Positron Production by Laser Light

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From Hawking to Unruh to ...

Hawking: An observer outside a black hole experiences a bath of thermal radiation of temperature

$$T = \frac{\hbar g}{2\pi c k},$$

where g is the local acceleration due to gravity.

Unruh: According to the equivalence principle an accelerated observer in a gravity-free region should also experience a thermal bath with:

$$T = \frac{\hbar a}{2\pi c k},$$

where a is the acceleration of the observer as measured in his instantaneous rest frame.

Unruh Radiation (?)

Suppose the observer is an electron, accelerated by a field E.

Thomson scattering off photons in the apparent thermal bath implies a radiation rate:

$$\frac{dU_{\rm Unruh}}{dt} = \text{thermal energy flux} \times \text{Thomson cross section} = \frac{\hbar r_e^2 a^4}{90\pi c^6}.$$

[Stefan-Boltzman: flux $\propto T^4$, Unruh: $T^4 \propto a^4$.]

This equals the Larmor radiation rate, $dU/dt = 2e^2a^2/3c^3$, when the acceleration $a = eE/m$ is about 10^{31} g, *i.e.*, when

$$E = \sqrt{\frac{60\pi}{\alpha}} \left(\frac{m^2c^3}{e\hbar}\right) \approx 3 \times 10^{18} \text{ V/cm}.$$

Can we do the experiment?

The QED Critical Field Strength

- O. Klein (Z. Phys. **53**, 157 (1929)) noted that the reflection coefficient exceeds unity when Dirac electrons hit a steep barrier (Klein's paradox).

- F. Sauter (Z. Phys. **69**, 742 (1931)) deduced that the paradox arises only in electric fields exceeding the critical strength:

$$E_{\text{crit}} = \frac{m^2c^3}{e\hbar} = 1.32 \times 10^{16} \text{ Volts/cm.}$$

- At the critical field, the energy gain across a Compton wavelength is the electron rest energy:

$$eE_{\text{crit}} \cdot \frac{\hbar}{mc} = mc^2.$$

- At the critical field the vacuum 'sparks' into e^+e^- pairs (Heisenberg and Euler, Z. Phys. **98**, 718 (1936)).

$$\text{Dimensionless measure of criticality: } \Upsilon = \frac{E}{E_{\text{crit}}}.$$

Where to Find Critical Fields

- The magnetic field at the surface of a neutron star approaches the critical field $B_{\text{crit}} = 4.4 \times 10^{13}$ Gauss.
- During heavy-ion collisions where $Z_{\text{total}} = 2Z > 1/\alpha$, the critical field can be exceeded and e^+e^- production is expected.
$$E_{\max} \approx \frac{2Ze}{\lambda_C^2} = 2Z\alpha E_{\text{crit}}.$$
The line spectrum observed in positron production in heavy-ion collisions (Darmstadt) is not understood.
- Pomeranchuk (1939): The earth's magnetic field appears to be critical strength as seen by a cosmic-ray electron with 10^{19} eV.
- The electric field of a bunch at a future linear collider approaches the critical field in the frame of the oncoming bunch.

Critical Fields in e-Laser Collisions

- The electric field due to a laser as seen in the rest frame of a high-energy electron is

$$E^\star = \gamma(1+\beta)E_{\rm lab} \approx 2\gamma E_{\rm lab},$$

$$\text{so} \qquad \Upsilon = \frac{E^\star}{E_{\rm crit}} = \frac{2\gamma E_{\rm lab}}{E_{\rm crit}} = \frac{\sqrt{(F_{\mu\nu}p^\nu)^2}}{mc^2 E_{\rm crit}}.$$

- The critical field is achieved with a laser beam of intensity

$$I = \frac{E_{\rm lab}^2}{377\Omega} = \frac{E_{\rm crit}^2}{4\gamma^2 \cdot 377}.$$

  Thus for 46-GeV electrons ($\gamma = 9 \times 10^4$) we can achieve $E_{\rm crit}$ with a focused laser intensity of 1.4×10^{19} Watts/cm^2 ($\Rightarrow E_{\rm lab} = 7 \times 10^{10}$ Volts/cm).

- Such intensities are now attainable in table-top teraWatt (T^3) lasers in which a Joule of energy is compressed into one picosecond and focused into a few square microns.

- At these intensities the photon density is $\sim 10^{27}$/cm^3, and the radiation length of this 'photon solid' is $\sim \lambda_0/\alpha \approx 100\ \mu$m.

Another Aspect of Electrons in Strong Wave Fields

Simplest to consider a circularly polarized laser beam incident on an electron at rest. Laser field is E, frequency is ω_0.

Classical response of electron is transverse motion in a circle with angular velocity ω_0 and velocity described by

$$\frac{v_\perp}{c} = \frac{eE}{m\omega_0 c} \equiv \eta.$$

[$\eta = e\sqrt{\langle A_\mu A^\mu \rangle}/mc^2$ where A_μ is the vector potential.]

The accelerating electron emits multipole radiation.

$\text{Rate}_n \propto \eta^{2n} \propto I^n$ for nth-order multipole ($\eta \lesssim 1$).

nth order $\Leftrightarrow$ absorption of n photons before emitting a single higher-energy photon $\Leftrightarrow$ nonlinear Compton scattering.

Υ and η are related by

$$\Upsilon = \frac{2\gamma E_{\text{lab}}}{E_{\text{crit}}} = \frac{2\gamma \hbar \omega_0}{mc^2}\eta \quad \approx \quad \eta \;\; \text{in our experiment.}$$

$\Rightarrow$ Two classes of strong-field effects to be untangled.

The Mass Shift Effect

An electron propagating in a (periodic) wave field of strength $\eta = eE/m\omega_0 c$ takes on an effective mass

$$\overline{m} = m\sqrt{1+\eta^2}.$$

Classical view: the transverse oscillations of the electron are relativistic, so it becomes 'heavier'.

As a result the kinematic limits in nonlinear Compton scattering (and threshold for pair creation) are shifted.

Pedagogic paradox: An electron with 4-momentum p_μ in the absence of the field takes on quasimomentum q_μ once in a field of 4-momentum k_μ:

$$q_\mu = p_\mu + \frac{\eta^2 m^2}{2k \cdot p} k_\mu, \qquad q^2 = \overline{m}^2.$$

In our experiment $\eta^2 m^2 / 2k \cdot p$ takes on a fractional value.

Summary of Motivation and Goals

- The Higgs mechanism implies that elementary particles have important interactions with strong background fields.
- Only with electromagnetism can intense, controllable, macroscopic fields be created in the laboratory.
- Explore the validity of QED for electromagnetic field strengths in excess of the 'critical field strength'

$$E_{\text{crit}} = m^2c^3/e\hbar = 1.6 \times 10^{16} \text{ V/cm}.$$

- Explore QED in the realm where multiphoton interactions dominate, *i.e.*, when $\eta \equiv eE/m\omega_0 c \approx 1$.

Proposal for a

STUDY OF QED AT CRITICAL FIELD STRENGTH

IN INTENSE LASER–HIGH ENERGY ELECTRON COLLISIONS

AT THE STANFORD LINEAR ACCELERATOR

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Proposed October 20, 1991

Conditional approval as Experiment 144 on December 20, 1991

Full approval on September 30, 1992

E-144 Home Page on World Wide Web

http://www.slac.stanford.edu/exp/e144/e144.html

E144

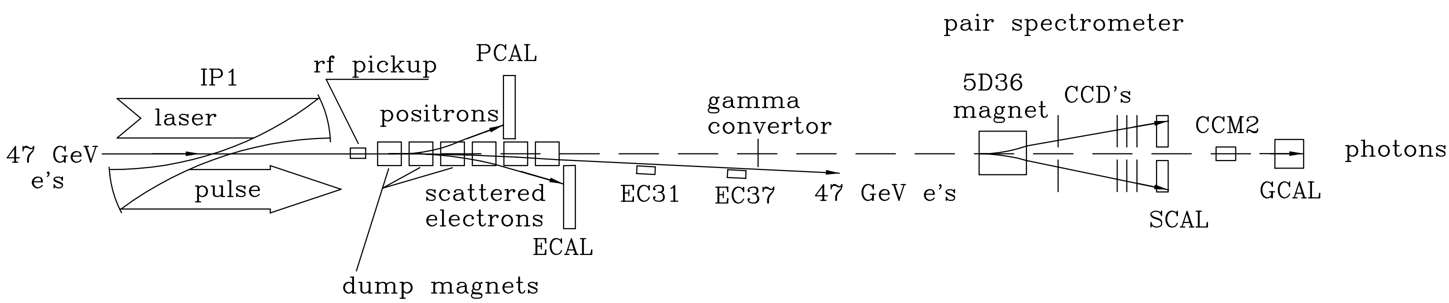
cranked beyond the limit

E-144 Physics Program

1. Compton Polarimetry
   - Both the E-144 laser and electron beams are polarized.
   - Compton polarimetry provides a basic check of the E-144 apparatus, as well as a confirmation of the SLC beam polarization.
2. Nonlinear Compton Scattering: $e + n\omega_0 \to e' + \omega$
   - Semiclassical theory $\Rightarrow$ data will diagnose laser intensity.
   - Provides high-energy-photon beam for light-by-light scattering.
3. Multiphoton Breit-Wheeler Process: $\omega + n\omega_0 \to e^+e^-$
   - Might show anomalous structure in e^+e^- invariant mass when $E > E_{\mathrm{crit}}$.

Experimental Ingredients

- Low-emittance electron beam.
- Terawatt laser.
- Synchronization of e and laser beams to 1 psec in time, and a few μm in space.
- Silicon calorimeters for 'coarse-grain' detection of e^-, e^+ and γ's.
- CCD pair spectrometer for 'fine-grain' measurements.
- Data-acquisition system based on PC's interconnected via a local ethernet.



E-144 is at the End of the FFTB

TeraWatt Laser Via Chirped-Pulse Amplification

1 Joule in 1 ps $\Rightarrow 10^{12}$ Watt.

Diffraction limited spot area $\approx \lambda^2 (f/D)^2 \approx 10\ \mu\text{m}^2$.

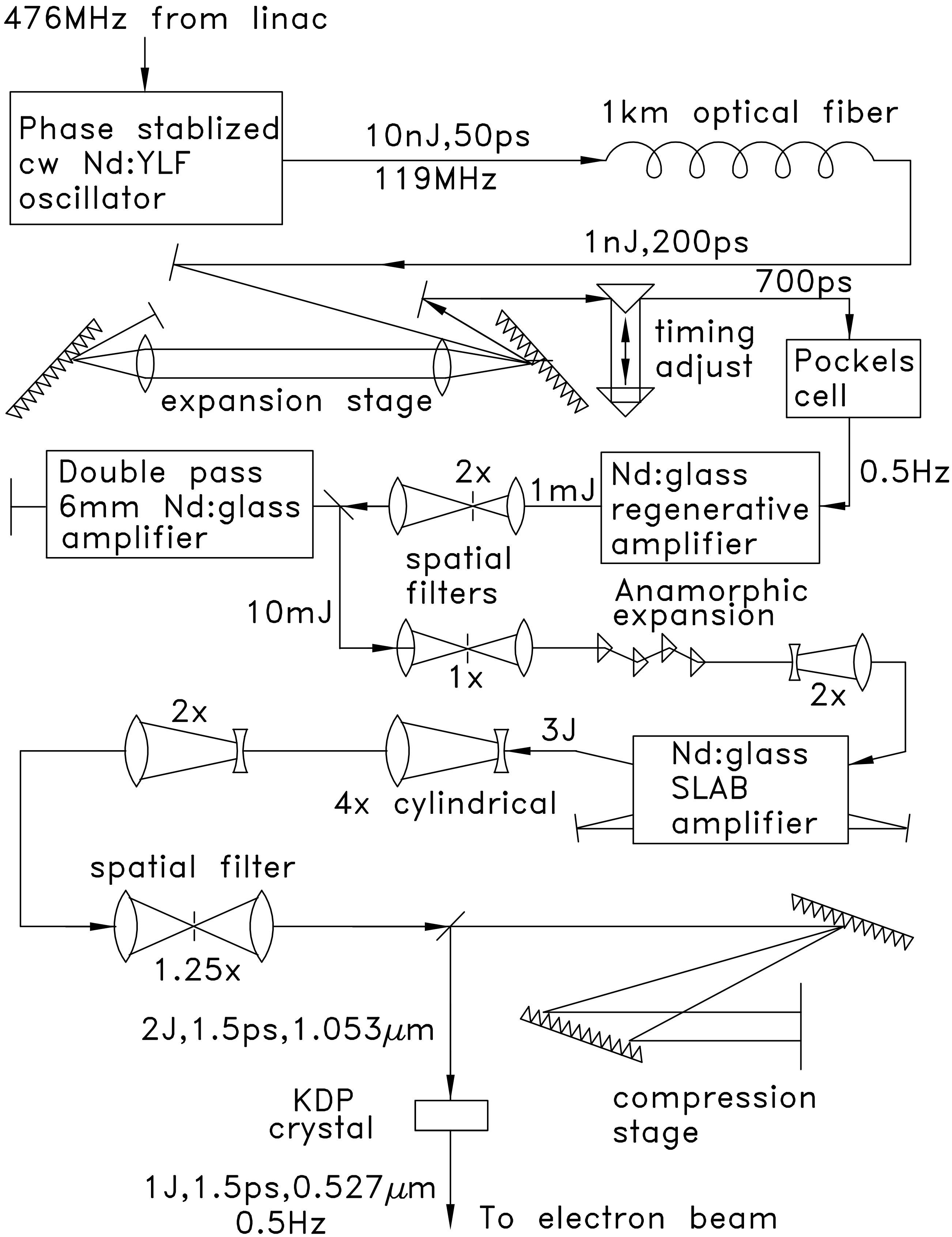
$\Rightarrow I \approx 10^{19}\ \text{W/cm}^2$.

High power pulses can damage optics!

$\Rightarrow$ stretch pulse, then amplify and compress.

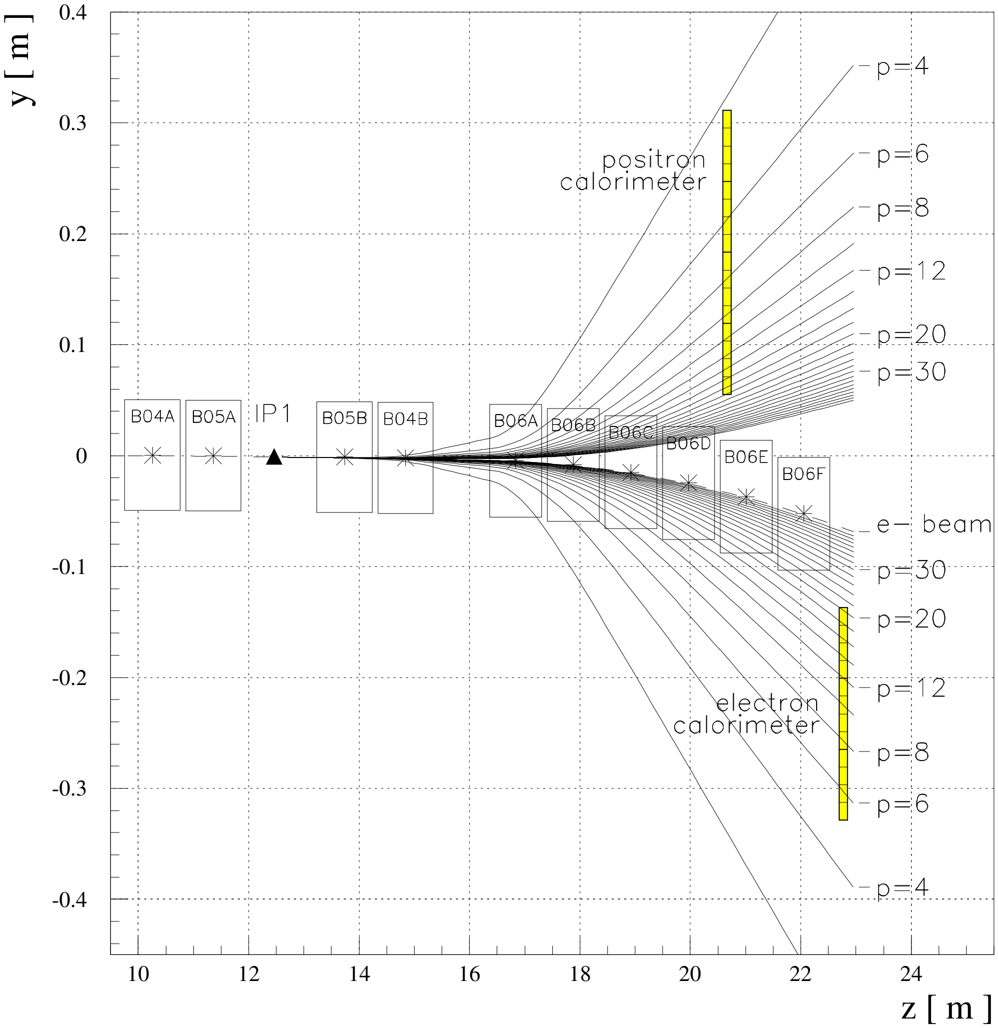
[D. Strickland and G. Mourou, Opt. Comm. **55**, 447 (1985).]

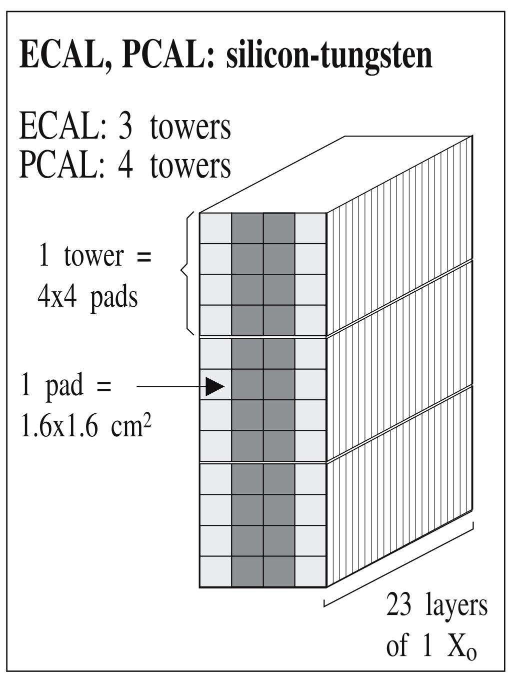
E-144 Laser Schematic



synchronization block diagram

Electron & Positron Spectrometers



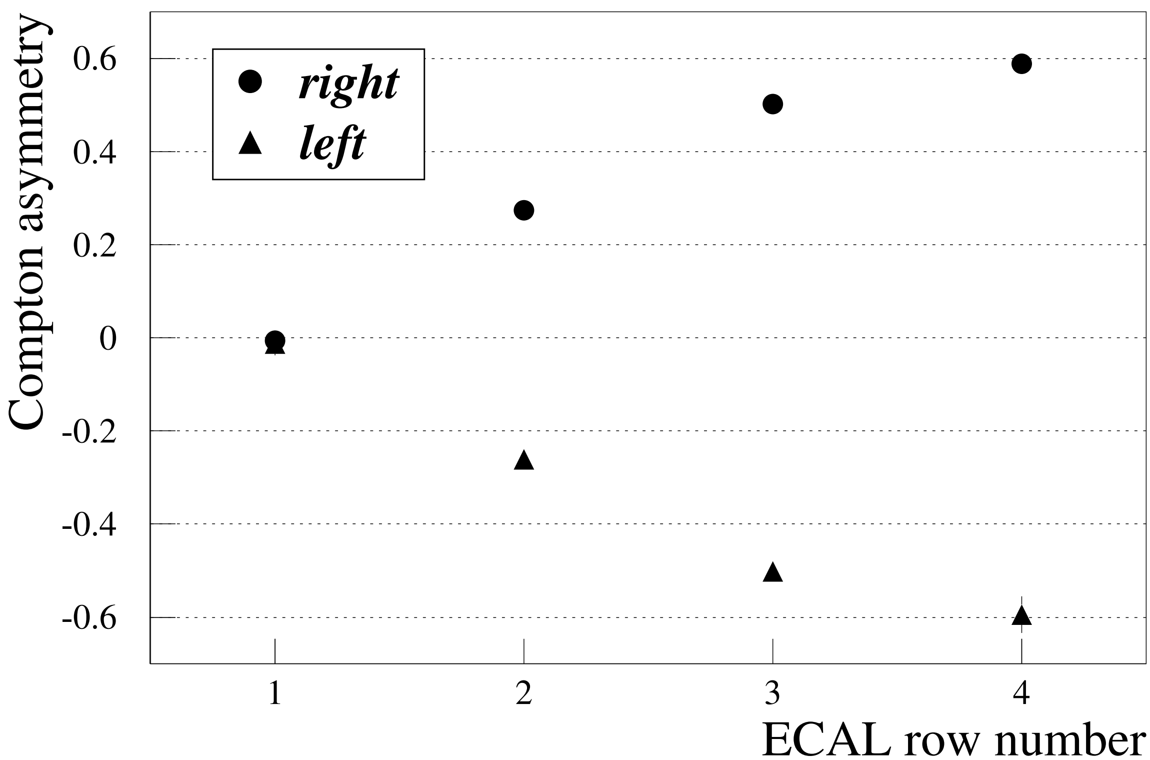


Measurement of e-Beam Polarization (May '94)

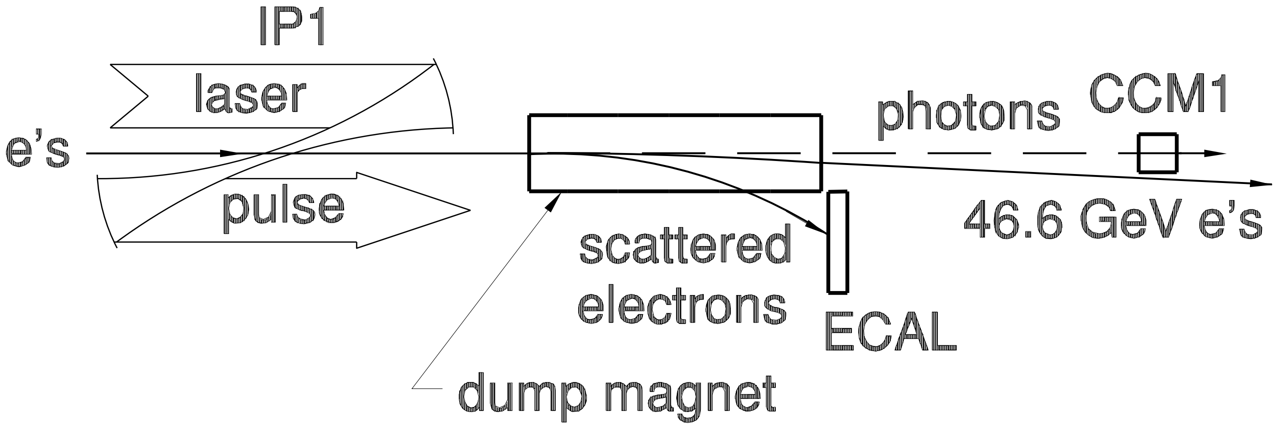
Fit to measured polarization asymmetry in 4 energy bins yields

$$P_e P_{\text{laser}} = 0.81 \pm 0.01.$$

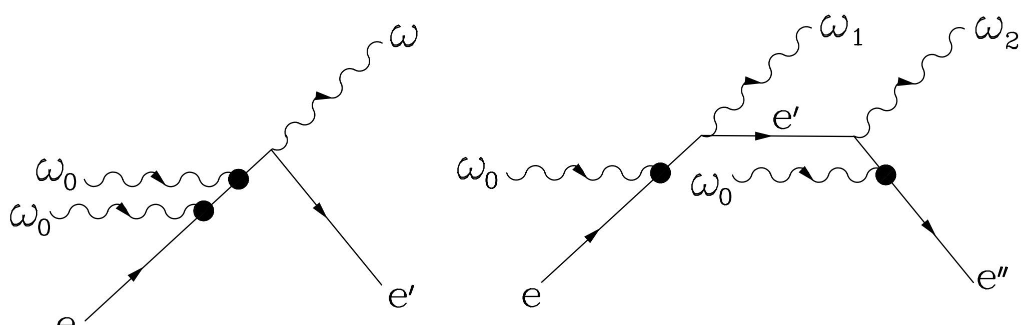
Laser polarization $> 0.96 \Rightarrow P_e = 0.81^{+0.04}_{-0.01}$.



Nonlinear Compton Scattering



$$(a) \qquad e + n\omega_0 \to e' + \omega$$



(a) (b)

(b) Background: multiple Compton scattering

Can distinguish process (a) from (b) by detecting scattered photon.

In first experiments, only the scattered electron was detected.

Theoretical Predictions for $e + n\omega_0 \to e' + \omega$

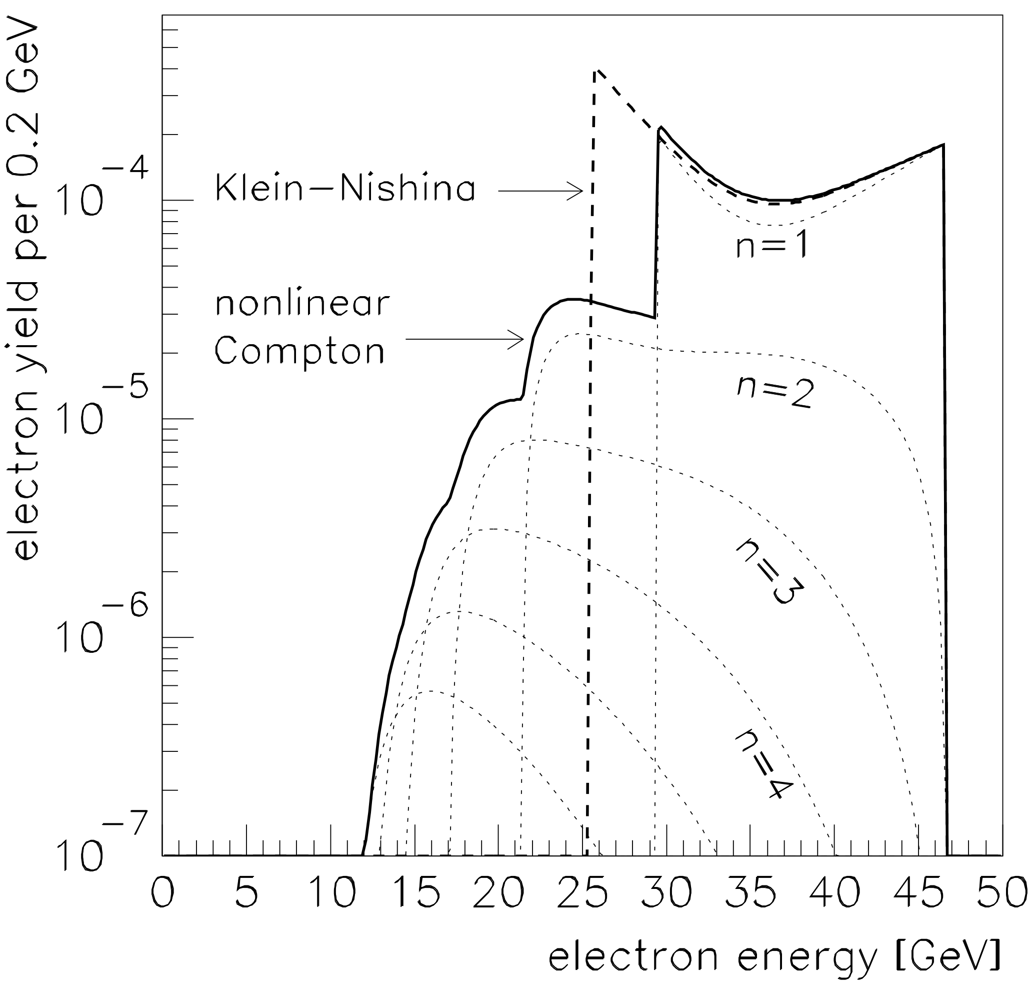
Circular polarization (Nikishov *et al.*, JETP **20** (1965) 622).

$$\frac{d\mathrm{Rate}_n}{dE_{e'}} = \frac{4\pi r_0^2 N_{\mathrm{laser}} N_e}{x E_e} \times$$

$$\left\{ \left(2 + \frac{u^2}{1+u}\right) \left[J_{n-1}^2(z) + J_{n+1}^2(z) - 2J_n^2(z)\right] - \frac{4}{\eta^2} J_n^2(z) \right\},$$

$$x = \frac{4\omega_0 E_e}{m^2}, \qquad u \approx \frac{E_e}{E_{e'}} - 1, \qquad z = \frac{2\eta}{x}\sqrt{nux - u^2(1+\eta^2)}.$$

Case of linear polarization is more intricate.



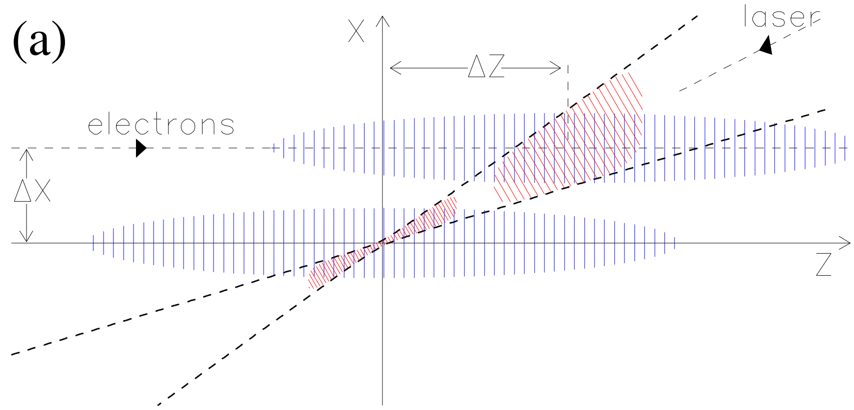
$\eta = 0.64$

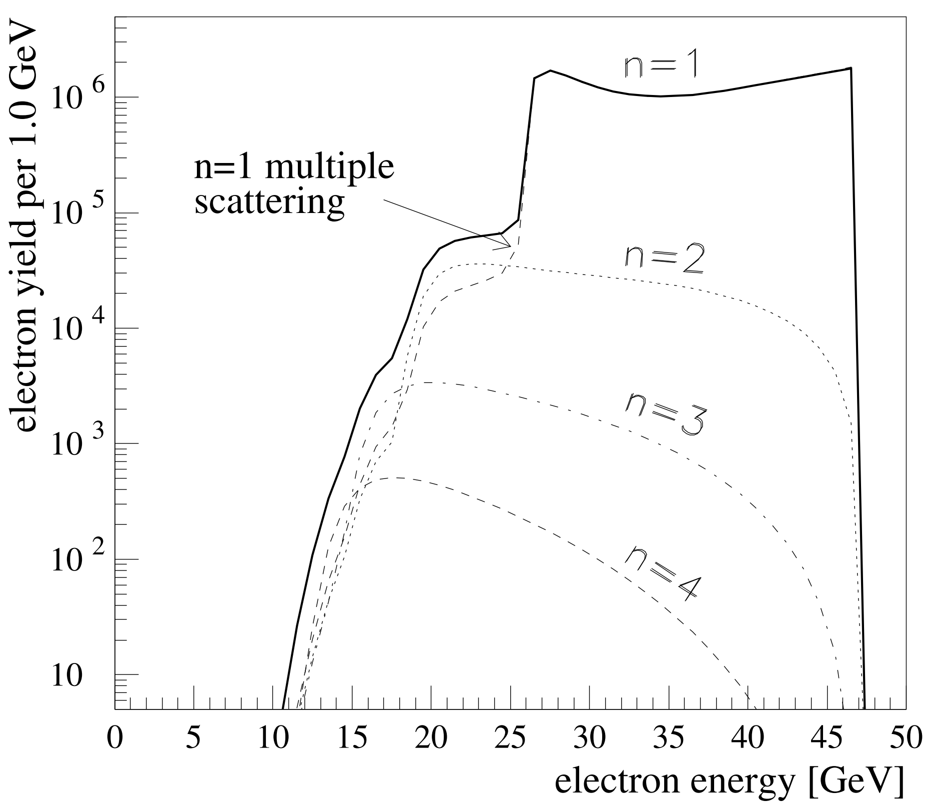
Effect of Laser and Electron Beam Spots

Beams cross at 17°.

Laser pulse is ≈ 2 ps long, focussed to $\approx 5\lambda_0$.

Electron pulse is ≈ 5 ps long.



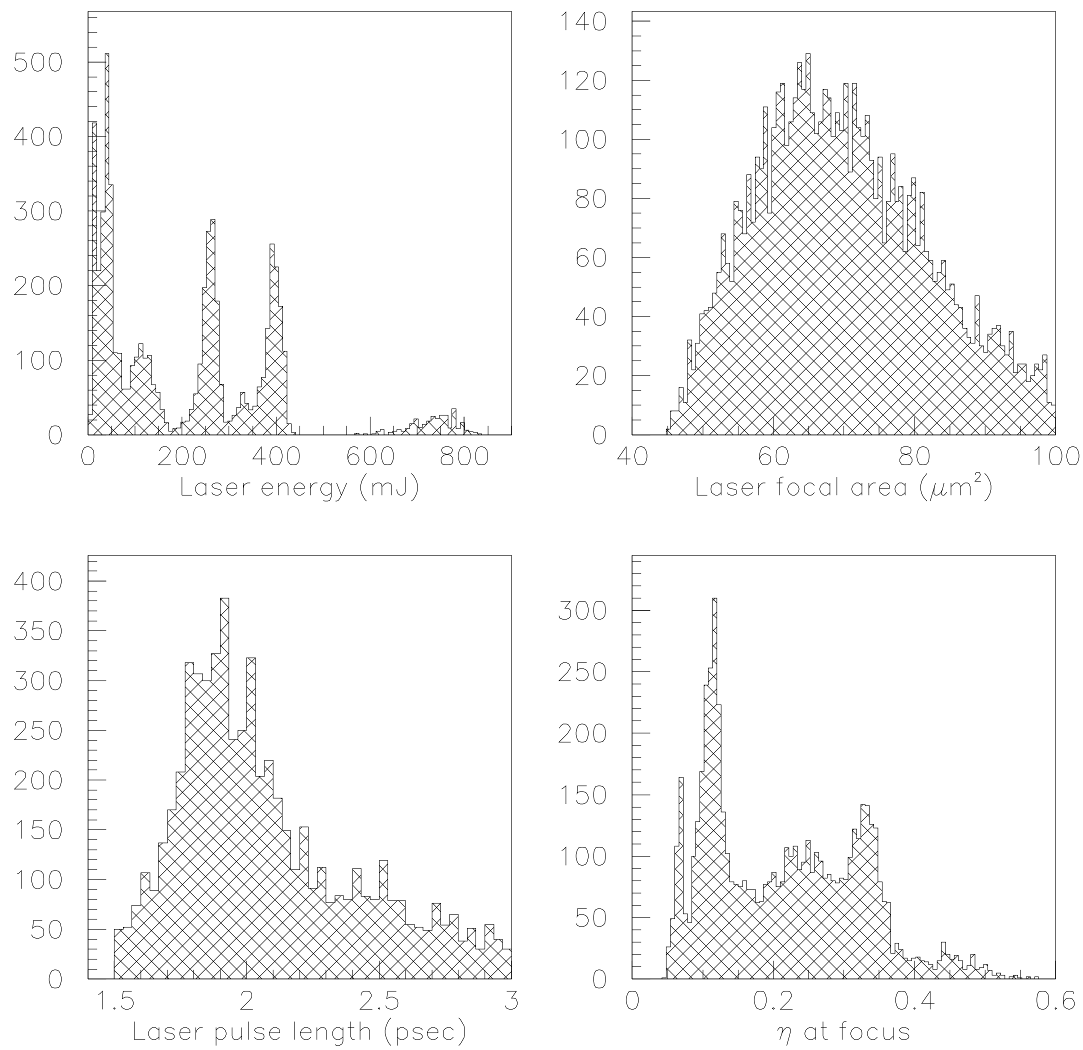


$\eta_{\max} = 0.64$

Measurements of Nonlinear Compton Scattering

[C. Bula *et al.*, Phys. Rev. Lett. **76**, 3116 (1996)]

18,000 infrared laser shots ($\omega_0 = 1.15$ eV):

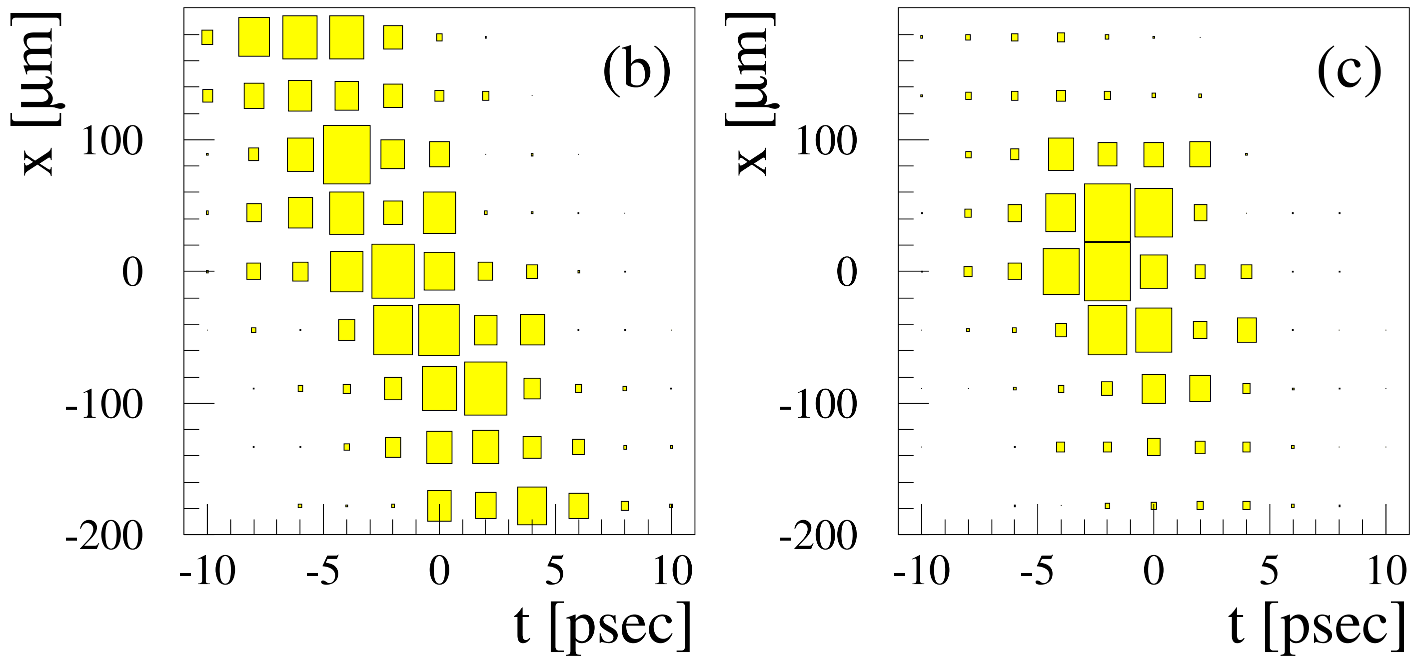


16,000 green laser shots ($\omega_0 = 2.3$ eV).

x-t Scans

Vary x and t offsets between laser and electron beam.

Detect scattered electrons in (a) $n = 1$ region and (b) $n = 2$ region.



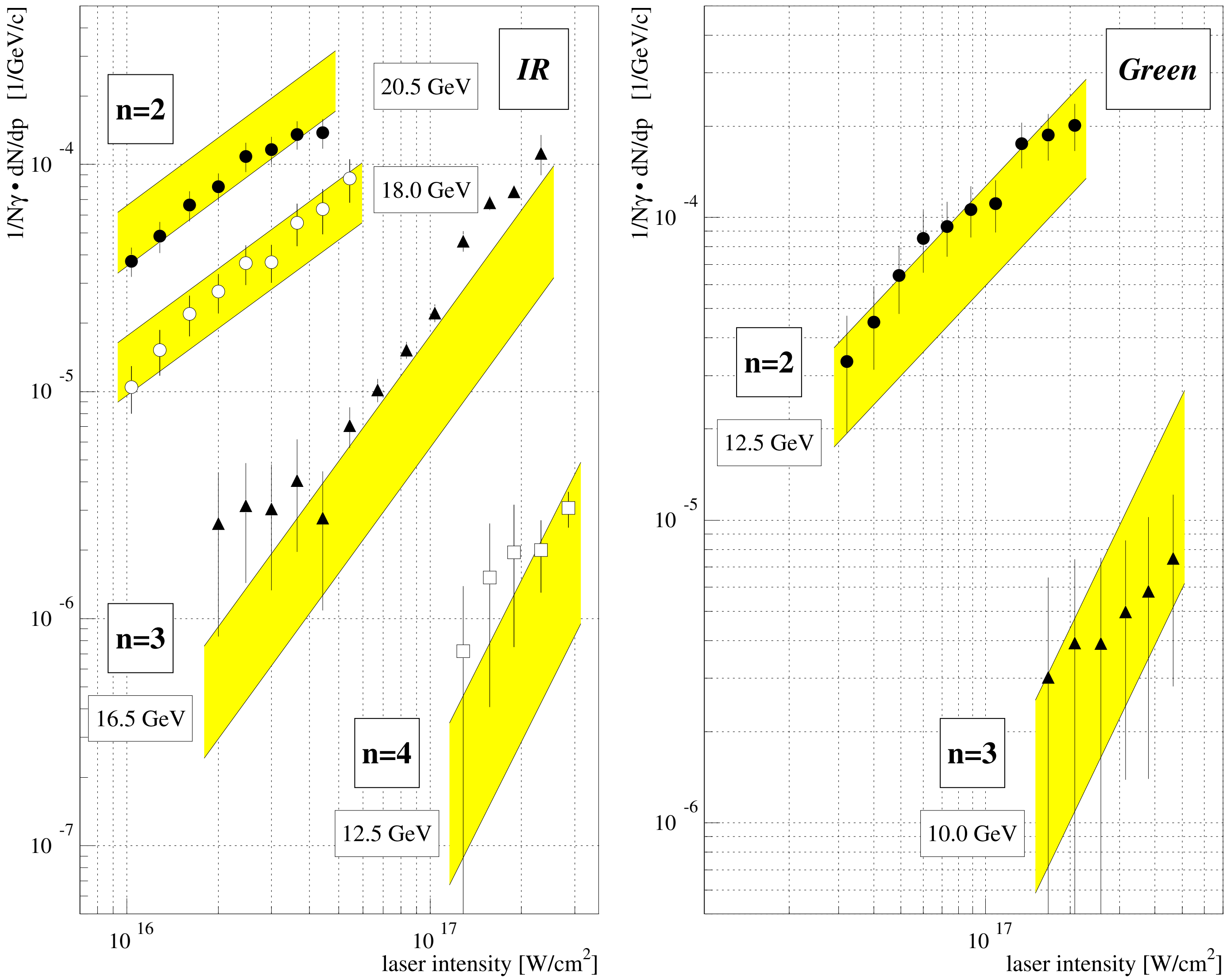
Nonlinear scattering confined to core of laser spot where intensity is the highest.

Observed Rates *vs.* Laser Intensity

Cross-section not a useful concept for nonlinear scattering.

Plot differential rates normalized to total scattering rate

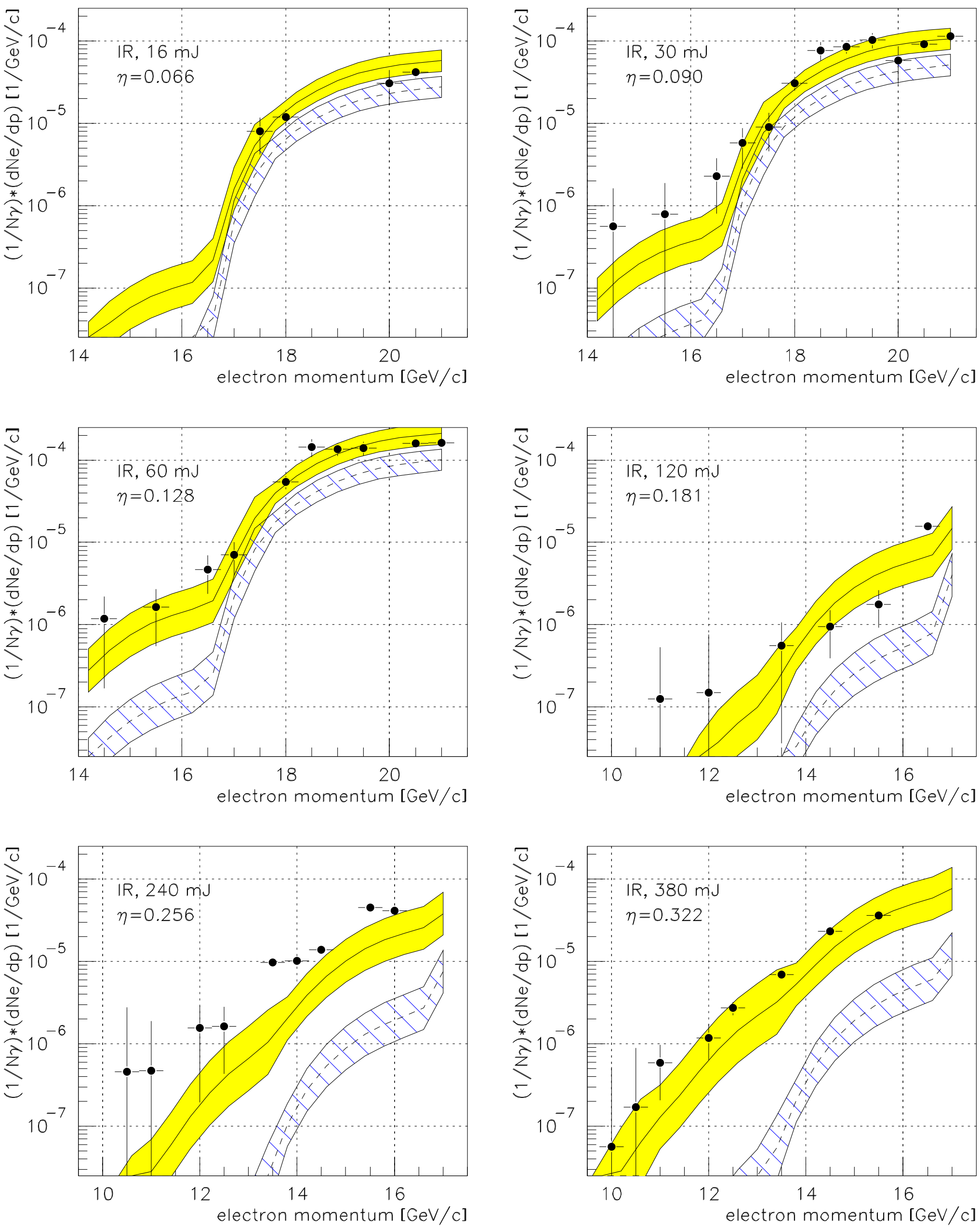
(= total rate of scattered photons).



Normalized to total scattered photon rate

$\Rightarrow$ Rate(order n) $\propto I^{n-1}$.

Observed Scattering Rates *vs.* Electron Energy



$n = 2$ edge at 17.6 GeV, $n = 3$ edge at 13.5 GeV.

Shaded = full simulation.

Striped = multiple-($n = 1$) scattering only.

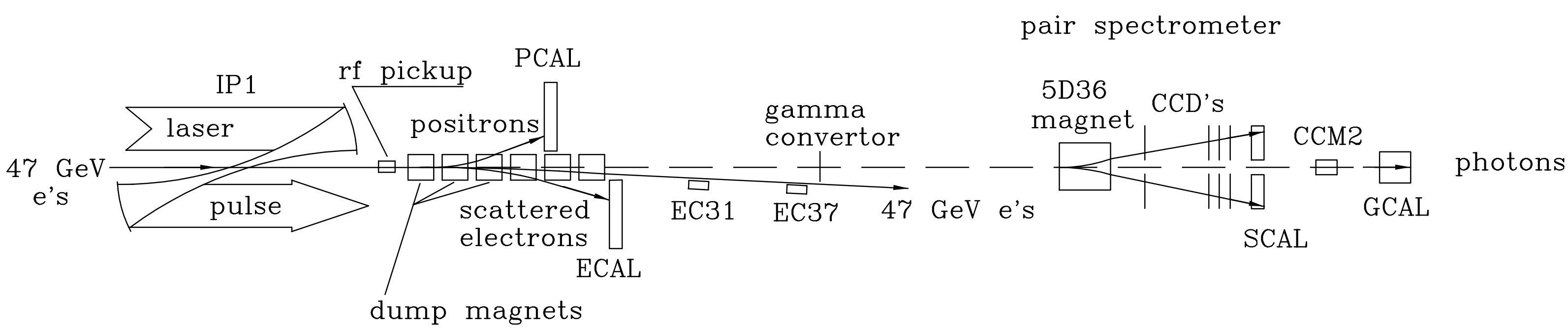
Measurements of the Scattered Photon

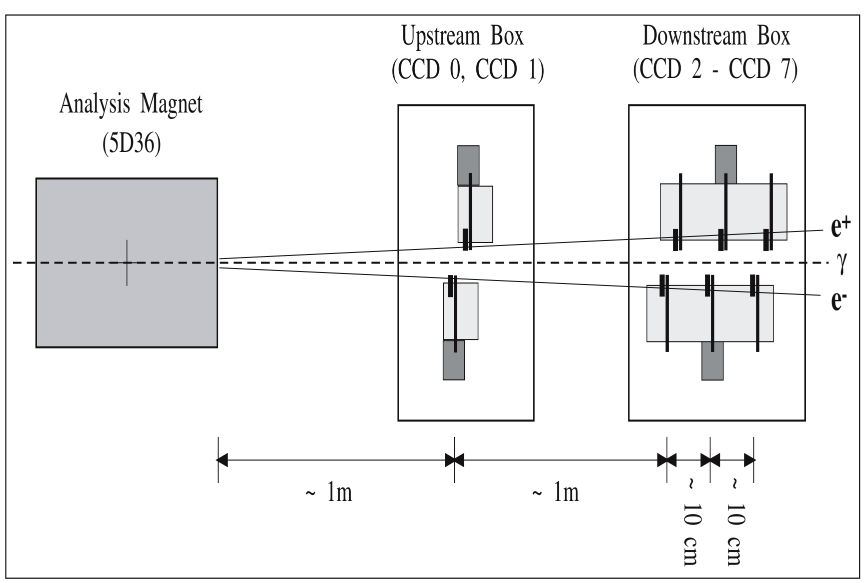
Multiple Compton scatters produce no photons with energy above the maximum for a single scatter.

$\Rightarrow$ No backgrounds for $n > 1$ nonlinear Compton Scattering

However, no simple spectrometer for high-energy photons:

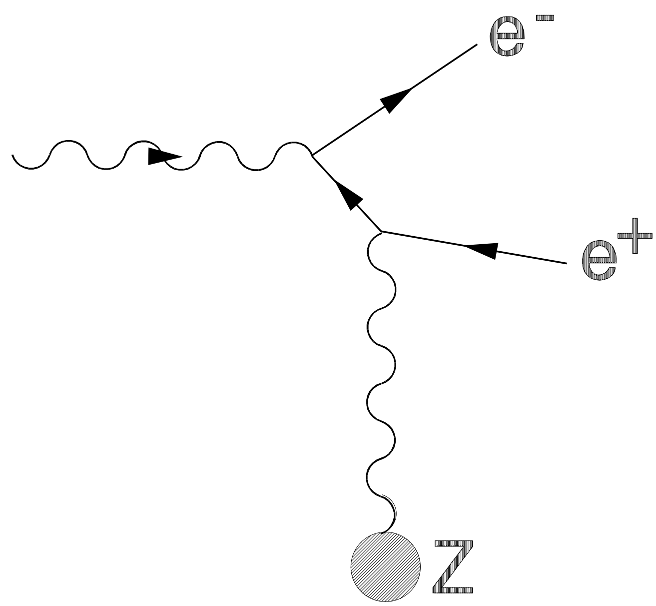
We convert the photons to e^+e^- pairs and analyze the latter in a magnetic spectrometer with CCD detectors





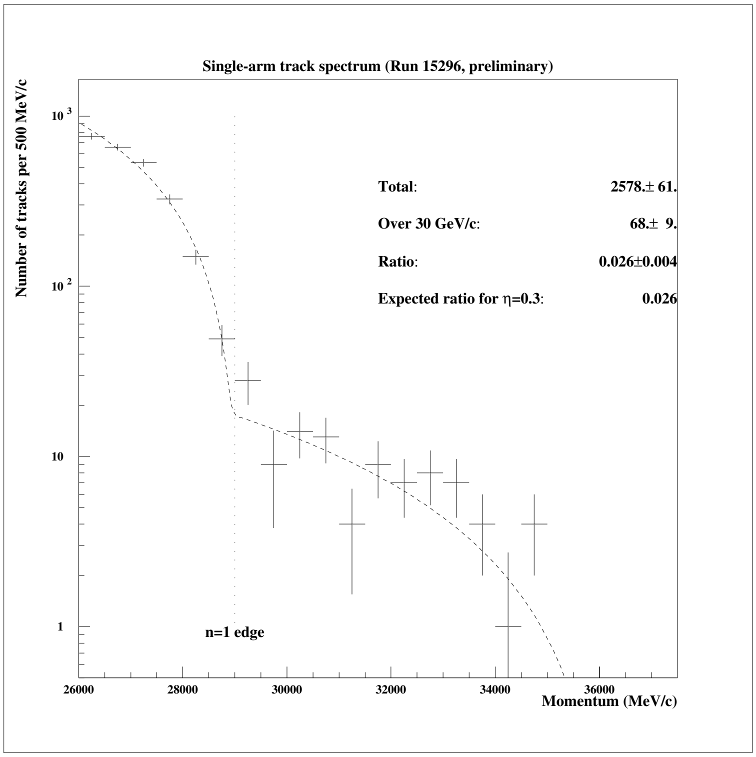
Making Positrons the Old-Fashioned Way

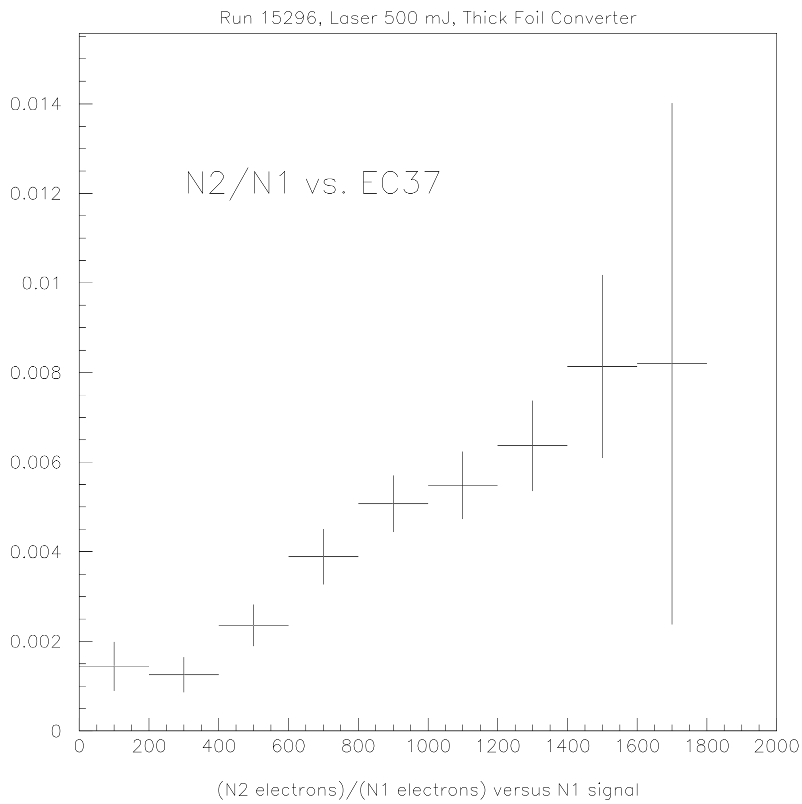
Bethe-Heitler (1934): A real photon combines with a virtual photon from the field of a nucleus to create an e^+e^- pair.



Nuclear electric fields are strong but not critical; Bethe-Heitler pair creation is well described in perturbation theory involving a single virtual photon.

e^+ and e^- from Converted Compton Photons



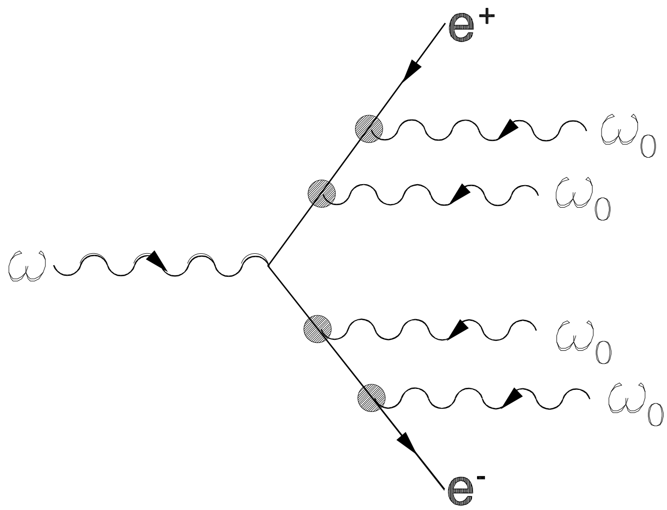


Threshold: $\hbar\omega_1 \, \hbar\omega_2 = (mc^2)^2$

Cross section near threshold : $$\sigma_{\mathrm{B-W}} \approx \pi r_e^2 \sqrt{1 - \frac{m^2c^4}{\hbar\omega_1 \, \hbar\omega_2}}.$$

Pair Creation by Light

Two step process: $e + \omega_0 \to e' + \omega$, then $\omega + n\omega_0 \to e^+e^-$.



Multiphoton pair creation is cross-channel process to nonlinear Compton scattering.

$\Rightarrow$ Similar theories [sums of Bessel functions whose arguments depend on η^2].

$\Rightarrow$ Breit-Wheeler cross section in weak-field limit.

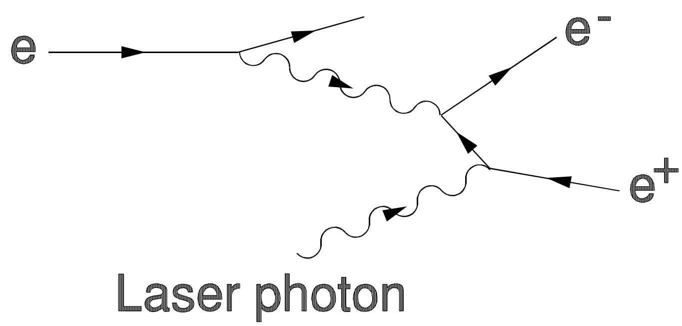
$\omega_{\rm max} \approx 29$ GeV for 46.6-GeV electrons + $(n = 1)$ green laser.

Then need at least $n = 4$ laser photons to produce a pair.

$\Leftrightarrow$ Below threshold for 2-photon pair creation.

Trident Production

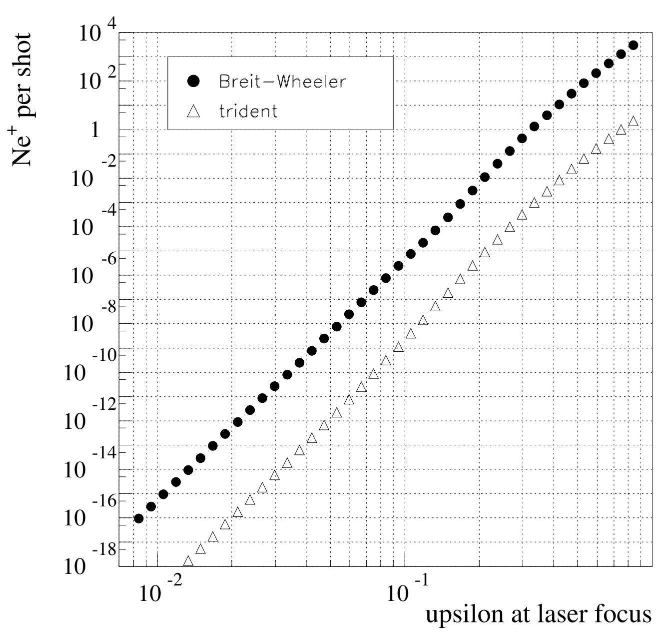
$$e + n\omega_0 \rightarrow e'e^+e^-$$



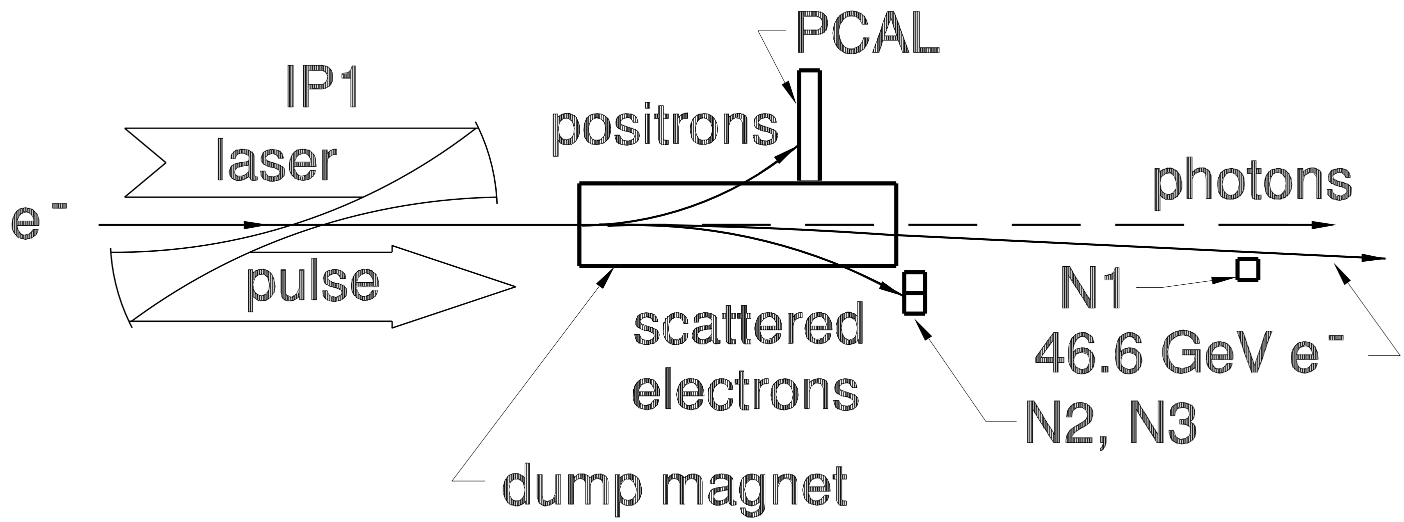
Background when scattering occurs in presence of electron beam.

Theory only approximate: Weizsäcker-Williams + multiphoton Breit-Wheeler.

Predicted to have rate only 1% that of the two-step process.



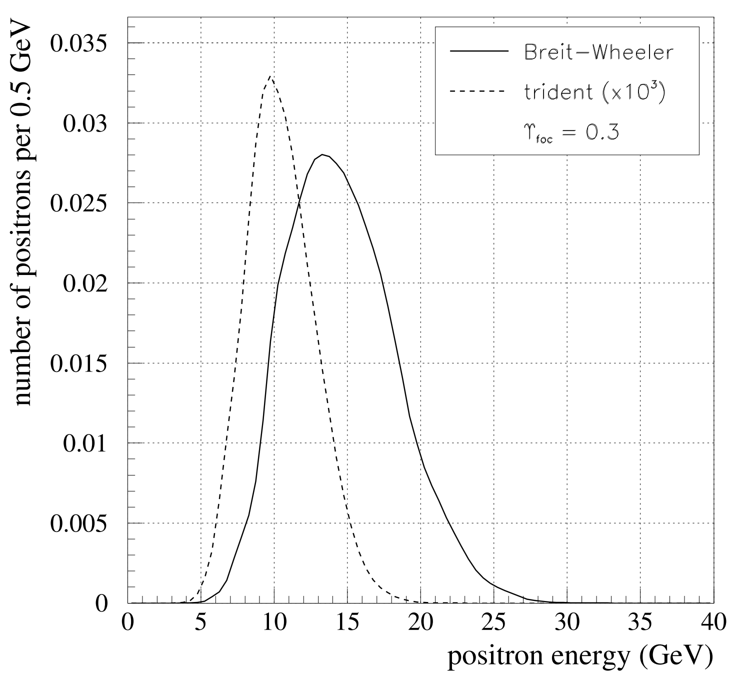
Positrons from e-Laser Interaction Region



$\approx 10^7$ electrons per laser shot from Compton scattering,

$\Rightarrow$ Only detect e^+ from e^+e^- pair.

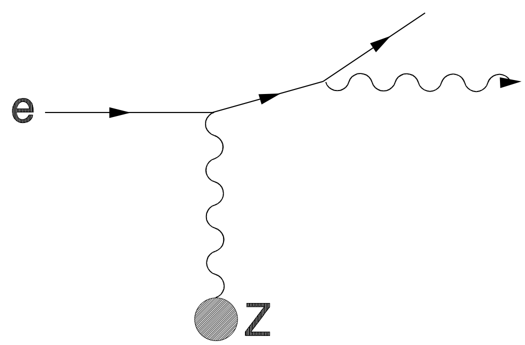
Predicted positron spectra:



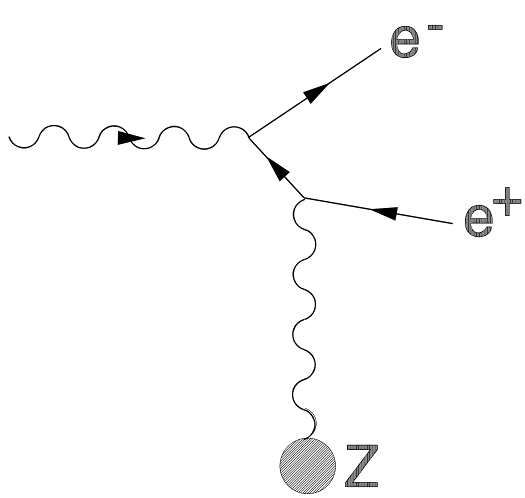
Laser-Off Positron Backgrounds

Laser-off positrons are from showers caused by electrons that have fallen out of the beam.

1. Bremsstrahlung.



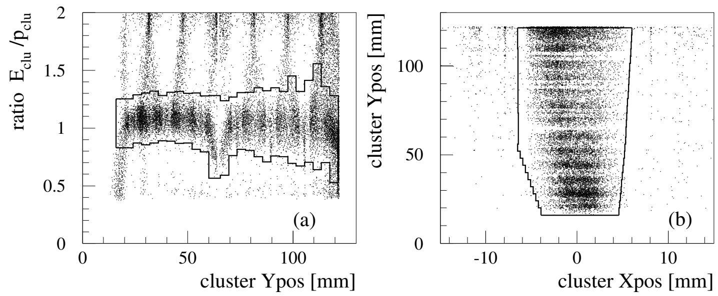
2. Bethe-Heitler pair creation.



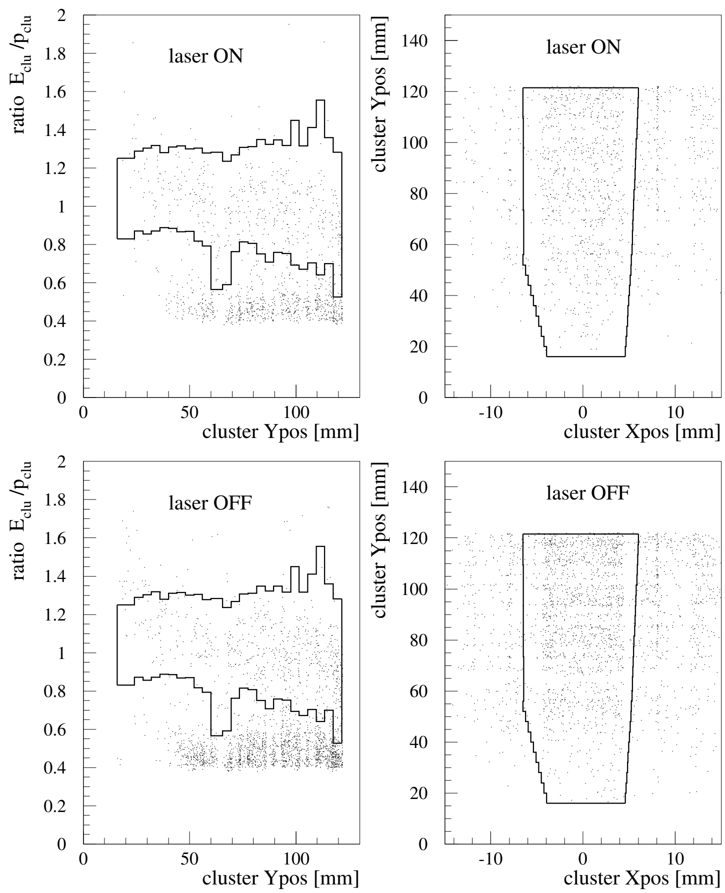
Study with data collected with laser off but electron beam on.

Signal Processing

1. 'Signal' positrons from a wire at IP1 (no laser)



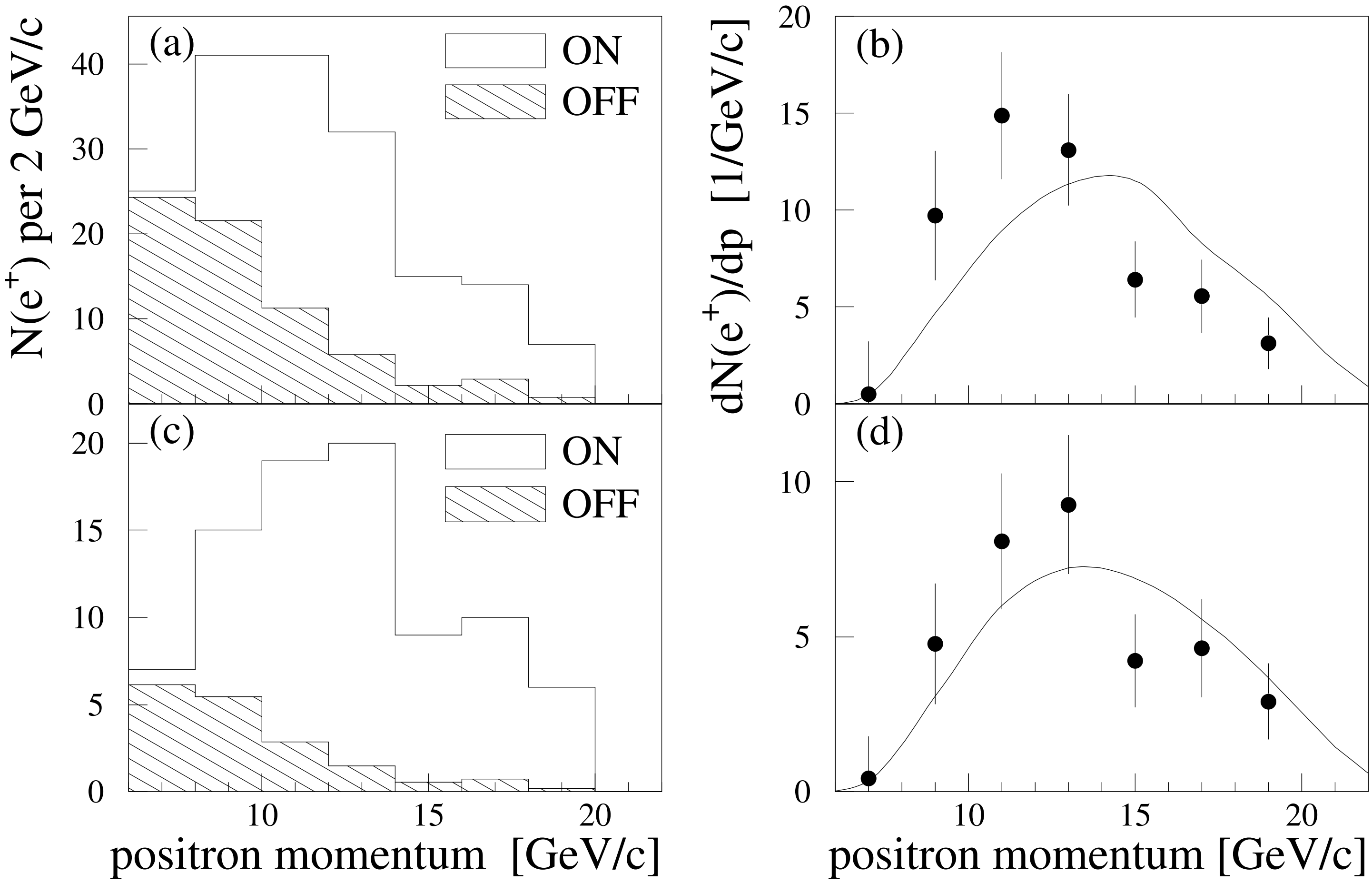
2. Define signal region for laser-on and -off data.



Evidence for Positron Production (August '96)

178 laser-on candidates - 0.175 $\times$ 398 laser-off candidates,

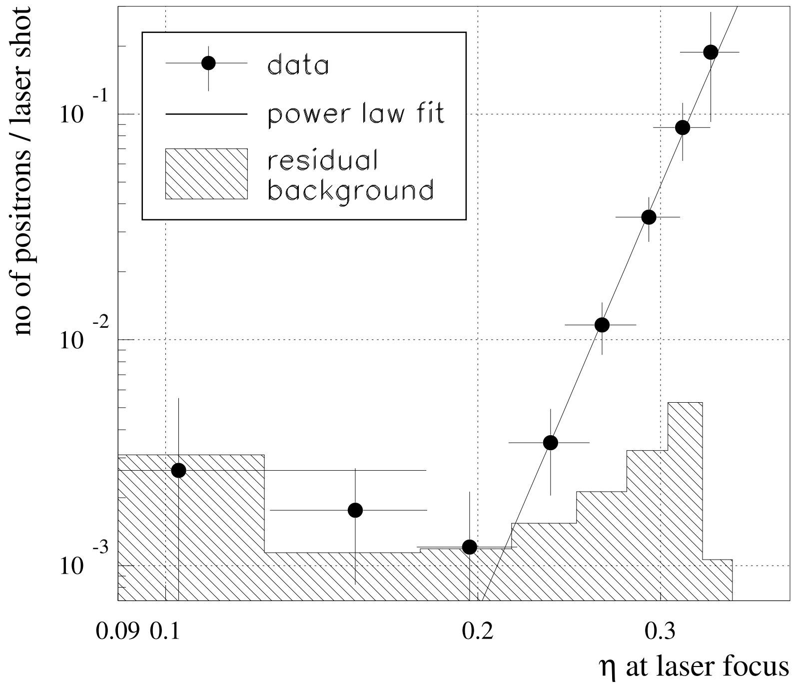
$\Rightarrow$ 106 $\pm$ 14 signal positrons (upper plots, no η cut)



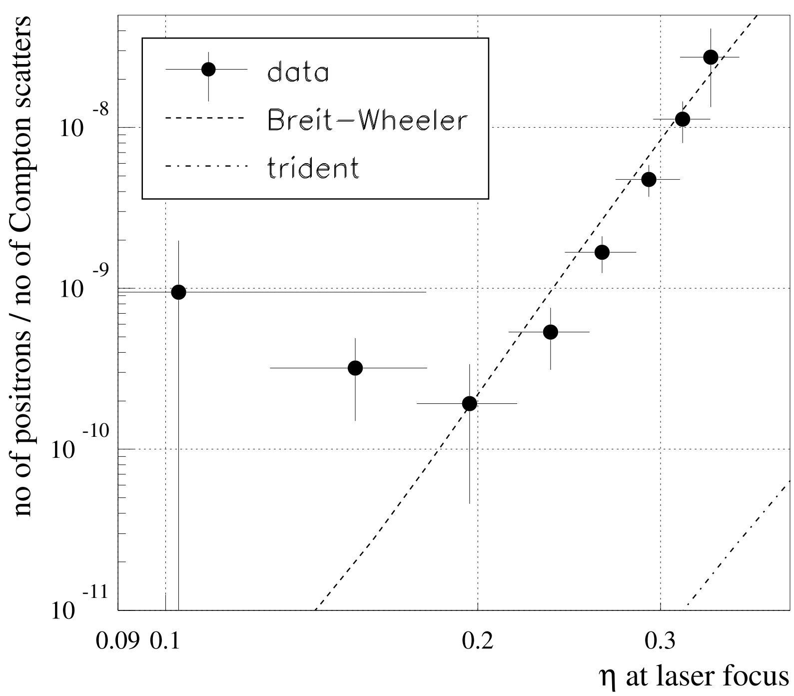
Lower plots: $\eta > 0.216 \Rightarrow 69 \pm 9$ signal positrons.

Positron Rate *vs.* η

Rate $\propto \eta^{2n}$ where $n = 5.1 \pm 0.2$ (stat.) $^{+0.5}_{-0.8}$ (syst.):



Normalized to Compton scattering rate:



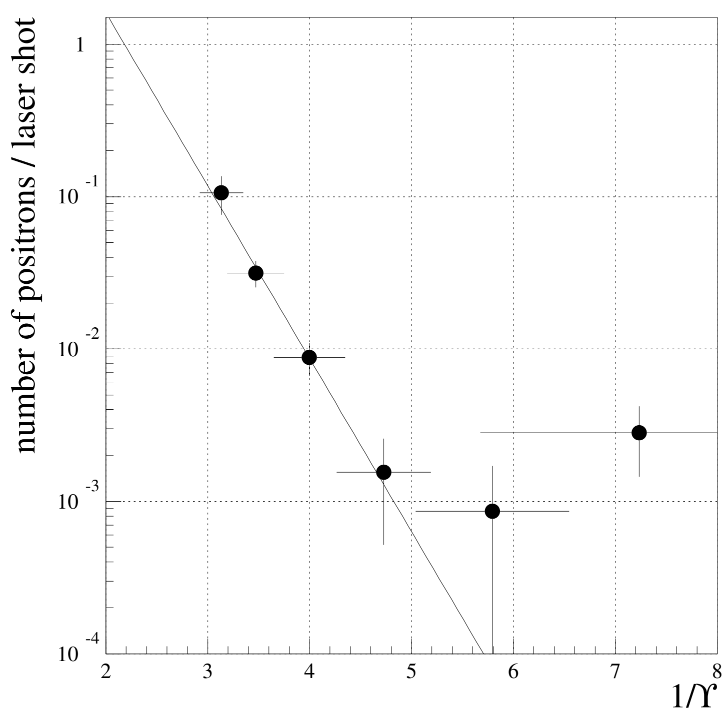
Strong Field Pair Creation as Barrier Penetration

For a virtual e^+e^- pair to materialize in a field E the electron and positron must separate by distance d sufficient to extract energy $2mc^2$ from the field:

$$eEd = 2mc^2.$$

The probability of a separation d arising as a quantum fluctuation is related to penetration through a barrier of thickness d:

$$P \propto \exp\left(-\frac{2d}{\lambda_C}\right) = \exp\left(-\frac{4m^2c^3}{e\hbar E}\right) = \exp\left(-\frac{4E_{\text{crit}}}{E}\right) = \exp\left(-\frac{4}{\Upsilon}\right).$$



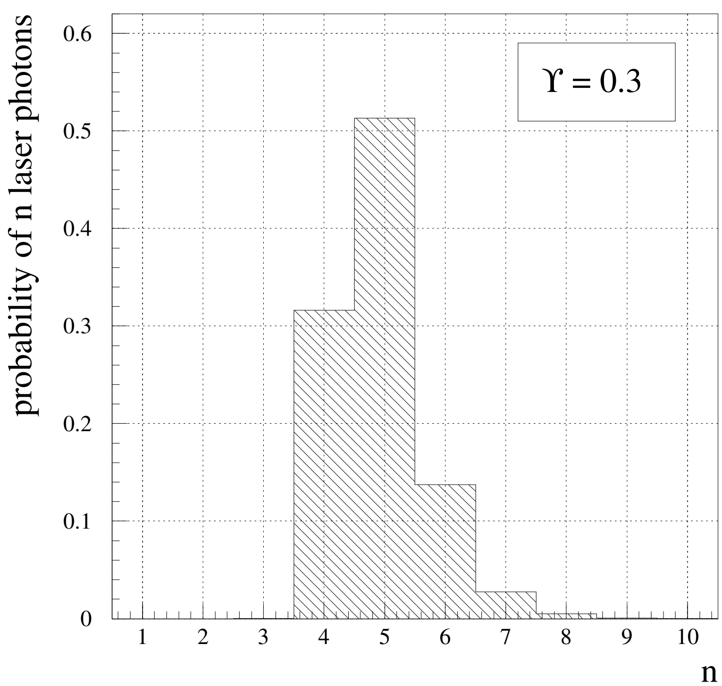
$$R_{e^+} \propto \exp[(-2.8 \pm 0.2\,(\text{stat.}) \pm 0.2\,(\text{syst.}))/\Upsilon].$$

Comments on Positron Observations

Signal rate ≈ 1 positron per 10 e-laser collisions at highest Υ.

The laser-induced positrons are $> 99\%$ from light-by-light scattering and $< 1\%$ from trident production.

In $n\omega_0 + \omega \to e^+e^-$ the average number n of laser photons is 5 (plus 1 more to produce the high-energy photon by Compton backscattering).



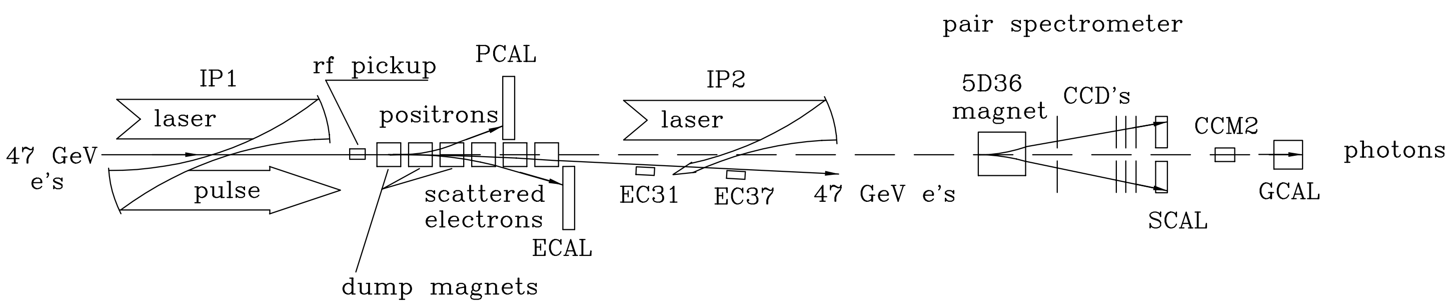
This is the first observation of positron production in light-by-light scattering with only real photons.

To Do: Basic Physics

1. Study the mass-shift effect in nonlinear Compton scattering.

   - Continue at SLAC, or use 50-Mev electrons and CO_2 laser at BNL.

2. Study pair creation in a pure light-by-light scattering situation:



   - No trident production.
   - Search for structure in the e^+e^- invariant-mass spectrum.
   - Upgrade laser to 10-Hz, 100-femtosecond pulses with $\Upsilon_{\max} \approx 5$.

To Do: Applied Physics

1. Copious e^+e^- Production.
   - e^+e^- pairs from e-laser collisions could be best low-emittance source of positrons.
   - No Coulomb scattering in laser 'target.'
   - Positrons largely preserve the geometric emittance of the electron beam $\Rightarrow$ 'cooling' of invariant emittance.
   - Can produce 1 positron per electron if $E^\star > E_{\rm crit}$.
   - Production with visible laser is optimal for $\sim$ 500 GeV electrons.

     [Or use a 50-nm FEL with 50-GeV electrons.]
2. High-energy e-γ and γ-γ colliders.
   - e-laser scattering can convert essentially all of an electron beam to a photon beam.
3. Picosecond/femtosecond pulsed-γ sources from Compton backscattering.