
- Theorists debate whether a $J = 1$ fixed pole (violating GDH Sum Rule and possibly Bjorken Sum Rule also) is likely, unlikely, or ruled out in QCD.

- Scale of convergence gives scale of highest spin-flip excitations of target.
- Oscillations in $\Delta\sigma^{\gamma N}(k)$ signal important excitations (such as $\Delta(1232)$ Resonance). Are there any oscillations above 4 GeV?
- $\Delta\sigma^{\gamma N}(k)$ must decrease with k at high k for integral to converge. Contrast to $\sigma^{\gamma N}(k)$, known to increase with k at high energies.
- Direct measurements only exist up to 800 MeV for proton, but various resonance region multi-pole analyses have made estimates of integrals.

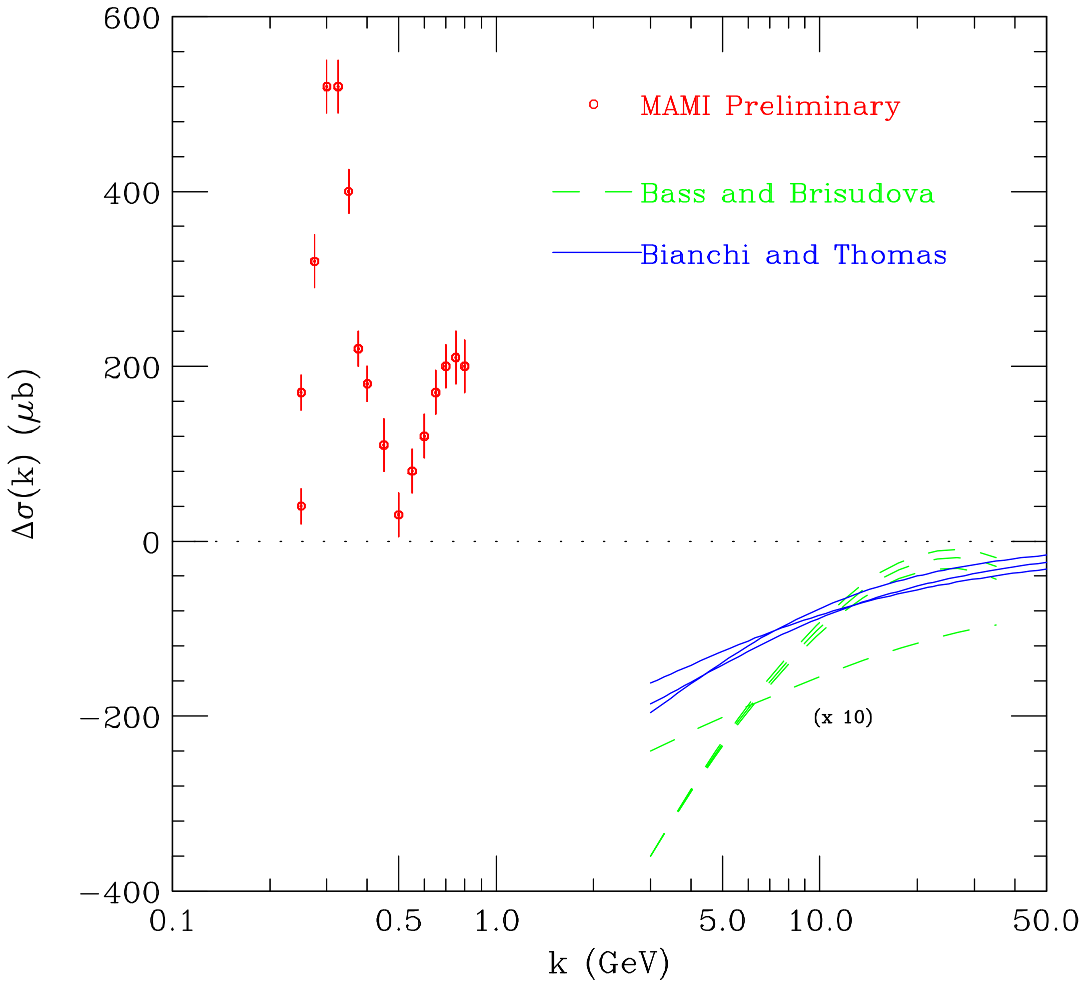
target	$2\pi^2\alpha\kappa^2/M^2$	Analyses
proton	204 μb	257 to 289 μb
neutron	232 μb	169 to 189 μb
isoscalar (p+n)/2	219 μb	213 to 239 μb
isovector (p-n)/2	-15 μb	34 to 65 μb

- Large discrepancy, especially isovector case.
- Non-resonant contribution important?
- High energy contributions important?
- Need data on both proton and neutron to find out.
- Worldwide program at Mainz, Bonn, GRAAL, SPIN8, LEGS, Jefferson Lab, TUNL, other, but limited to 5 GeV.

LOW ENERGY BEHAVIOR OF $\Delta\sigma(k)$

Preliminary data from Mainz on proton.

Resonant excitations are evident (especially $\Delta(1232)$).

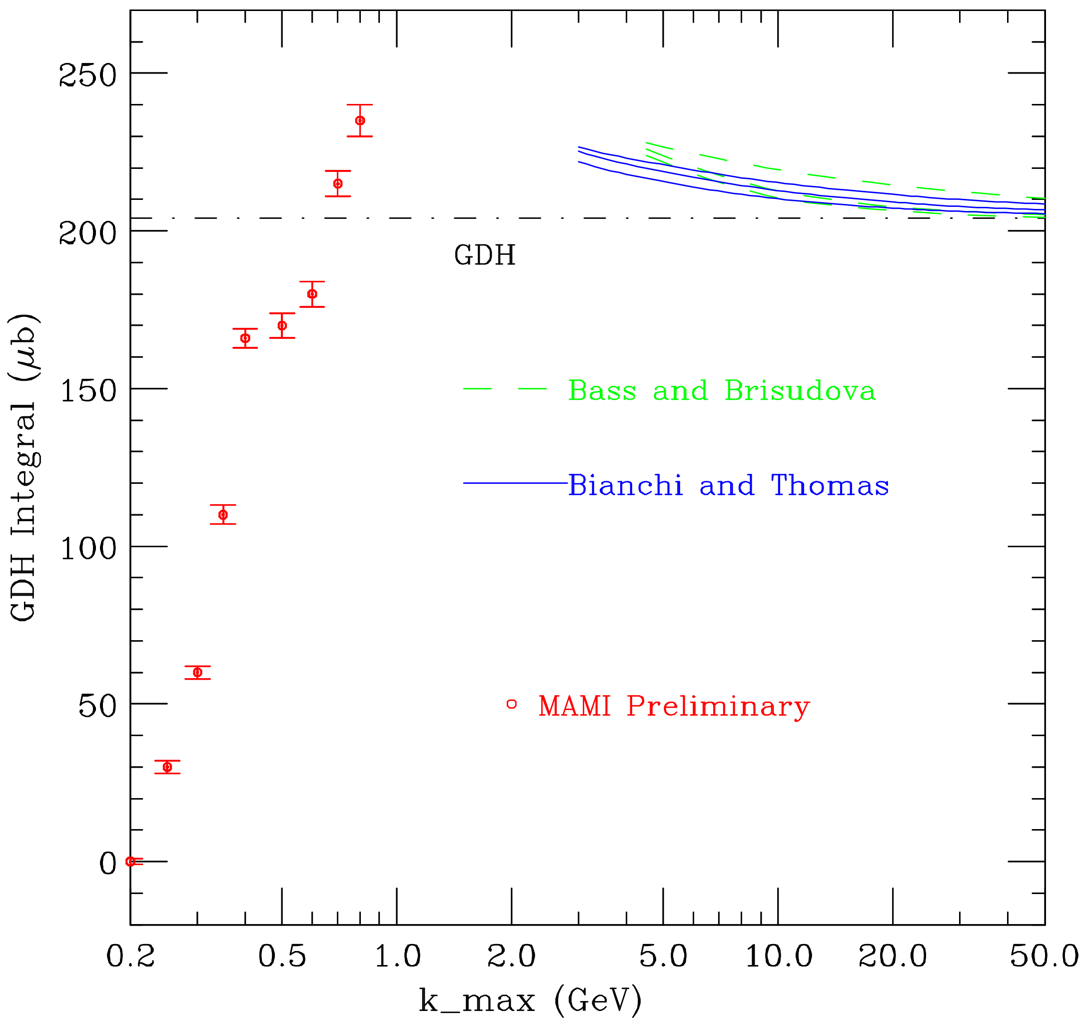


HIGH ENERGY BEHAVIOR OF $\Delta\sigma(k)$

- Regge theory describes many reactions. Has been applied to measurements using virtual photons $\Delta\sigma(k, Q^2)$. Can fit SLAC data for $Q^2 > 0$ quite well.
- Isovector contribution dominated by poorly known $a_1(1260)$ axial vector meson trajectory.
- Isoscalar dominated by better known $f_1(1285)$ meson trajectory.
- Isoscalar non-perturbative gluon exchange $[(\ln s)/s]$?
- Pomeron-pomeron cut contributions $[1/\ln s^2)]$?

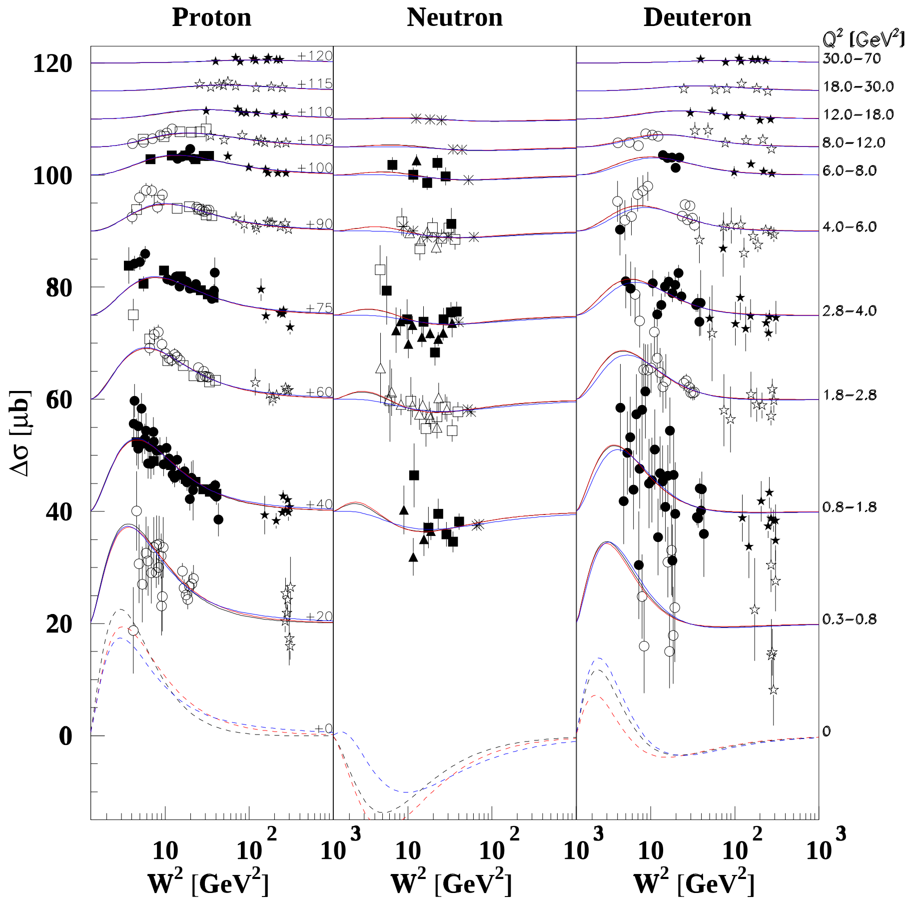
INTEGRAL CONVERGENCE?

Curves are various Regge theory fits to virtual photoproduction data, plotted assuming proton integral converges.



FIT OF BIANCHI AND THOMAS

Regge theory fits virtual photon data well: predicts dramatic change in neutron at $Q^2 = 0$ compared to $Q^2 \geq 1$ GeV^2.



WHY MEASURE $\Delta\sigma(k)$ AT SLAC?

- Measures a very fundamental quantity.
- Test convergence GDH Sum Rule.
- Compare isoscalar and isovector: latter has connection to Bjorken Sum Rule.
- Help in understanding of $g_1(x, Q^2)$ at low x, and convergence of integrals over g_1.
- Look for unexpected spin-flip strength: probe relevant energy scale.
- No existing data: field wide open for surprises.
- Drell and Hearn suggested SLAC should measure this in 1966. Now technology exists to do a good job.

EXPERIMENTAL OVERVIEW

- Coherent bremsstrahlung provides circularly polarized photons $4 < k < 40$ GeV.
- Subtract incoherent contributions to obtain $\Delta\sigma(k)$ at discrete values of k.
- Longitudinally polarized NH_3 and ND_3 targets.
- Measure total cross section asymmetry with large calorimeters.
- Reject E.M. backgrounds with cuts, longitudinal segmentation of detector, and/or calculations
- Measure in Counting Mode for lower systematic error (each hadronic interaction is individually counted)
- Use Flux Integration Mode for smaller statistical errors (total hadronic energy summed over many interactions).

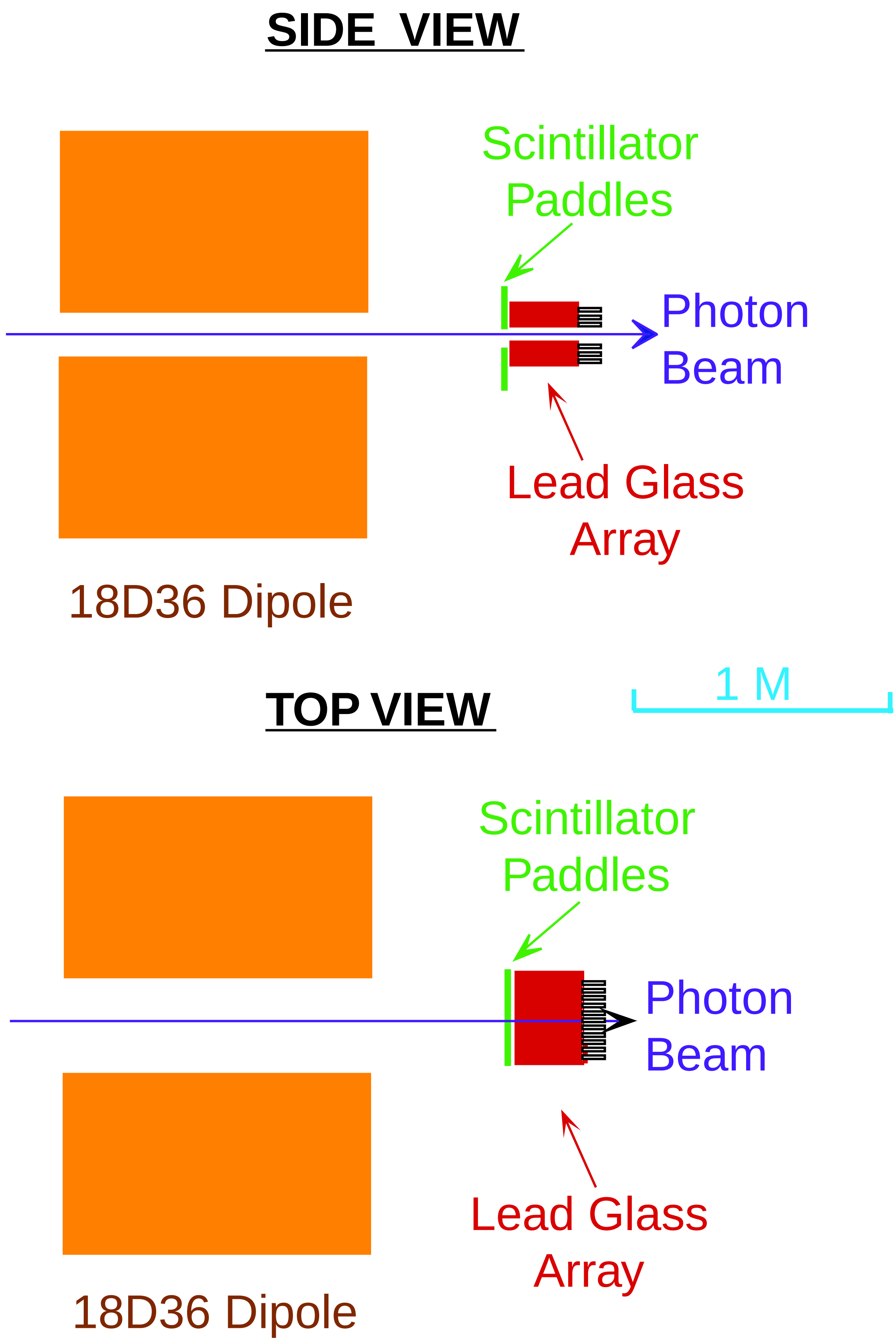
PHOTON BEAM

Described earlier. Summary of important parameters for four of 10 to 12 settings that will be used:

Electron Energy (GeV)	9.9	13.2	26.6	48.3
k_0/E of Main Coherent Peak	0.5	0.77	0.50	0.77
Incident Electrons/spill	5×10^9	8×10^9	1.5×10^9	2×10^9
collimator Radius (mm)	3	3	1	1
Total photons/spill	1.5×10^5	3.0×10^5	5×10^4	1.1×10^5
Coherent NI/spill	6.8	3.2	3.7	2.7
Coherent $< P_\gamma/P_e >$	0.59	0.87	0.57	0.82
r with energy cut	0.59	0.31	0.80	0.58
$\delta\Delta\sigma^{\gamma p}$ (μb)	0.5	0.7	0.6	0.6

COMPTON POLARIMETER

- Designed to measure flux, energy distribution, and circular polarization of beam photons.
- Use Atomic Compton scattering $\gamma e \to \gamma e$.
- Helicity-dependent cross section:
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2m_e^2}\Big(\frac{k}{k_0}\Big)^2\Big[\frac{k}{k_0} + \frac{k_0}{k} - \sin^2\theta - P_\gamma P_e(1-\cos\theta)\cos\theta\frac{(k+k_0)}{m_e}\Big],$$
- For flux measurements, electrons in NH_3 and ND_3 targets can be used for continuous monitoring.
- For circular polarization measurements, use special purpose iron target (similar to that used in E155, etc. for Møller measurements).
- Electrons in foil polarized using same magnet as for NH_3 (5 T). Expect average P_e about 0.08.


SIDE VIEW
Scintillator Paddles
Photon Beam
Lead Glass Array
18D36 Dipole
TOP VIEW
1 M
Scintillator Paddles
Photon Beam
Lead Glass Array
18D36 Dipole

- Polarimeter uses dipole magnet (1-m-long 18D36) to bend electrons to north.
- Electrons and photon energies measured in 3 by 10 arrays of lead glass blocks, one below, one above the beam line.
- Small scintillator hodoscope used to separate scattered electrons and photons.
- Allows energy measurement of primary photon to 3%-5%.
- Polarimeter is movable on a cart to accommodate opening angle decrease with increasing photon energy.
- With reasonable counting rates (a few per spill), polarization can be measured to 3% in about 1 hour.

z_{det} (m)	θ range	γ_{coh}/spill	k-range	C/spl	time(hr)
4.5	6-20 mr	3×10^5	8-14	1.5	0.5
9.0	3-10 mr	2×10^6	20-40	1.0	0.9

TARGETS

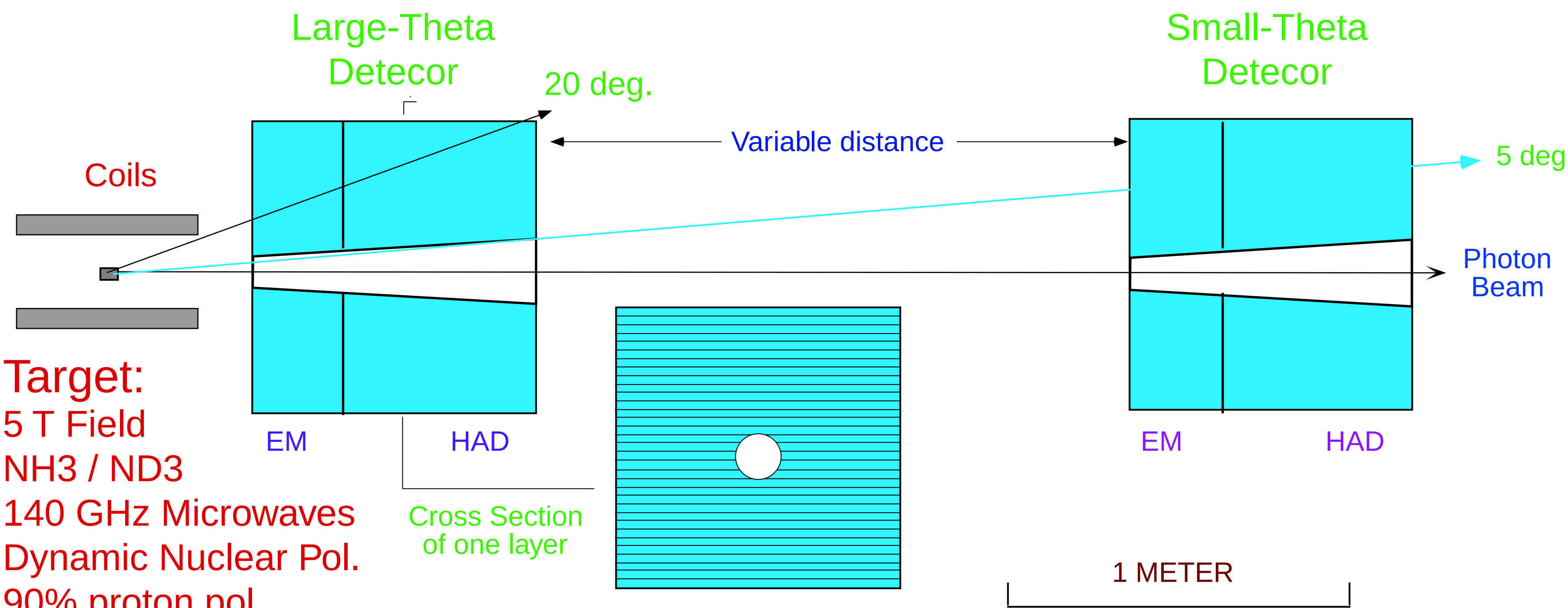
- Very similar to those used in E143, E155, and E155x.
- Will use 3-cm-long cells with NH_3 for longitudinally polarized protons. Expect polarization $P_t = 0.9$ and dilution factor $f = 0.18$.
- Will use ND_3 for longitudinally polarized deuterons. Expect polarization $P_t = 0.4$ and dilution factor $f = 0.30$.
- Beam heating and radiation damage very low compared to E155: expect higher average polarizations, less time for annealing, etc.

- Will use 5T field (new magnet) and 140 GHz microwaves (existing klystrons), as in E155. Dilution refrigerator will be used for cooler temperatures.
- Magnet allows front calorimeter to be close, and accept particles up to ±20 degrees.
- Will extract neutron results with small corrections for D-state and shadowing.
- Deuteron photodisintegration, coherent π^0 production, relativistic effects, etc. expected to be very small at high energies of this experiment (have big effects only for $k < 500$ MeV).

DETECTORS

- Based on concept of previous SLAC experiment which measured spin-averaged cross section: D.O. Caldwell *et al.*, Phys. Rev. D7 (1973) 1362.
- No Magnetic Field or Tracking
- Two identical detectors: Small Angle for as low as 0.5 to 5 degrees (moves): Large Angle for 5 to 20 degrees (does not move).
- Detectors are sampling calorimeters, made from 80 alternating layers of 3-mm-thick scintillator hodoscopes and lead plates 6 mm (1 r.l.) thick.

Target and Detectors



Target:
5 T Field
NH3 / ND3
140 GHz Microwaves
Dynamic Nuclear Pol.
90% proton pol.
40% deuteron pol.
nitrogen unpolarized

Alternating planes
of horizontal and vertical
scintillator strips

TOP VIEW

27 EM and 53 Had layers summed
with longitudinal wave-shifter bars

- Scintillator hodoscopes alternate horizontal and vertical, with about 40 elements/plane.
- Longitudinal segmentation of each detector: separate read-out of first 27 r.l. (E.M.) and subsequent 53 r.l. (HAD).
- Readout uses longitudinal wave-shifter bars with PMT's down-beam ends. Total is 640 PMTs.
- Electronics: each PMT output to ADC, discriminator, and multi-hit TDC (as in E155).
- Large-θ calorimeter at fixed distance from target, Small-θ moves on cart so $\theta_{min} = 10\sqrt{40/k_0}$ mr

DETECTOR RATES

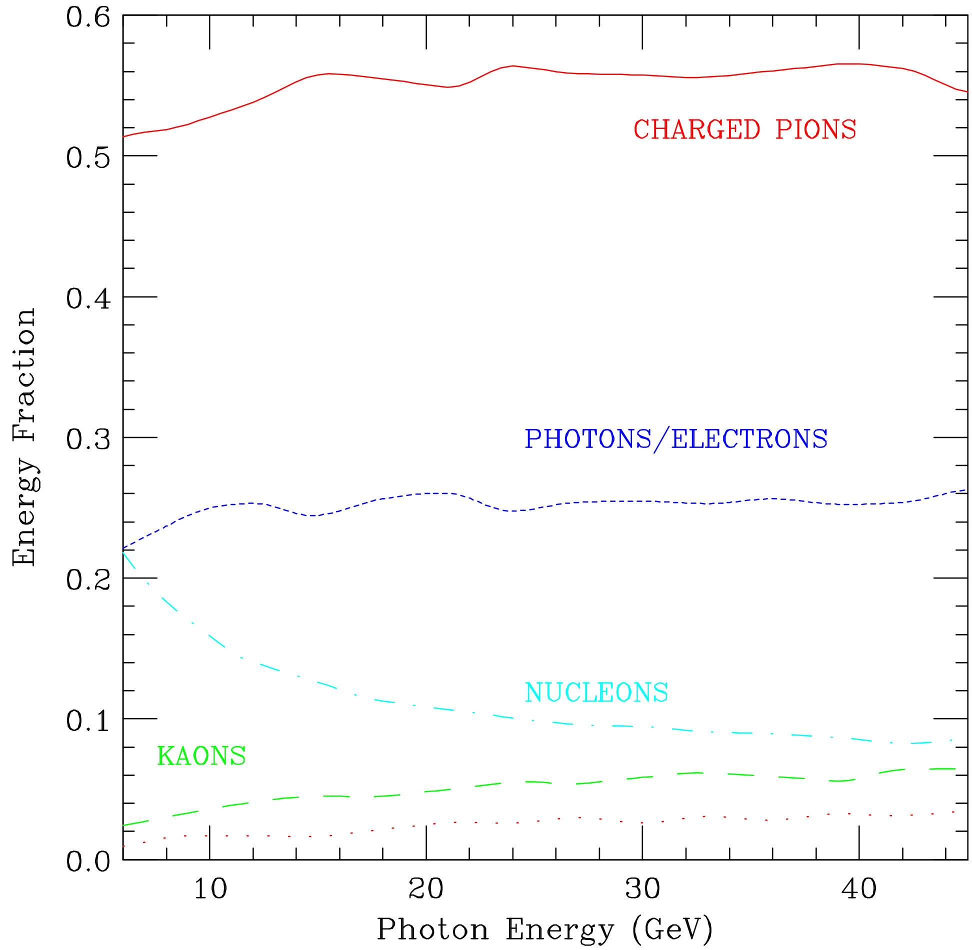
- In Counting mode, 30 to 50 hadrons/spill in Small-θ detector. This establishes luminosity limit, given 500 nsec beam pulse length.
- About 4 to 12 hadrons/spill in Large-θ detector.
- Several 100 low energy (10 to 50 MeV) electrons and photons/spill. Most will be below discriminator threshold. Tolerable "sprinkle hit" rate remaining.
- Estimate 100 neutrons/spill, most with kinetic energy less than 50 MeV. Most below detector threshold.
- In Flux Integration mode, total energy from neutrons estimated to be less than 1% of hadronic energy.

HADRONIC SIGNAL

- Using PYTHIA, find 99.5% (99%) probability, at least one final state "hadron" (includes photon from π^0 decay) has $p_T > 0.05$ GeV ($p_T > 0.1$ GeV).
- Most ($> 80\%$) events have a charged pion or kaon in final state with $P > 1$ GeV
- Good efficiency ($> 97\%$) obtained in counting mode with requirements $p_T > 0.1$ GeV or $E_{min} = 0.6 \ln(k_0)$ and $p_T^{HAD} > 0.05$ GeV.
- Efficiency slightly lower if count only energy in HAD calorimeter [flux integration method B].

HADRONIC EVENTS

Fractional energy into charged pions (solid), photons/electrons (short dashed), nucleons/anti-nucleons (dot-dashed), kaons (long dashed), and neutrinos (dotted).



Hadronic Efficiency

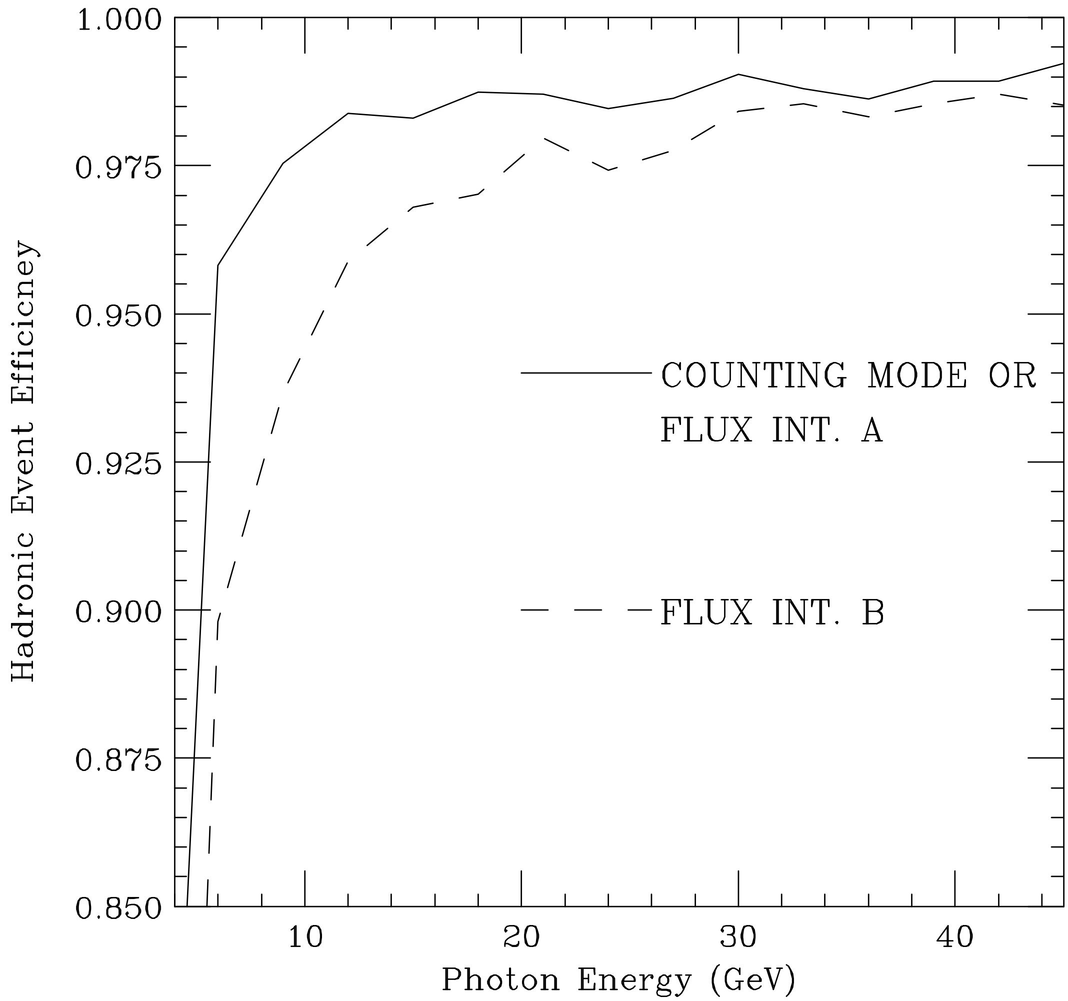
- Less than 1% of events lost using $\theta_{min} = 0.010\sqrt{40/k}$ mr. Similar to $\theta_{min} = 400/k$ mr cut used by Caldwell.
- Find $\theta_{max} = 20$ degrees gives good efficiency for $k > 10$ GeV. Some loss at lower energies, but need this compromise to keep reasonable target costs.
- Find using energy cut $E_{min} = 0.6\ln(k_0)$ preserves almost all events from coherent peak.

EFFICIENCY VERSUS K

Flux integration Methods:

A: E.M. background subtracted;

B: only energy in HAD calorimeter



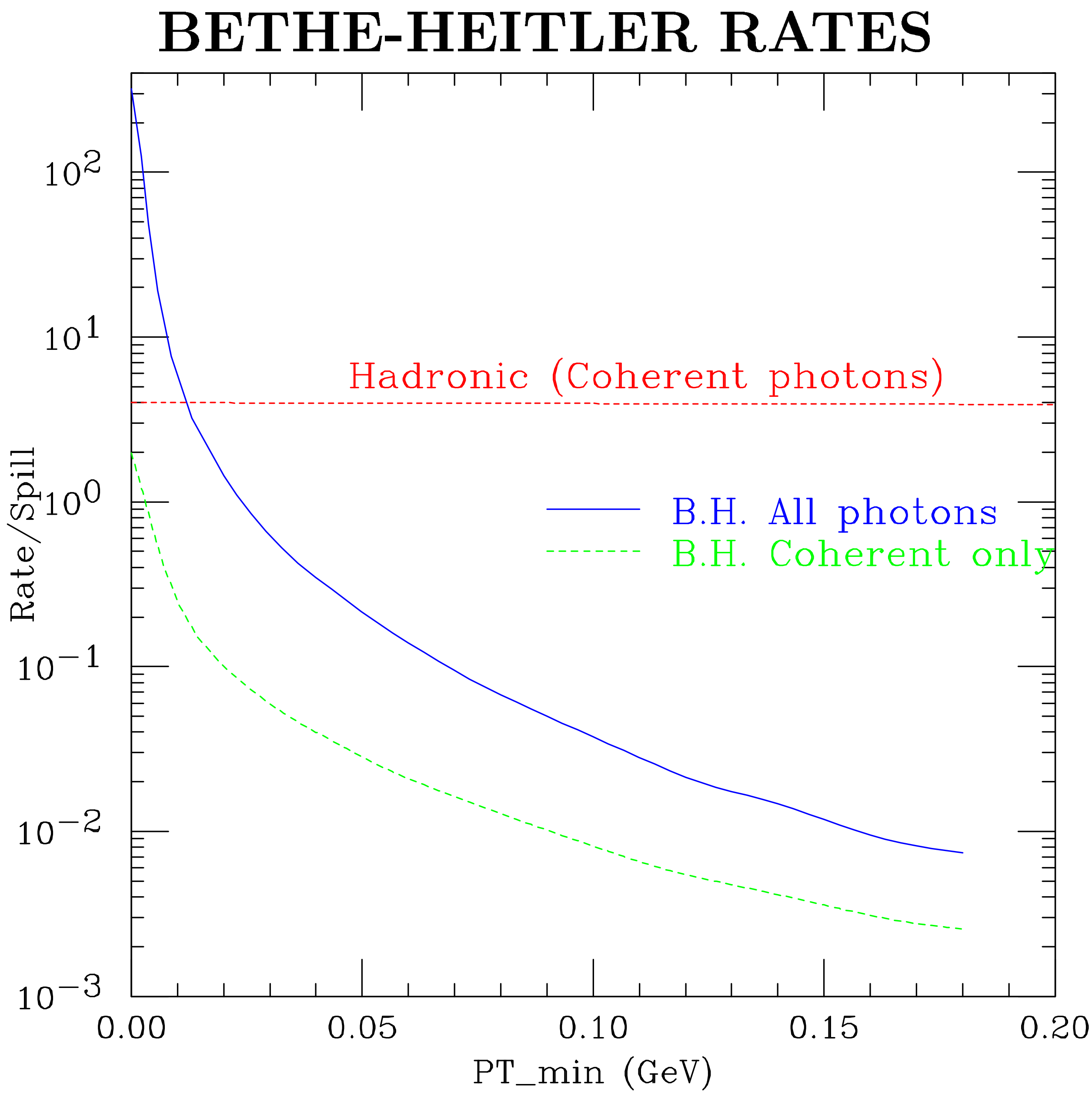
PHYSICS BACKGROUND SUMMARY

Data Analysis	B.H. Rates	Compton Rates
Counting Mode	$< 1\%$	negligible
Flux Integration A	50%	10% to 20%
Flux Integration B	negligible	negligible

Rates and physics asymmetry for both backgrounds well-known and calculable.

BETHE-HEITLER BACKGROUND

- Calculations include quasi-elastic and nuclear elastic e^+e^- pair production.
- Inelastic not included (part of GDH).
- Cross sections and asymmetry readily calculated in terms of F_1, F_2, g_1, and g_2.
- Find several 100/spill, but have low energy and mainly come from low energy incoherent photons. Total energy/spill similar to total hadronic energy per spill, with asymmetry close to zero. Applies to flux integration method A.
- Rate very low ($< 1\%$) with $p_T > 0.1$ GeV cut and subtraction of incoherent photon contribution (applies to counting mode).
- Negligible contribution to flux integration method B since all of energy absorbed in EM calorimeter.

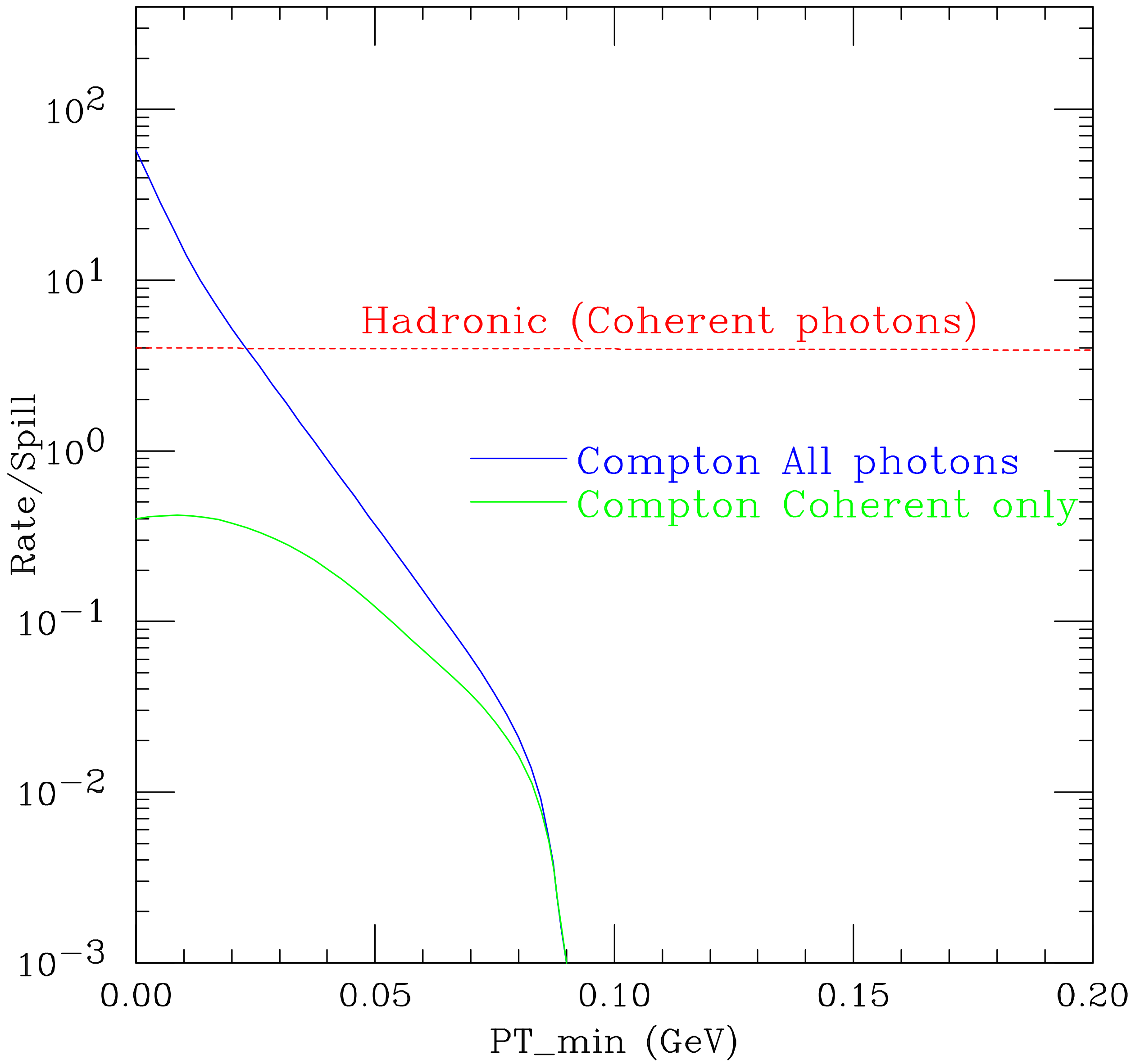


BETHE-HEITLER RATES
Hadronic (Coherent photons)
B.H. All photons
B.H. Coherent only
Rate/Spill
PT_min (GeV)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0.00
0.05
0.10
0.15
0.20

ATOMIC COMPTON BACKGROUND

- Cross section strongly peaked at low energy photons.
- Final state includes both soft photon and electron, typical energy 10 to 50 MeV.
- Asymmetry expected to be essentially zero for polarized target (electrons not polarized when microwaves are on).
- Find several 100/spill, but total energy less than Bethe-Heitler (about 10% to 20% of total hadronic energy).
- Makes 10% to 20% dilution for flux integration method A.
- Rate drops to zero for $p_T > 0.1$ GeV (kinematic limit), so no background to counting mode.
- No contribution to flux integration method B [no energy in HAD calorimeter].

ATOMIC COMPTON RATES



EXPECTED RESULTS

- More conservative (larger error) analysis method assumes subtraction of results with/without coherent bremsstrahlung peaks.
- Error on $A_1(k) = \Delta\sigma^{\gamma N}(k)/2\sigma^{\gamma N}(k)$ given by

$$\delta A_1(k) = \frac{1}{P_\gamma P_t f \sqrt{N_c}} \frac{\sqrt{2-r}}{\sqrt{r}}$$

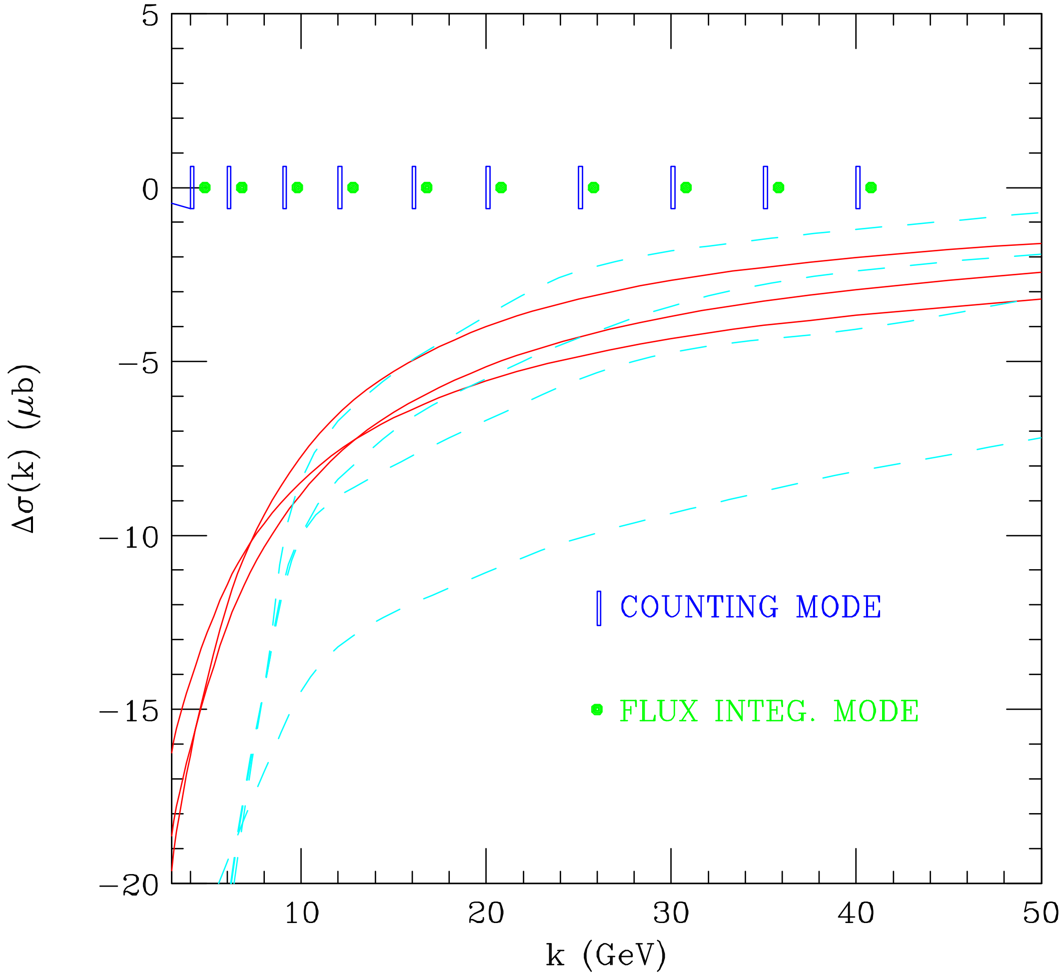
where r is fraction of counts from coherent peaks, and $0.3 < r < 0.8$, depending on setting.

- In counting mode, rate of coherent counts $N_c \approx 4 \times 10^7$/day. In flux integration mode, $N_C \approx 10^9$/day.
- Error on $\Delta\sigma$ obtained by scaling by $2\sigma \approx 250\ \mu$b.

- Analysis using simultaneous fit to all data (includes highly polarized incoherent photons near endpoint) estimated to reduce statistical errors by factor of two.
- Most systematic errors in counting mode scale with size of A_1: estimate 6% to 8% relative error from combined beam and target parameters and modeling uncertainties. Expect to be smaller than counting mode statistical errors.
- Run plan will be optimized depending on preliminary results: if asymmetries large, more time will be spent on counting mode.
- Final results on both proton and neutron will be small enough to clearly determine magnitude and energy dependence of $\Delta\sigma$ for $4 < k < 40$ GeV.

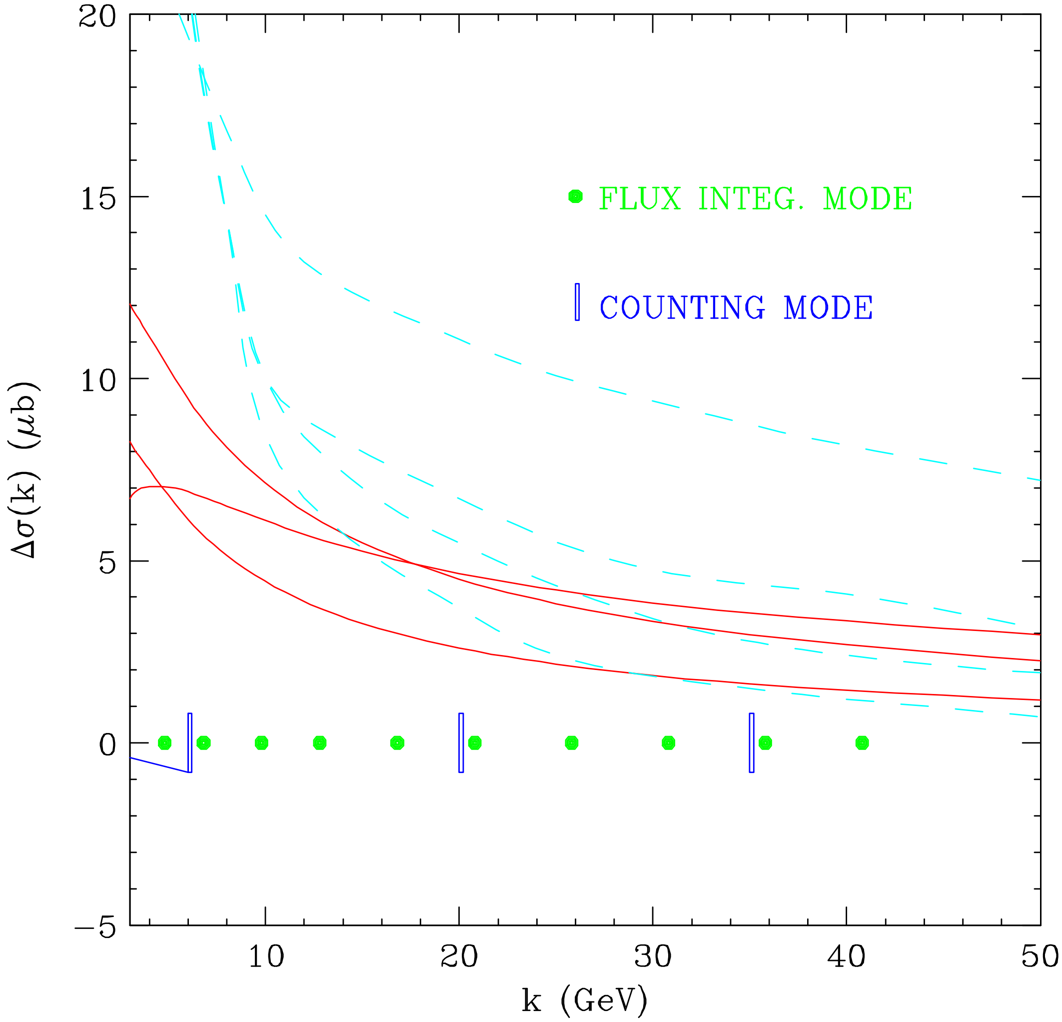
EXPECTED ERRORS FOR PROTON

Systematic errors (not shown) expected to be 6% to 8% (relative).



EXPECTED ERRORS FOR NEUTRON

Systematic errors (not shown) expected to be 6% to 8% (relative).



ERROR ON GDH INTEGRALS

- To estimate systematic error and provide scale of expected results, will arbitrary assume results follow Bianchi and Thomas Fit II.
- Total errors are small compared to expected values and total integrals.
- Can readily determine sign and magnitude of controversial isovector contribution (limit of Bjorken Sum Rule at $Q^2 = 0$).

target	$2\pi^2\alpha\kappa^2/M^2$	$4 < k < 40$ GeV
proton	204 μb	$-14 \pm 0.5 \pm 1.0$ μb
neutron	232 μb	$14 \pm 0.8 \pm 1.0$ μb
isoscalar (p+n)/2	219 μb	$0 \pm 0.4 \pm 0.7$ μb
isovector (p-n)/2	-15 μb	$-28 \pm 0.4 \pm 0.7$ μb

REQUEST

- Two weeks checkout (plus one week for photon beam).
- Two months data taking at nominal 120 Hz, assuming 50% efficiency due to PEP-II.
- Resources for photon beam, polarimeter, detectors, and some target equipment.
- Collaboration will provide much target equipment, some diamonds, and assembly of detectors.

SUMMARY

- A solid, fundamental experiment, providing baseline for studies of spin structure of nucleon.
- Test convergence of isovector and isoscalar GDH Sum Rule.
- Connections to g_1 at low x, Bjorken Sum Rule.
- No existing data: surprises possible!
- Study QCD in non-perturbative regime with one of simplest possible interactions.
- SLAC is only place experiment can be done $5 < k < 40$ GeV.
- Energy range extends factor 8 beyond Jefferson Lab.
- Strong collaboration with experience and resources needed to do experiment.