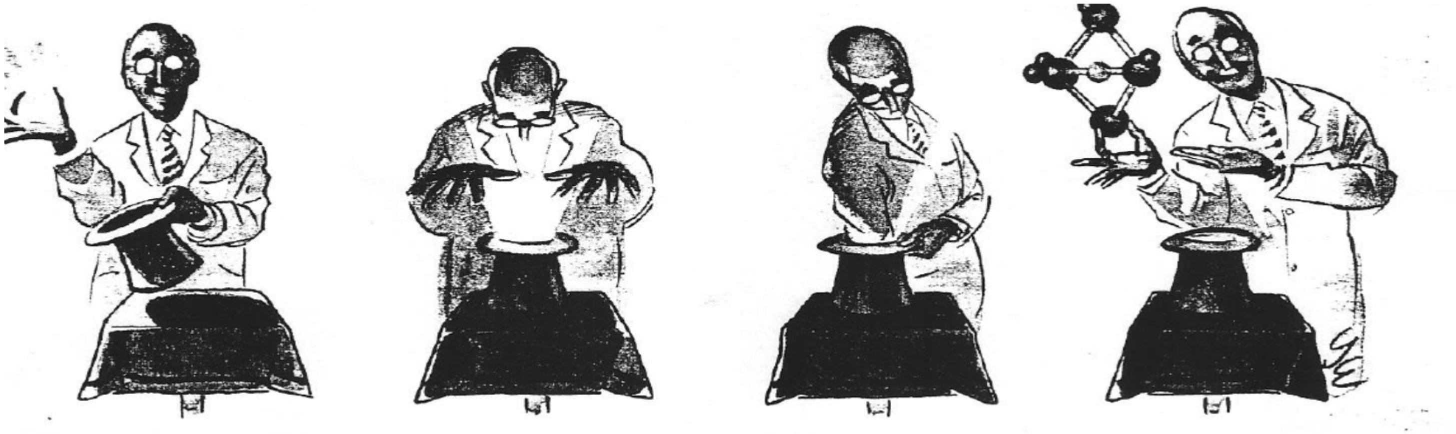
Kirk conjures Matter from Light



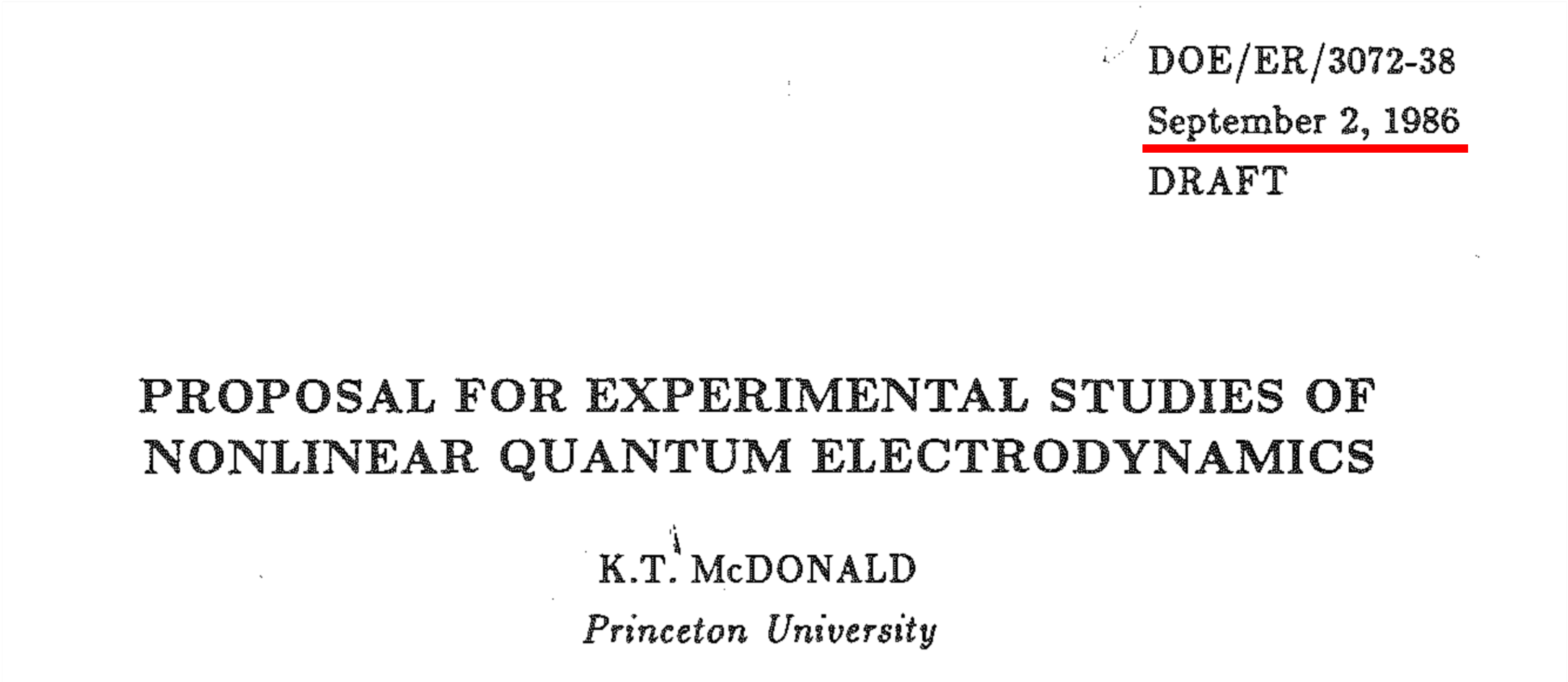
Pair creation in photon-photon inelastic scattering

Princeton - Rochester - SLAC – Tennessee

June 17, 2016

D.L. Burke *et al.*, PRL 79. 1626 (1997)
C. Bamber *et al.*, Phys. Rev. D 60, 090024 (1999)

How it all started

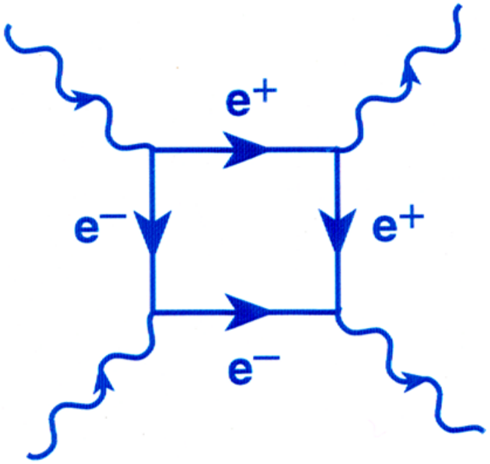


DOE/ER/3072-38
September 2, 1986
DRAFT

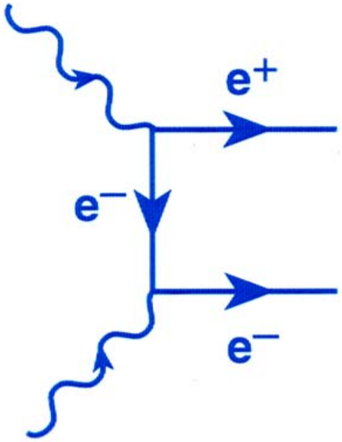
PROPOSAL FOR EXPERIMENTAL STUDIES OF NONLINEAR QUANTUM ELECTRODYNAMICS

K.T. McDONALD
Princeton University

The Physics of photon-photon scattering

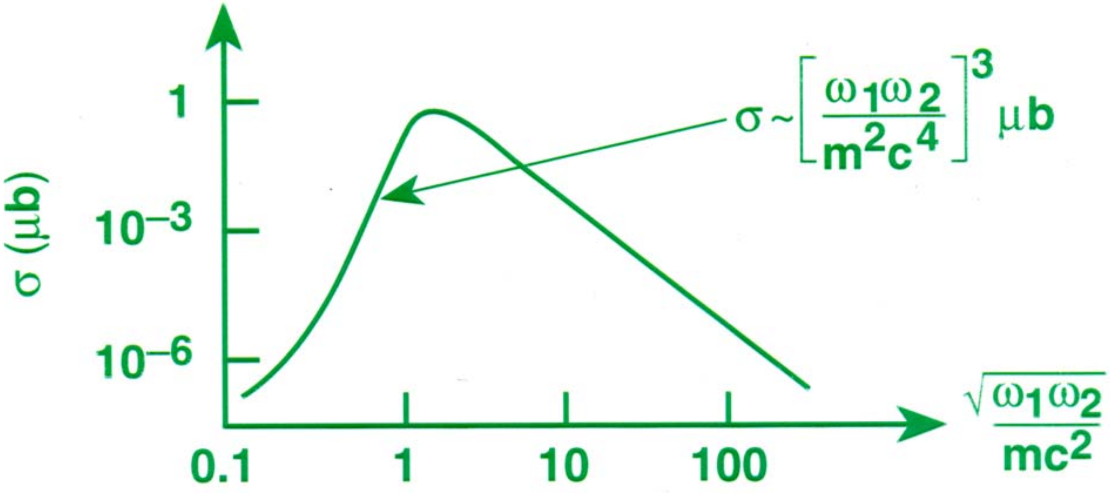


Delbrück



Breit–Wheeler

$4\omega_1\omega_2 > (2mc)^2$



Need High Energy Photons: obtain by backscattering the laser photons from highly relativistic electrons

ω = incident photon frequency $\hbar\omega = 2.34$ eV

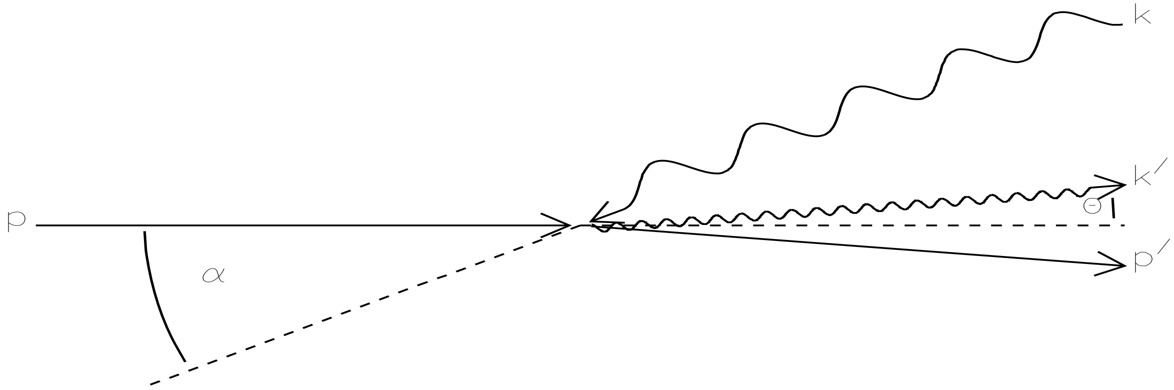
ω' = scattered photon frequency $\hbar\omega' = 27$ GeV

$\gamma = E_e/mc^2$ normalized electron energy 9×10^4

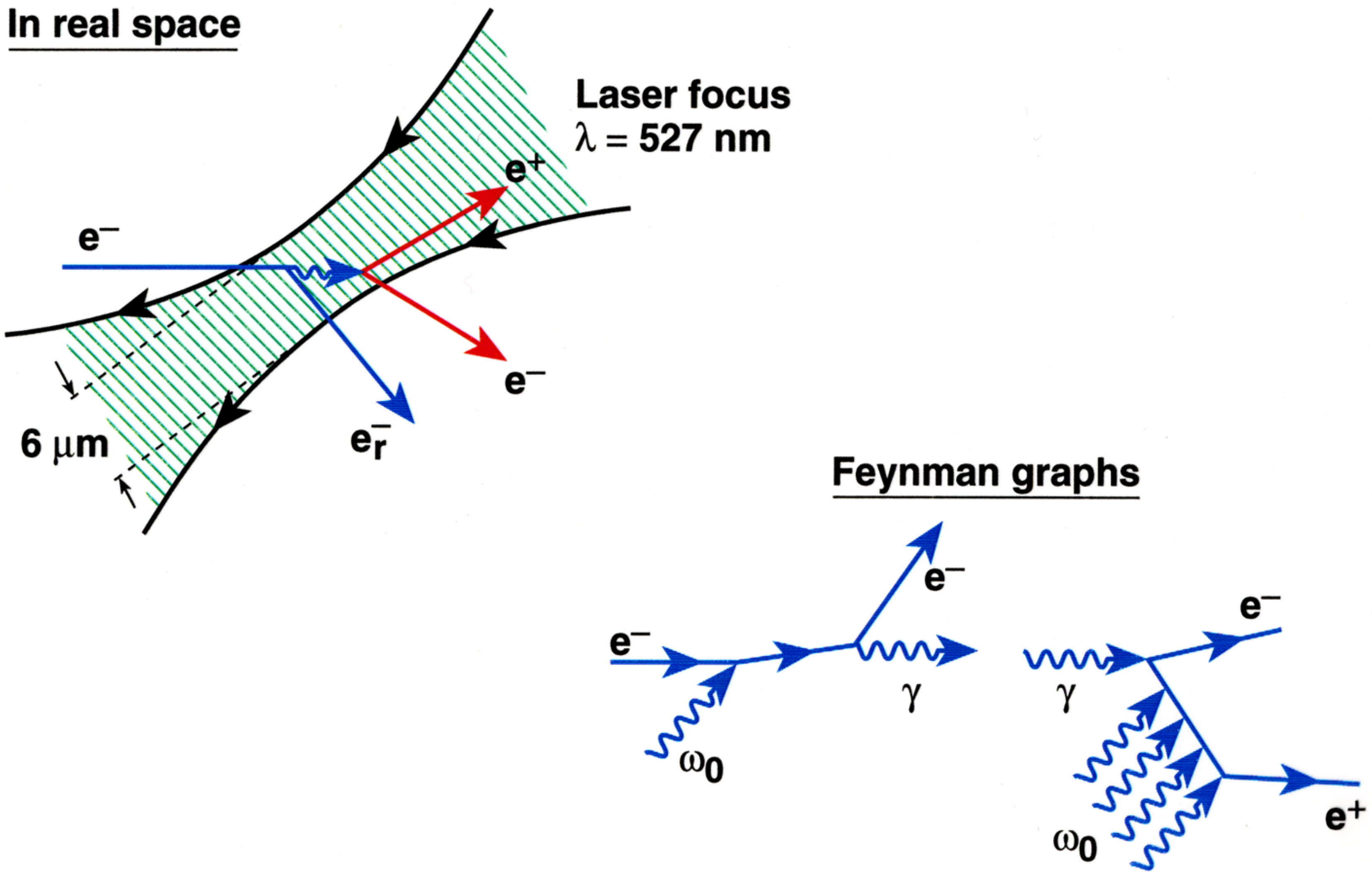
$$\omega'_{max} = 4\gamma^2\omega/[1 + 4\gamma\hbar\omega/mc^2] \approx 27 \text{ GeV}$$

In these conditions the recoil term, $2\gamma\hbar\omega/mc^2 \approx 1$

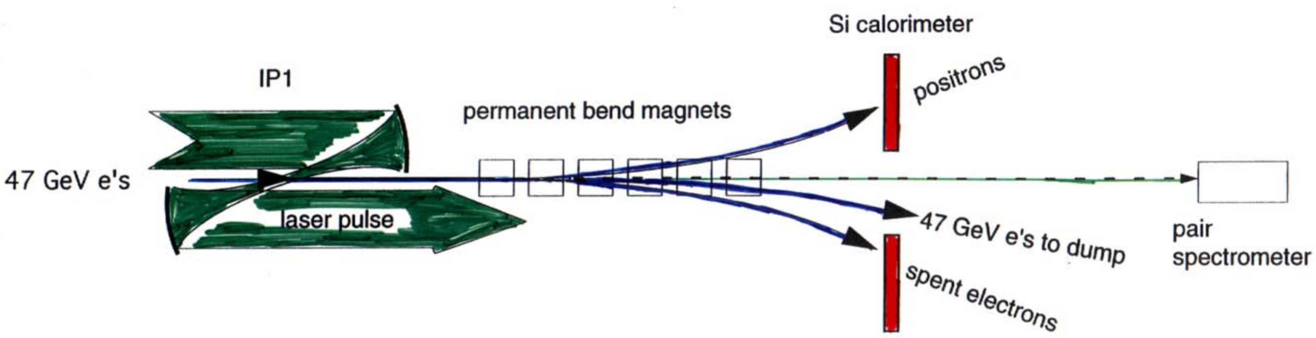
therefore we speak of Compton scattering

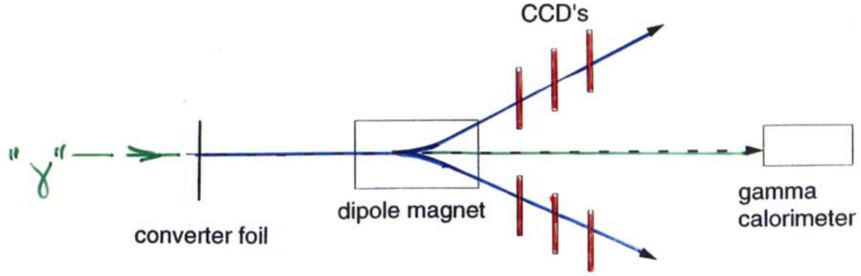


Experiment to demonstrate the nonlinear properties of the vacuum

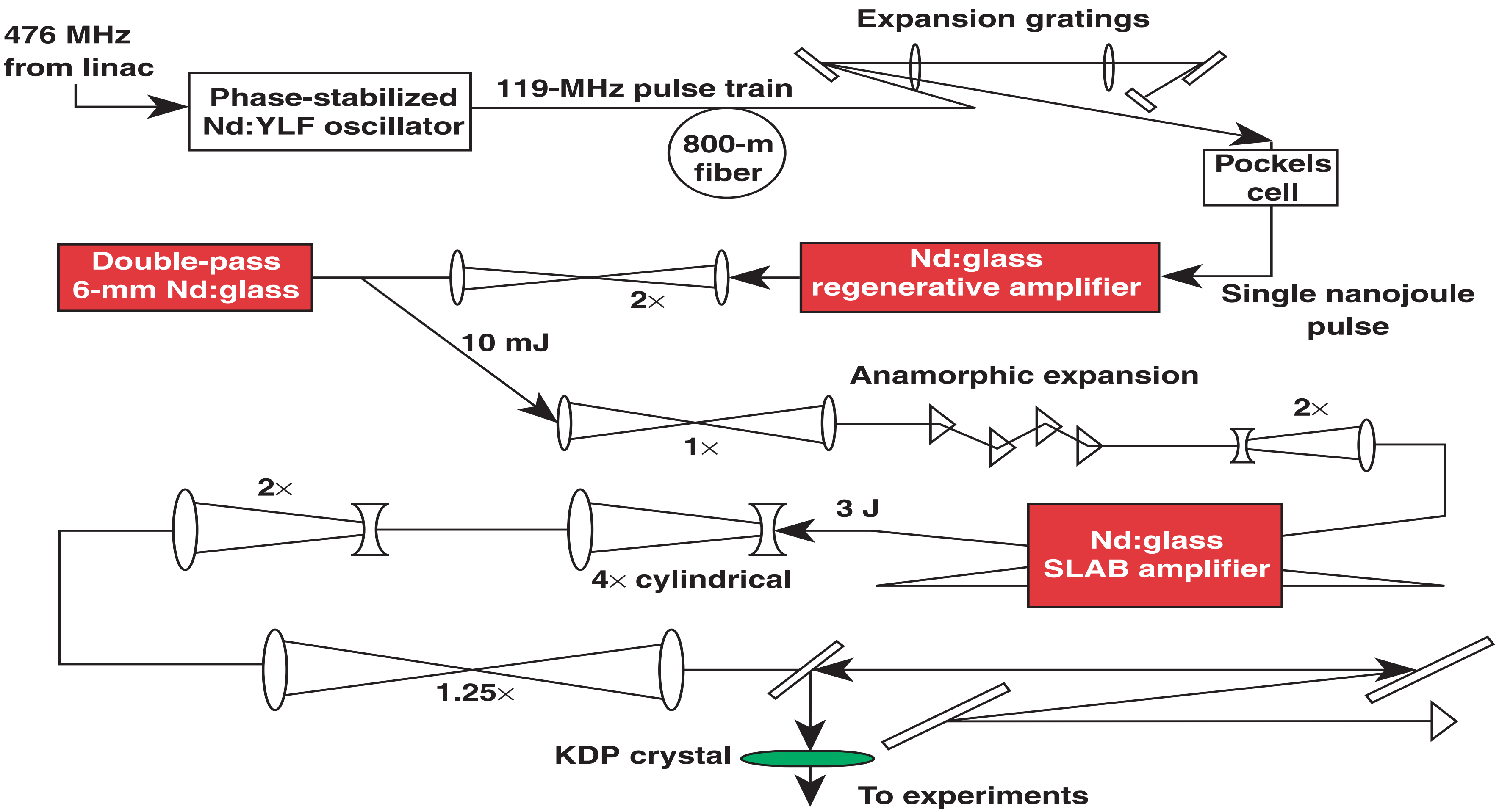


LAYOUT OF THE EXPERIMENT





THE LASER SYSTEM



LASER PULSE PARAMETERS

$\lambda = 527$ nm → $\hbar\omega = 2.34$ eV

$U = 1$ J $\quad \tau_{FWHM} = 1.7\times10^{-12}$ s $\quad$ Area = 30 μm^2

Derived properties

Terawatt laser

Power = 0.6×10^{12} W $\quad$ Intensity = 2×10^{18} W/cm^2

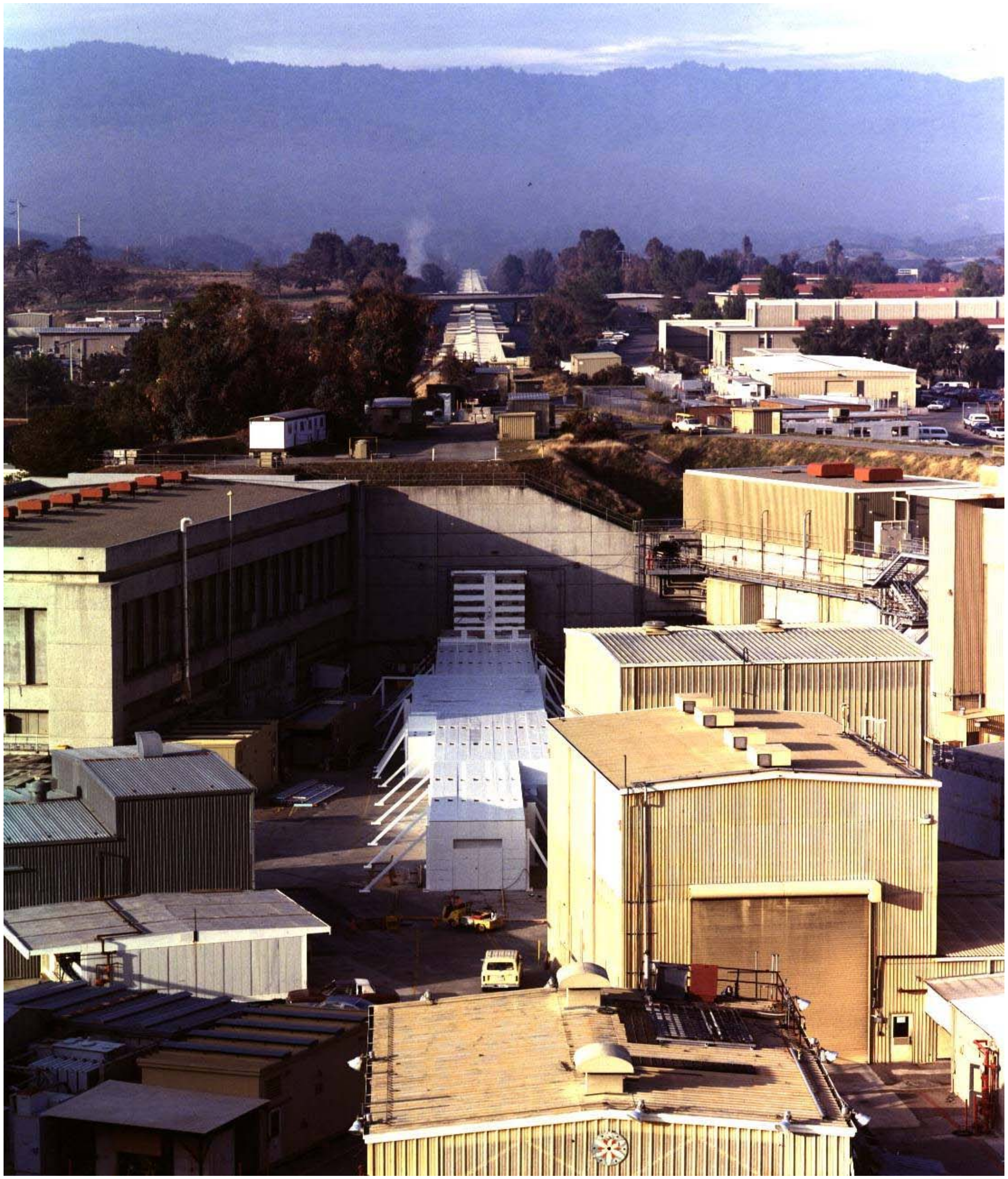
$E = 3.9\times10^{10}$ V/cm $\quad \rho = 1.8\times10^{26}$ photons/cm^3 !

ELECTRON BEAM PARAMETERS

$E_e = 46.6$ GeV $\quad N = 5\times10^9$ electrons/pulse

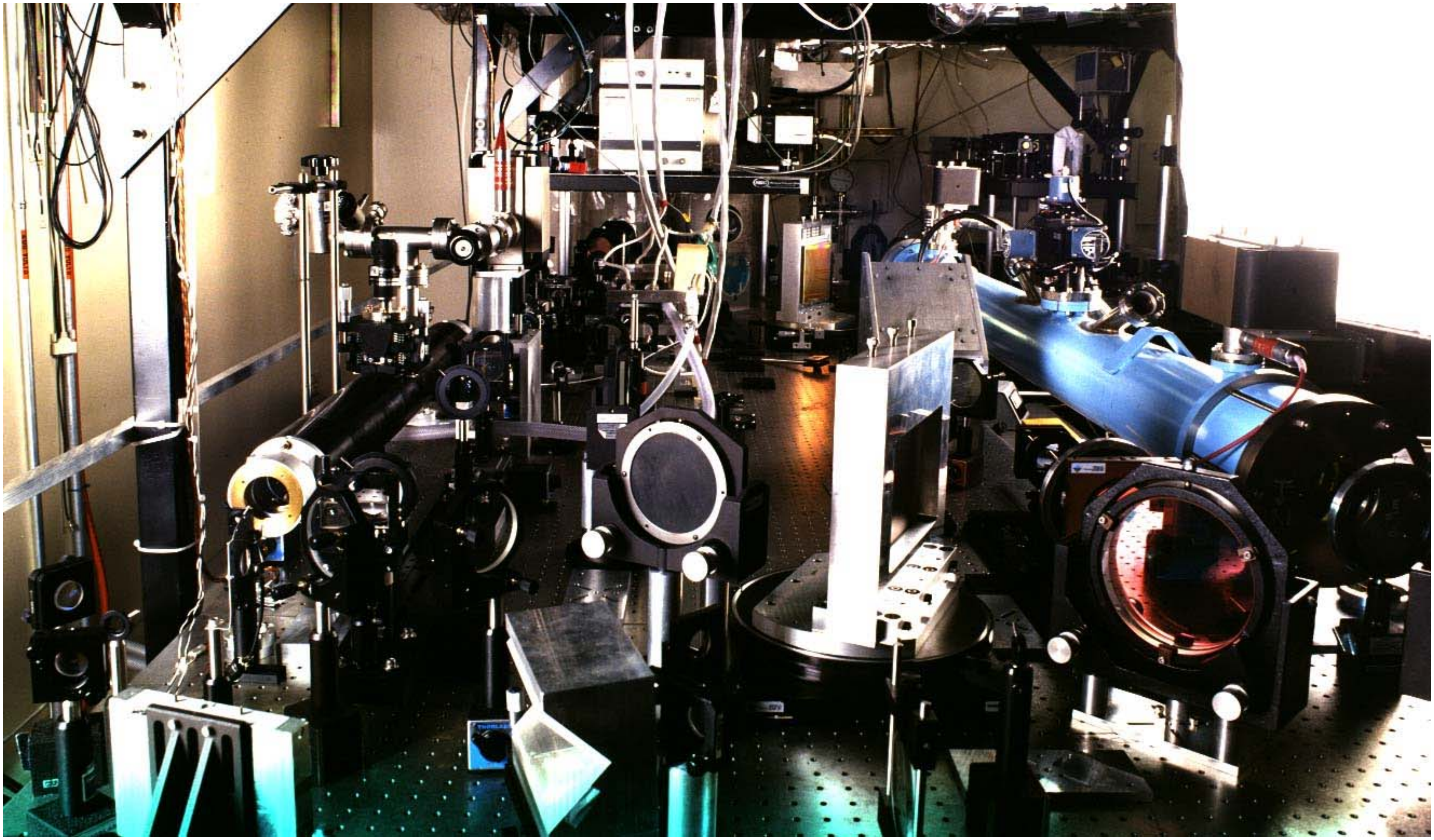
$\sigma_x = \sigma_y = 60$ μm $\quad \sigma_z = 0.5$ mm → $\tau_{FWHM} = 4$ ps

Final Focus Test Beam in the SLAC Switchyard

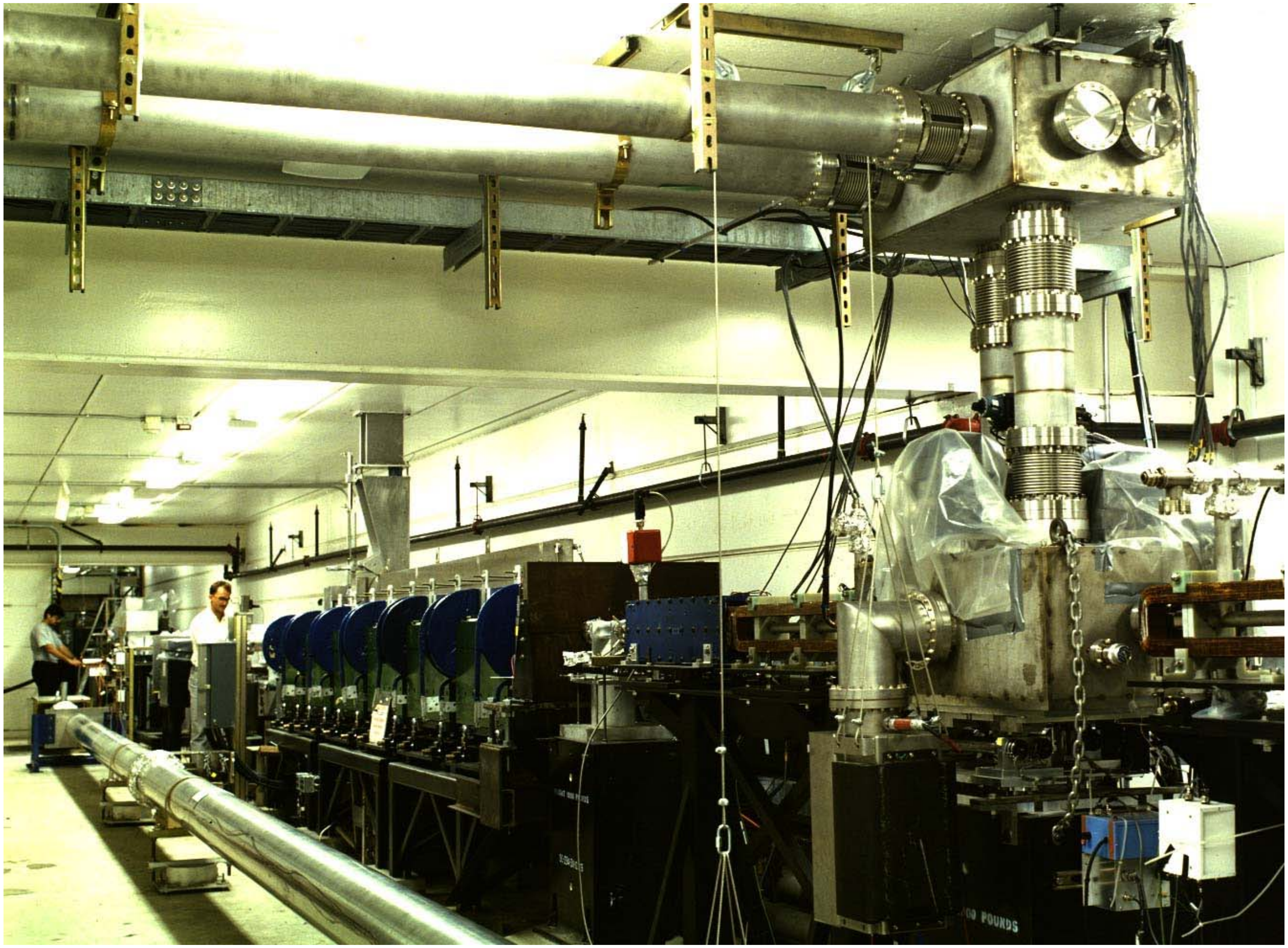


LAST STAGE OF THE LASER SYSTEM

Slab amplifier and compression gratings

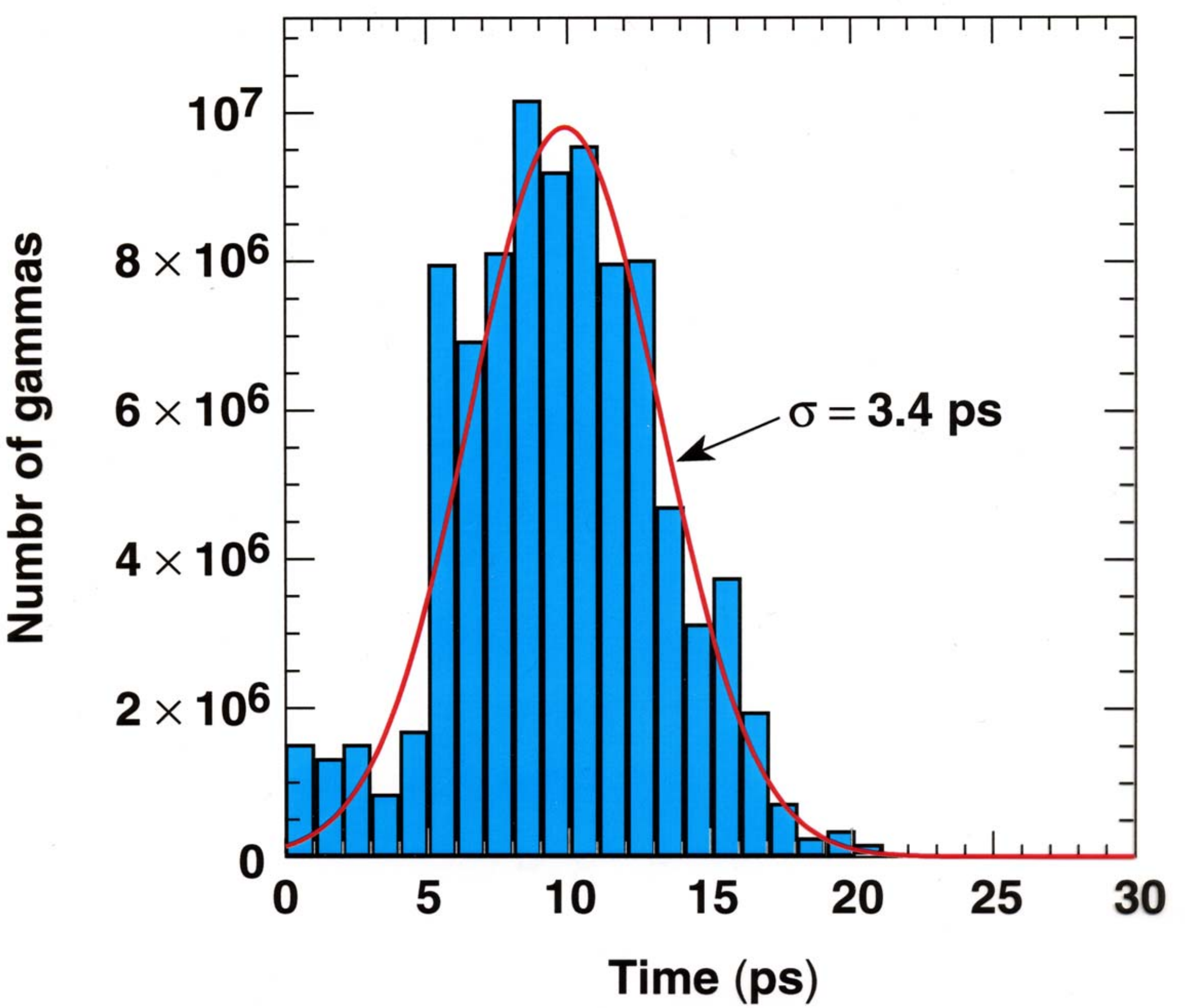


THE ELECTRON BEAM LINE and the LASER–e^- INTERACTION CHAMBER

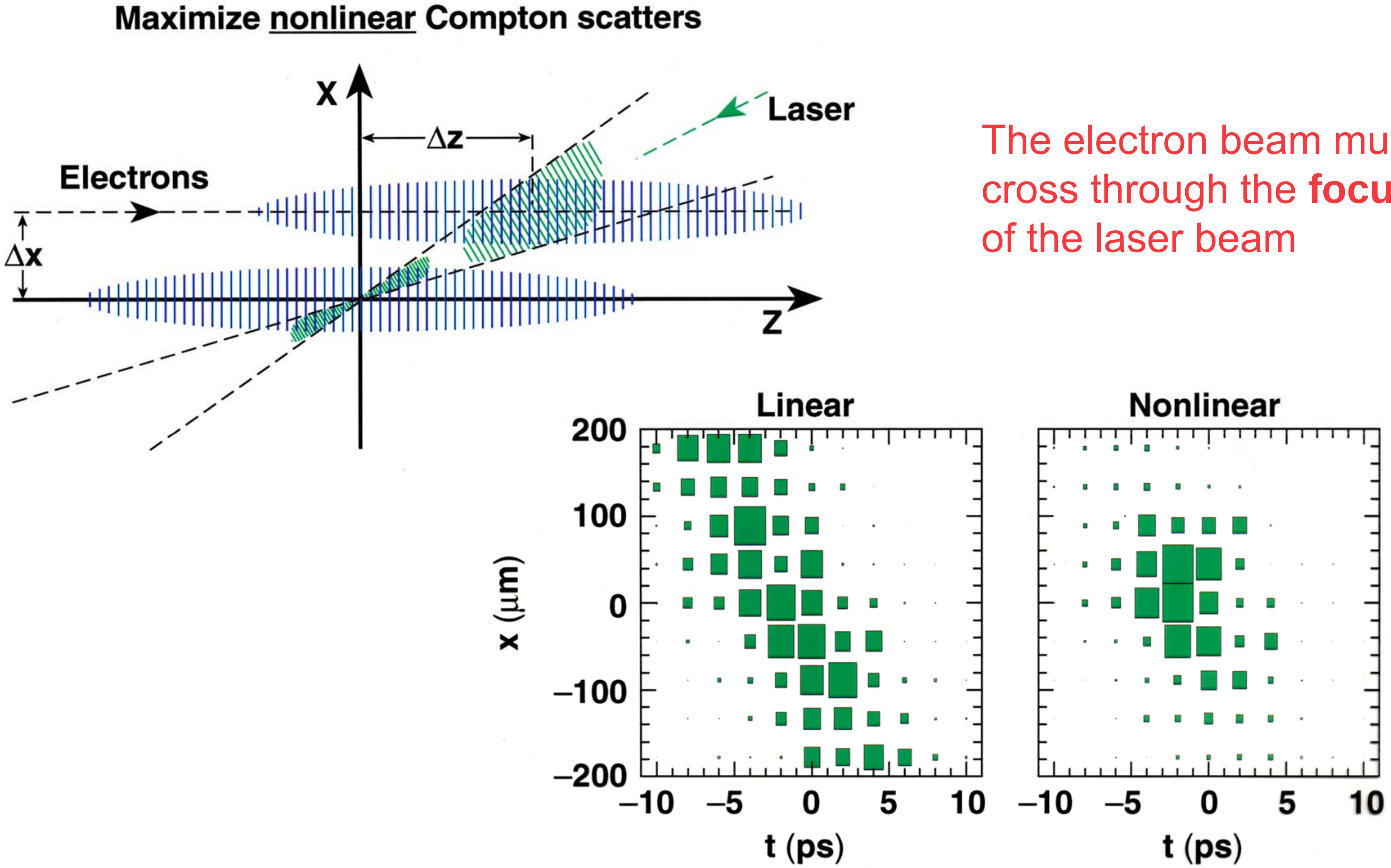


Overlap in time (synchronization) of LASER and ELECTRON pulses

- **Use a subharmonic of the accelerator frequency (2856 MHz) to drive the laser modelocker (119 MHz).**

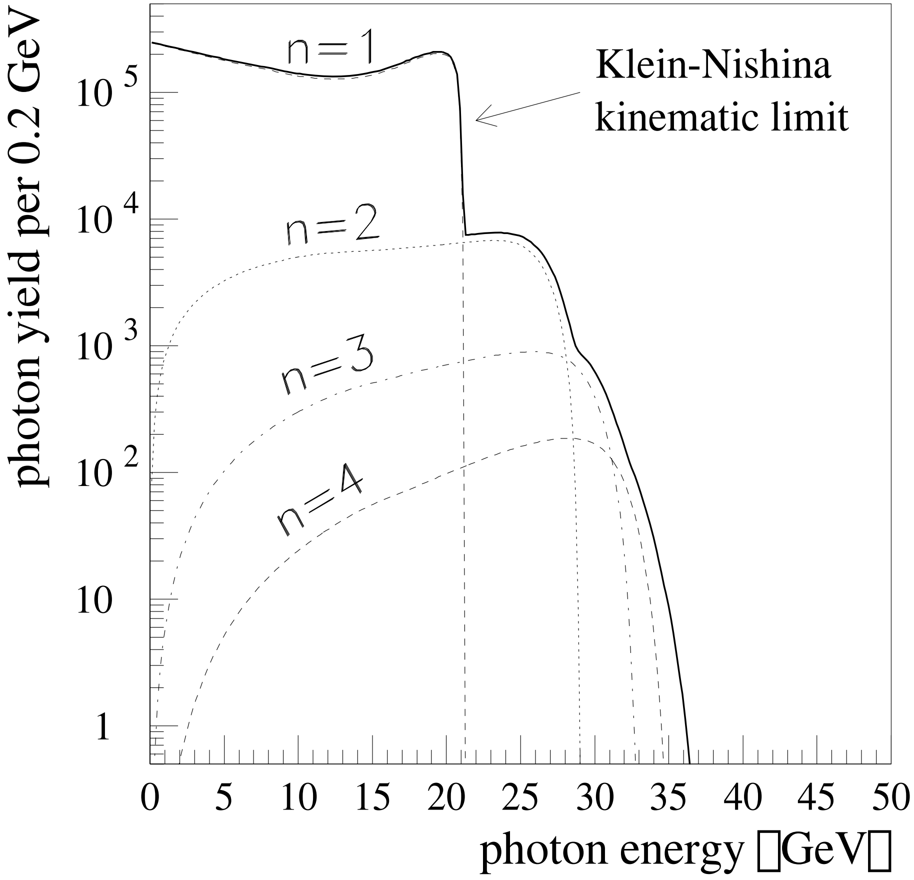


Overlap in space of LASER FOCUS and ELECTRON pulses

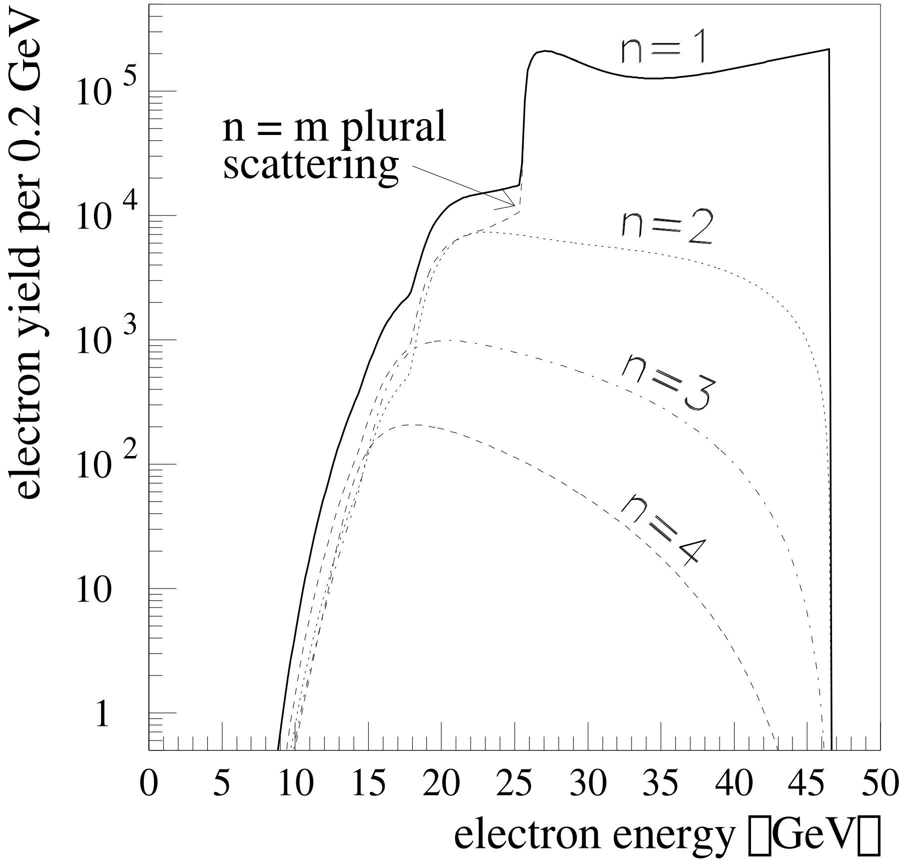


The electron beam must cross through the **focus** of the laser beam

Non linear (multiphoton) Compton Scattering
n is the number of photons absorbed
The plots are for incident IR laser λ = 1054 nm

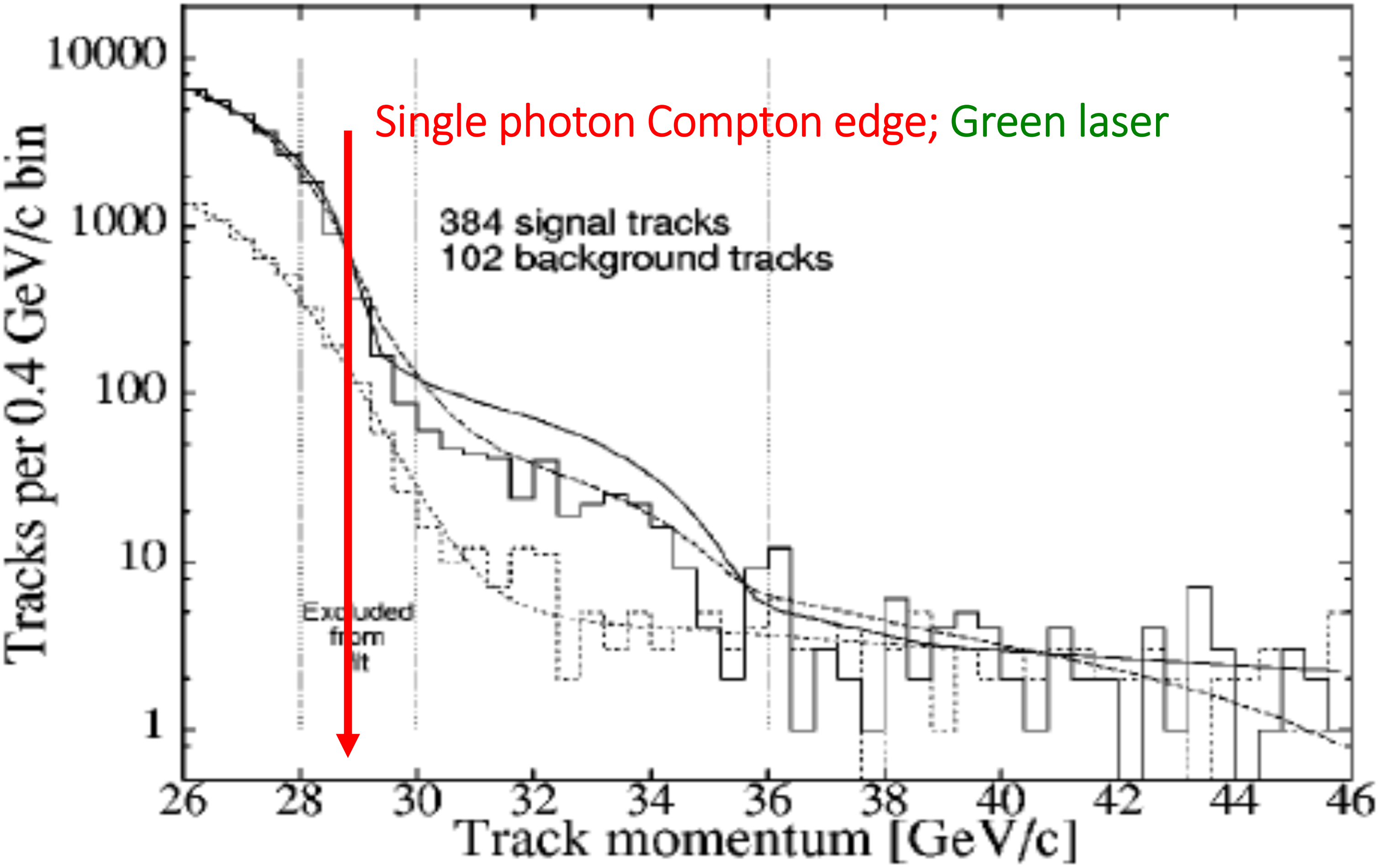


Photon energy in GeV, for IR laser



Electron energy in GeV, for IR laser

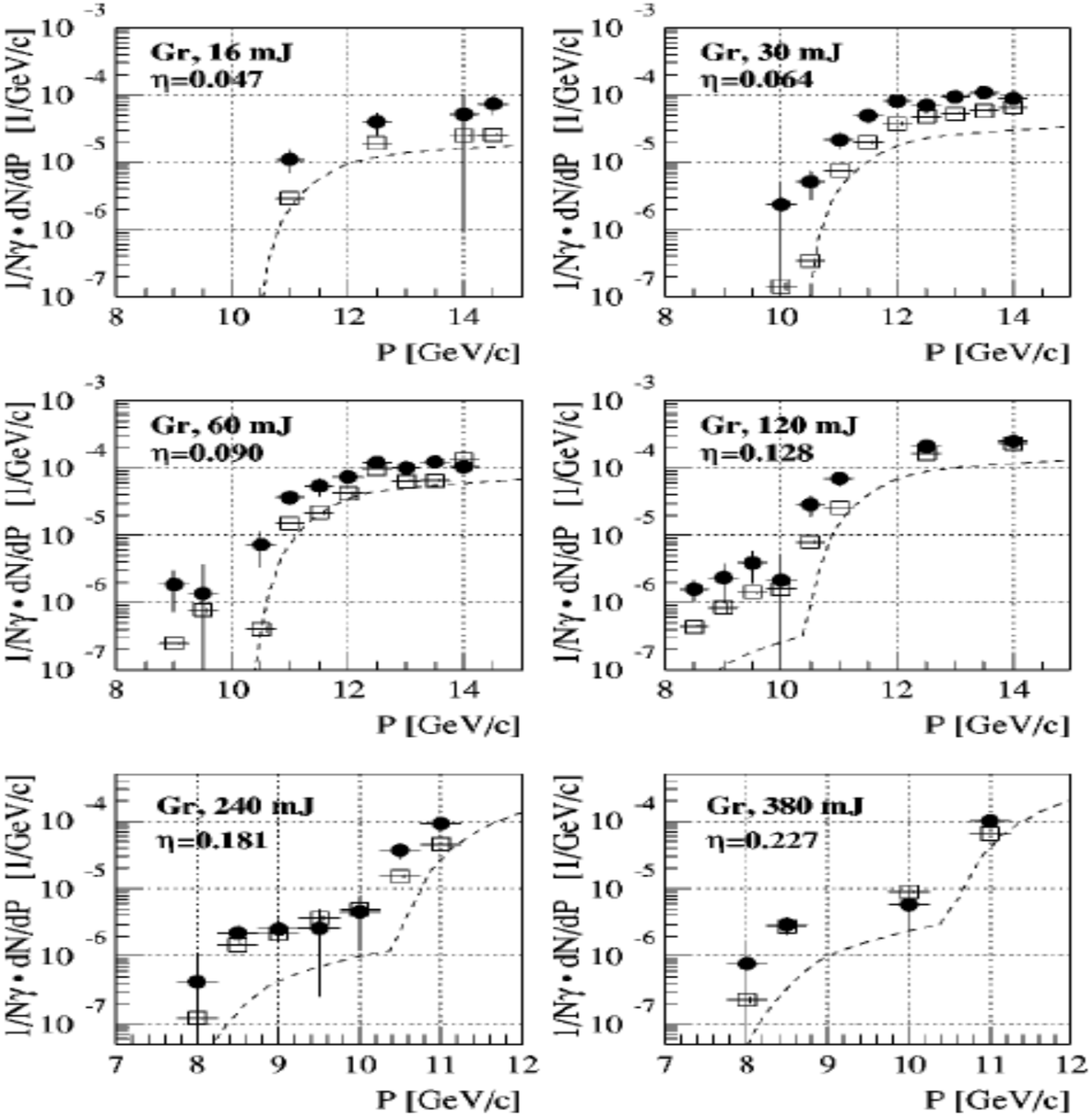
Forward going γ-rays measured in CCD pair spectrometer extend **beyond** the single photon Compton limit



Recoil electrons measured in the *e*-calorimeter extend **below** the single photon Compton limit of 17.6 GeV for green laser

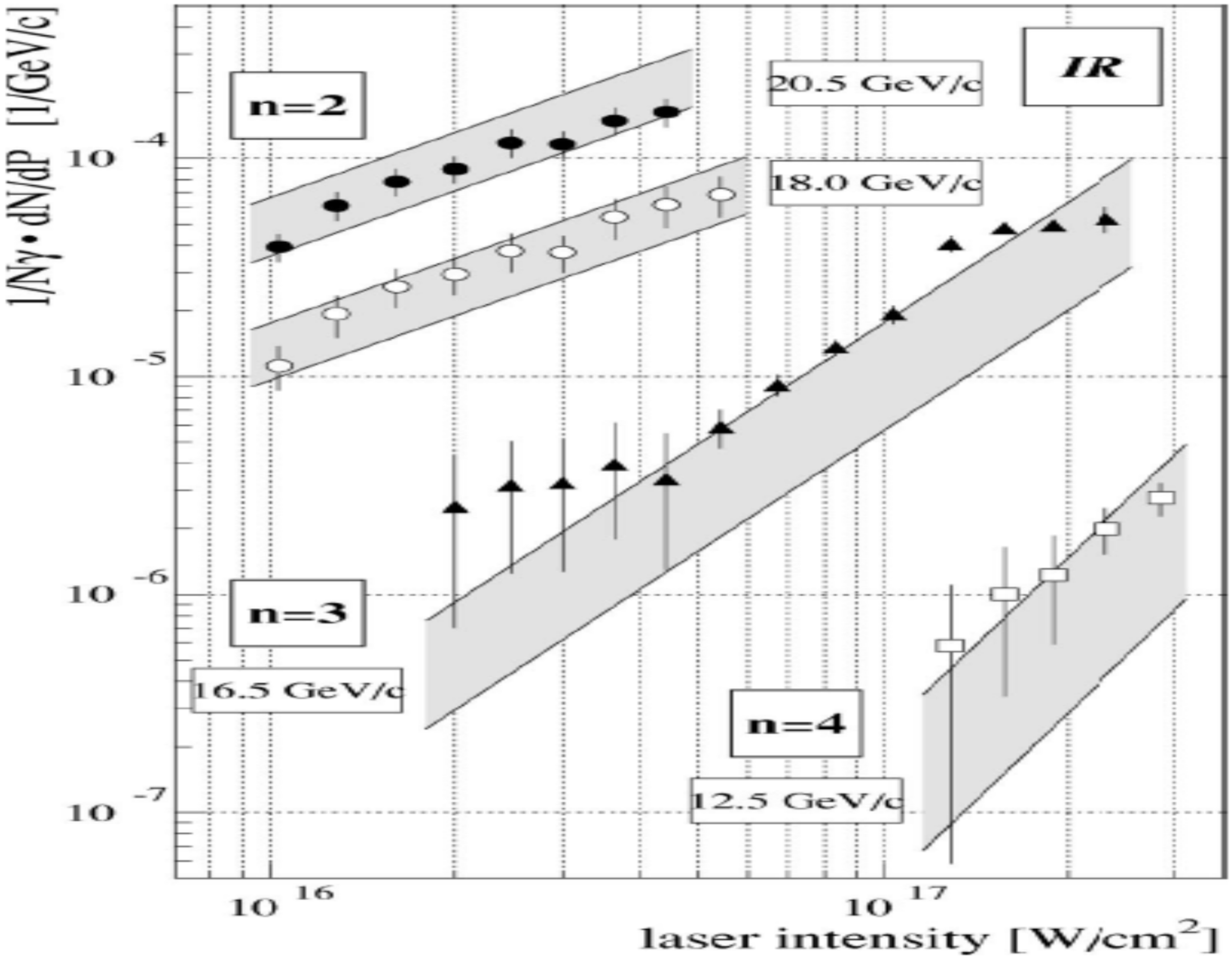
n=2 plateau

n=3 plateau



Dashed curves are for "plural scattering"

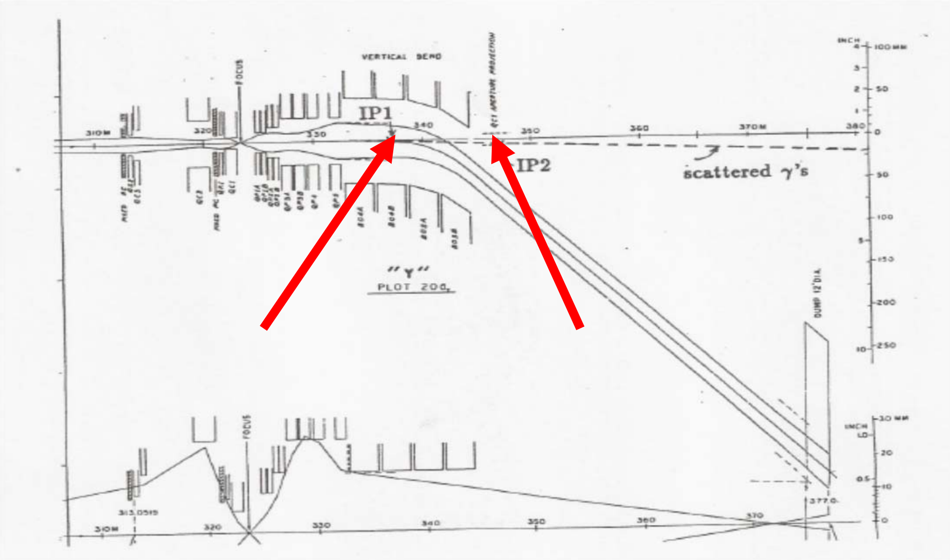
Scattered electron yield as a function of laser intensity (1/N)dN/dp proportional to (Intensity)$^{n-1}$



Serendipity

In the proposal we planned to use two interaction regions: the first to produce the high energy γ, and the second for the γ to collide with the laser beam… Of course, the γ collides within the same laser pulse in which it is produced… and it suffices to detect the positron to establish the production of a pair !!

The original scheme was technically too challenging to have worked!!



The beam trace after the FFT final focus. The vertical dimensions are amplified by a factor of 100.

Note the location of the two proposed interaction regions, IP1 and IP2.

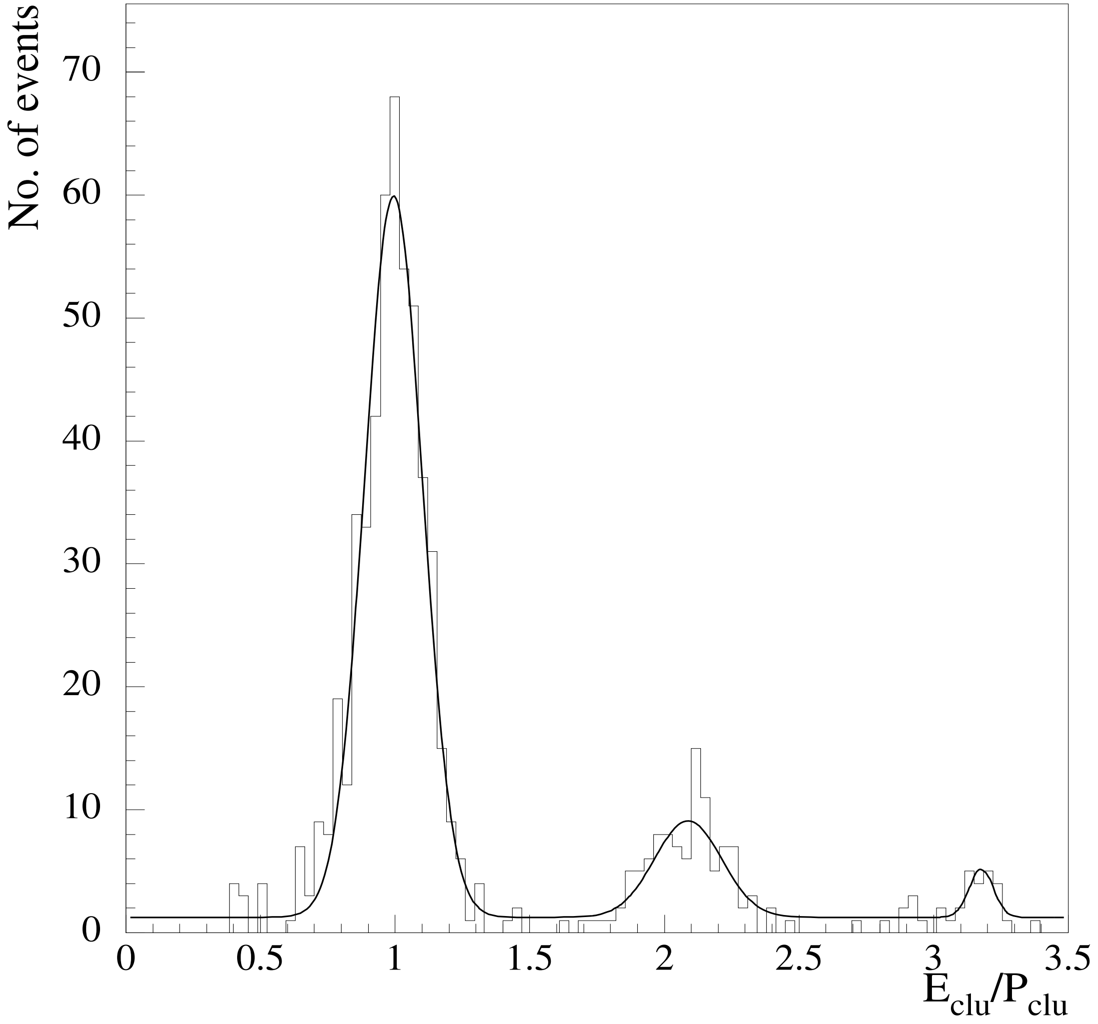
IDENTIFICATION OF POSITRONS

Measure energy in calorimeter cluster $E_{cluster}$

Measure momentum from impact position $p_{cluster}$

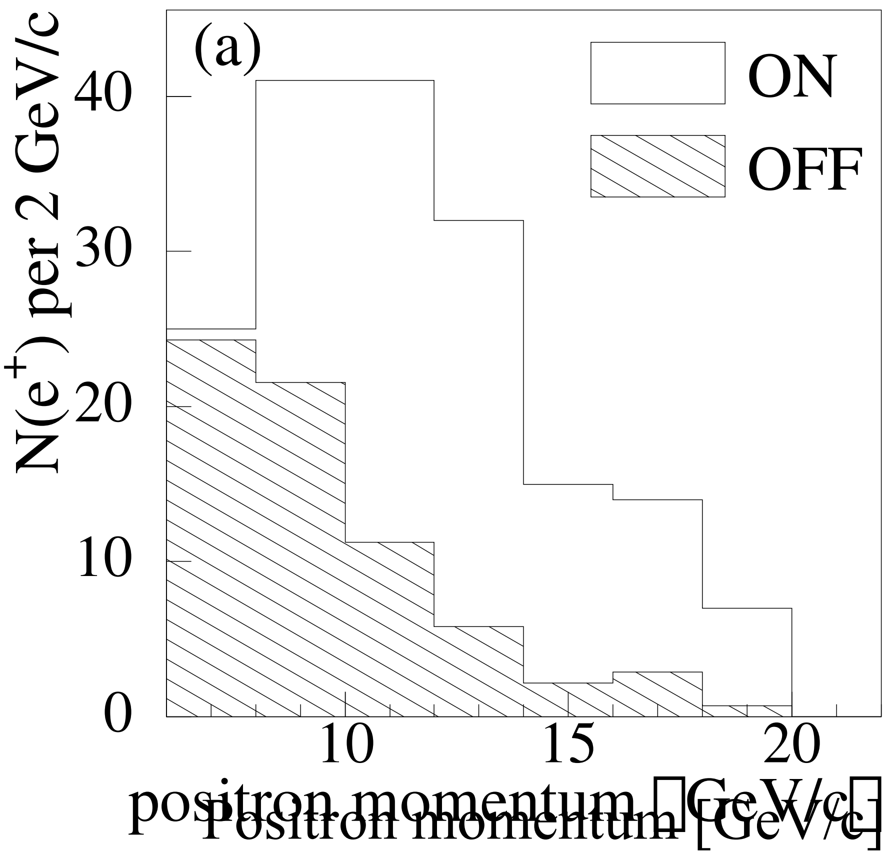
For positrons (no multiple hits) $E_{cluster}/p_{cluster} = 1$

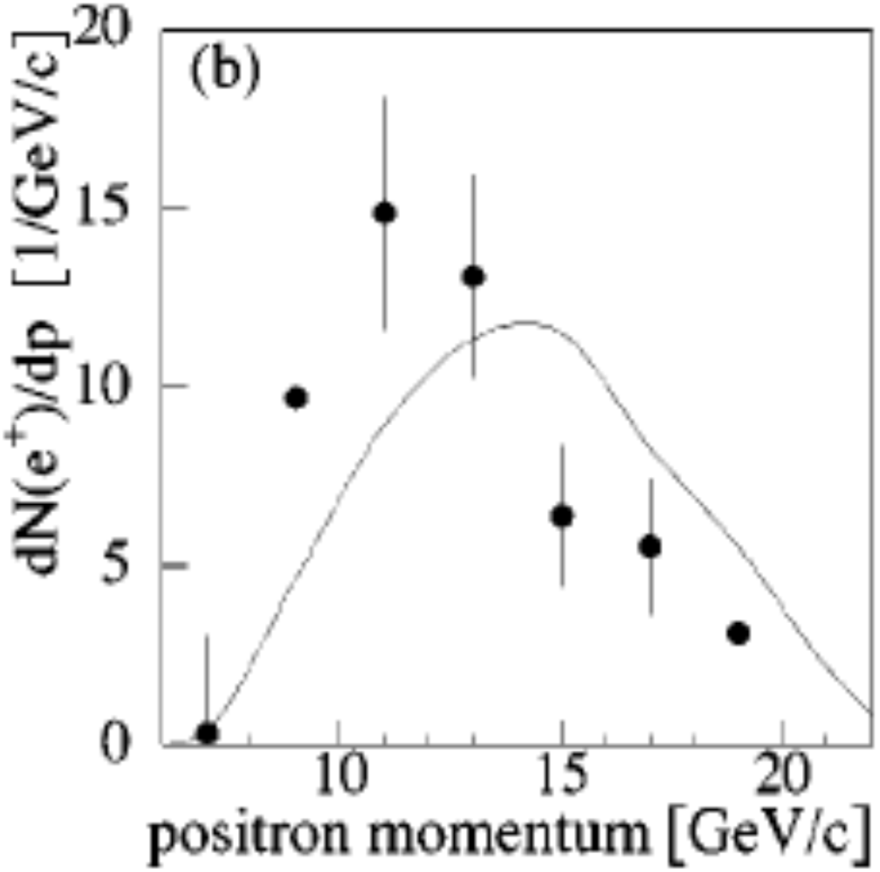
Test data obtained by inserting a thin wire instead of the laser at the focus



Spectrum of observed positrons

Momentum spectrum symmetric around   p = $E_\gamma/2$ = 13 GeV

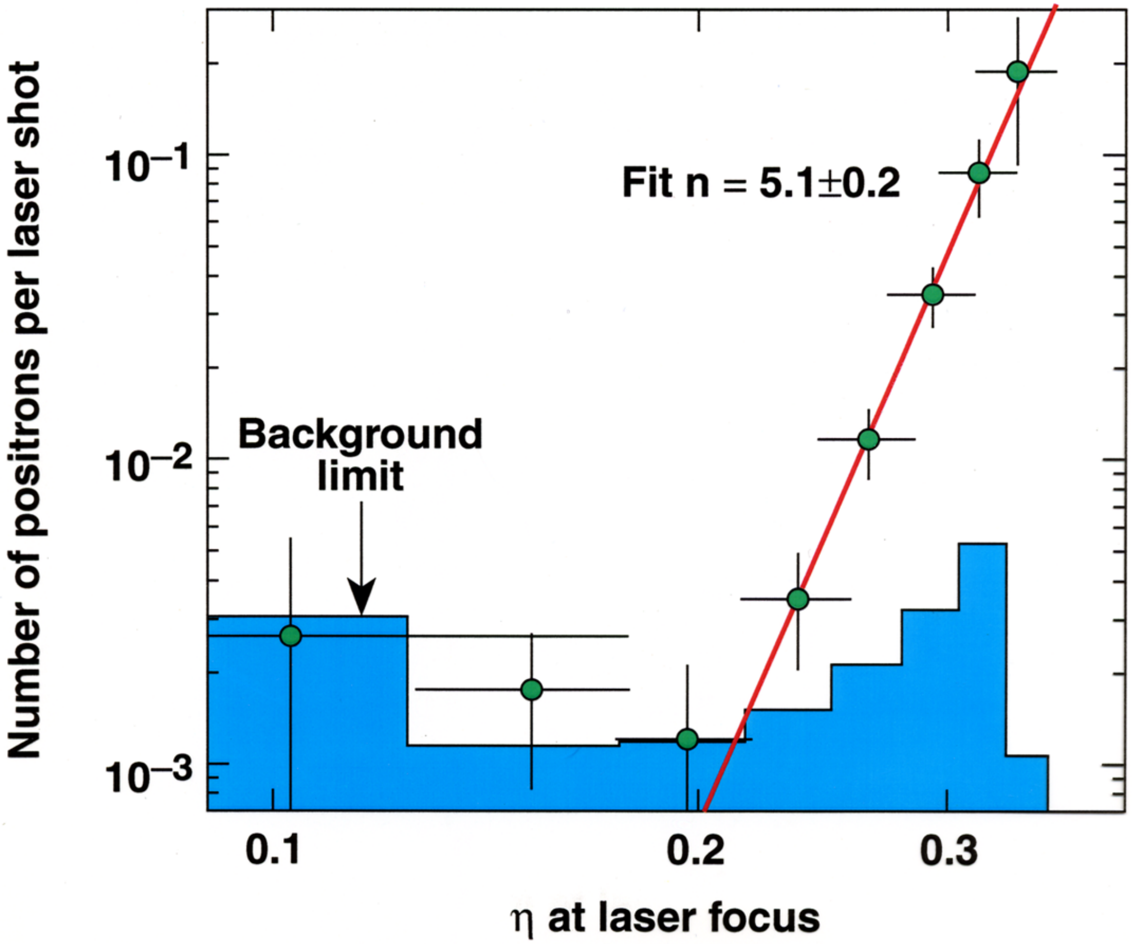




POSITRON YIELD vs. LASER FIELD STRENGTH

Process involving *n* laser photons has probability

$$P \sim \eta^{2n} \quad \text{where} \quad \eta^2 = \left[\frac{eE}{\omega mc}\right]^2 = \left[\frac{e}{\omega mc}\right]^2 Z_0 I$$



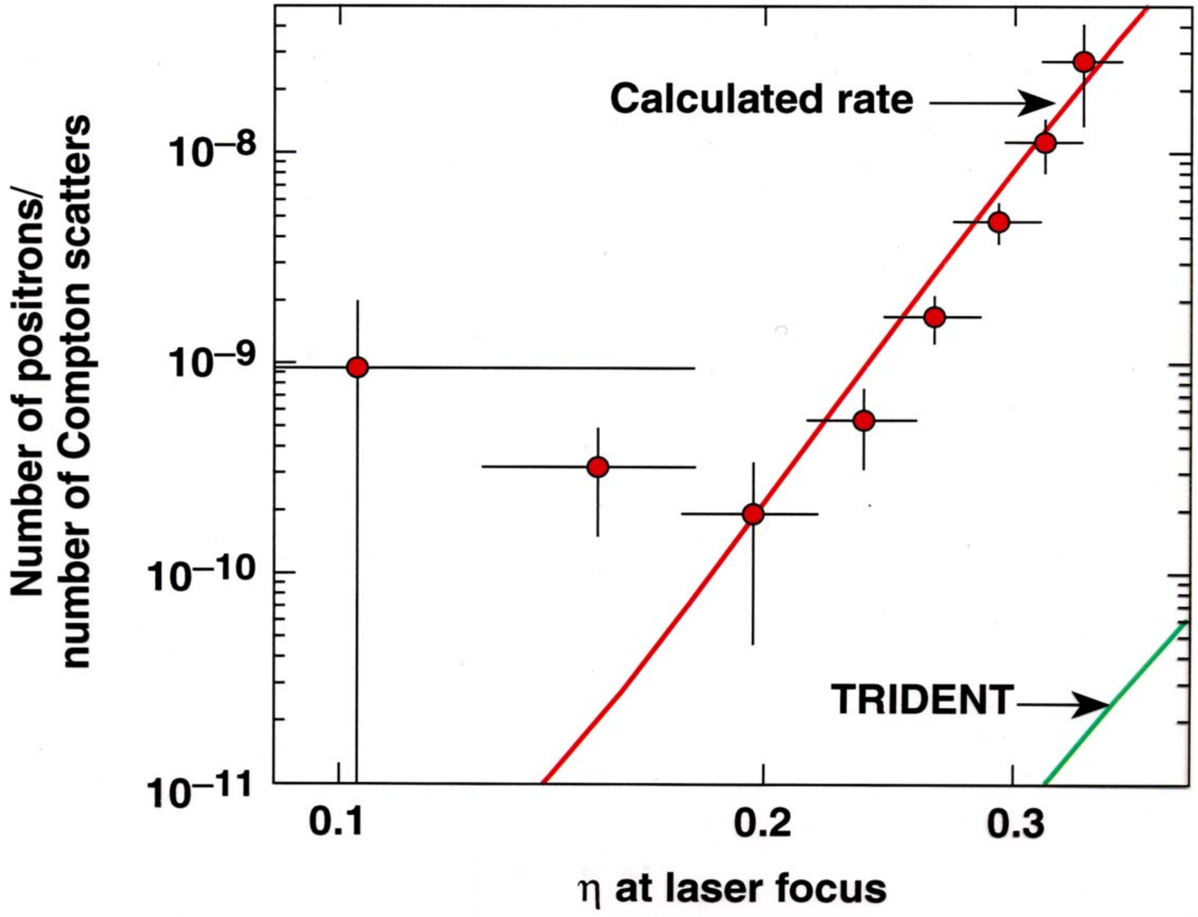
OBSERVED and CALCULATED RATE OF POSITRON PRODUCTION

- **Exact calculation**

$$e^- + \omega_0 \to e^- + \gamma$$

$$\hookrightarrow \gamma + n\omega_0 \to e^+e^-$$

- **Agrees with data**



Note log-log scale

Breakdown of the Vacuum

J.Schwinger Phys. ReV. **82**, 664 (1951)

Define critical field $E_c = mc^3/e\hbar$ and $Y = E/E_c$

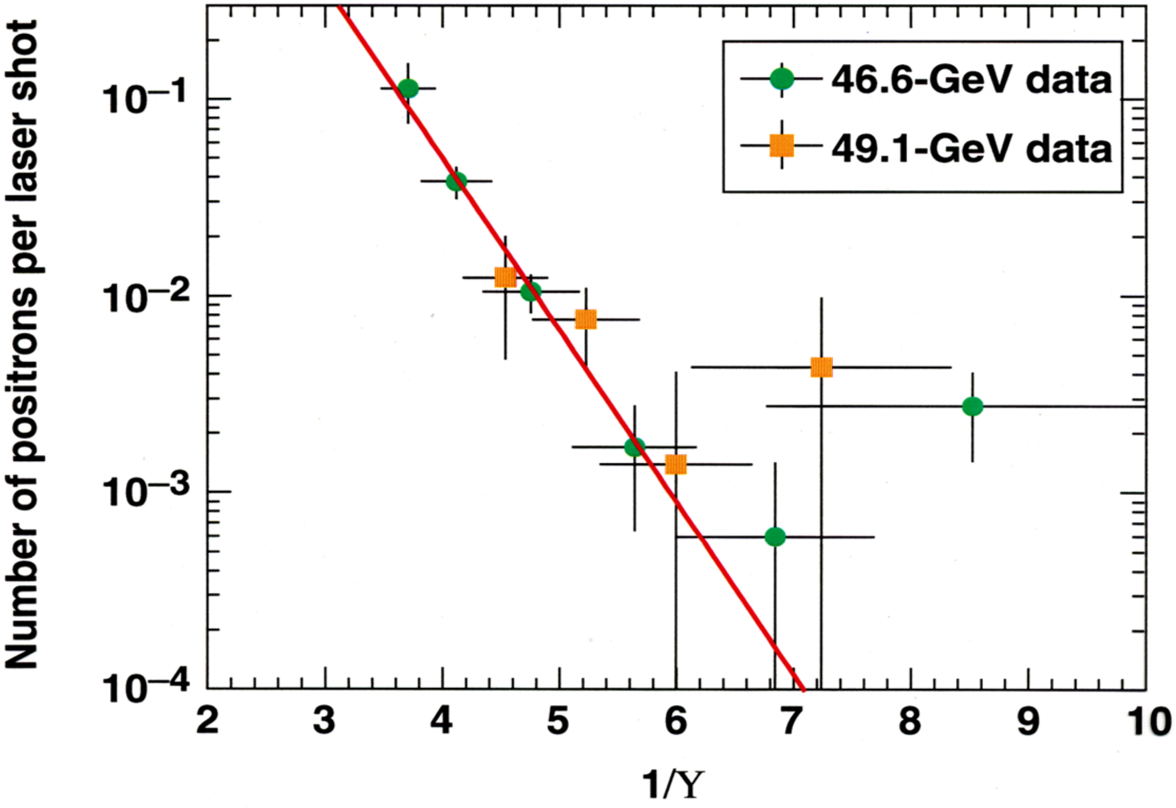
The probability for pair production is

$$W = \alpha\,(E/\pi)^2\, e^{-\pi/Y}$$

In our case the Lorentz boosted E-field seen by the high energy photon leads to

$$Y_\gamma = (2\mathcal{E}_\gamma/mc^2)(E_{rms}/E_c)$$

POSITRON YIELD *vs.* 1/Y



Fit to $e^{-\alpha/Y} \rightarrow \alpha = 2.02 \pm 0.12$

but $\alpha' = \alpha\sqrt{2}\left(\frac{30}{46.6}\right) = 1.84 \pm 0.11$

predicted $\alpha' = \pi\, g(\eta) = 2.06$


UNIVERSITY
ROCHESTER

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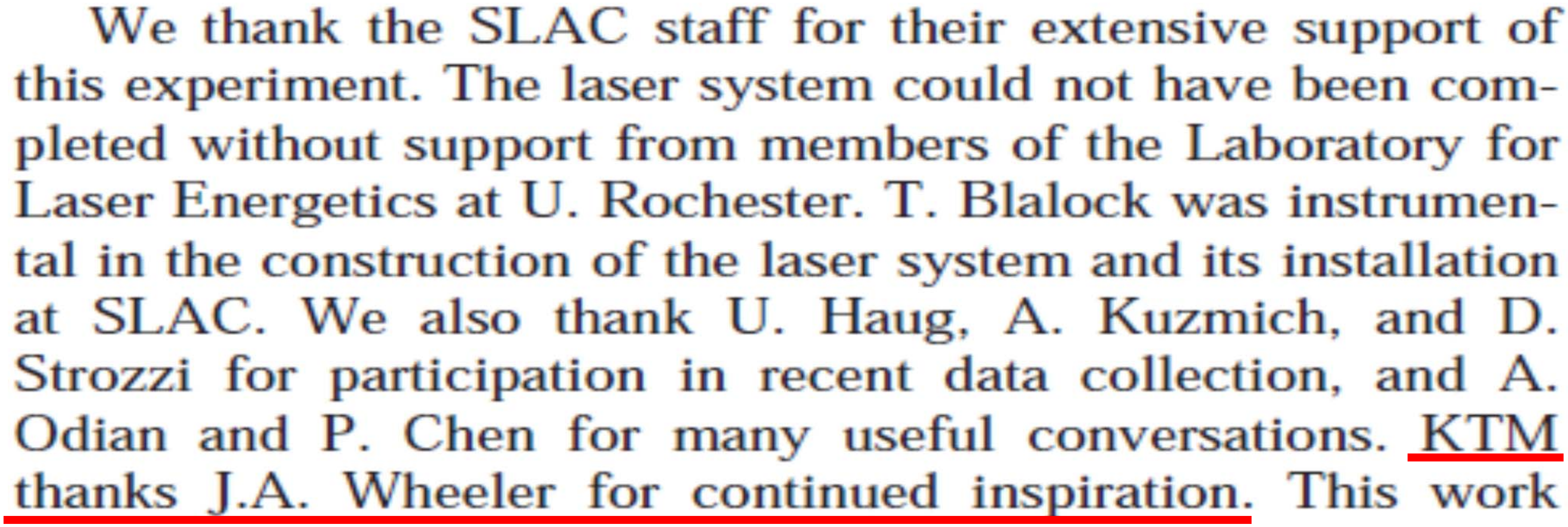


We thank the SLAC staff for their extensive support of this experiment. The laser system could not have been completed without support from members of the Laboratory for Laser Energetics at U. Rochester. T. Blalock was instrumental in the construction of the laser system and its installation at SLAC. We also thank U. Haug, A. Kuzmich, and D. Strozzi for participation in recent data collection, and A. Odian and P. Chen for many useful conversations. KTM thanks J.A. Wheeler for continued inspiration. This work

Supplementary Slides

FREQUENTLY MISSED POINT

A **single** laser beam can not produce e^+e^- pairs

TO PRODUCE A **MASSIVE** PAIR THE INVARIANT

$I = E^2 - B^2$ must be > 0

STATIC ELECTRIC FIELD	**$I > 0$**
STATIC MAGNETIC FIELD	**$I < 0$**
E.M. FIELD	**$I = 0$**

A standing wave is OK, but this is equivalent to **photon-photon scattering.**

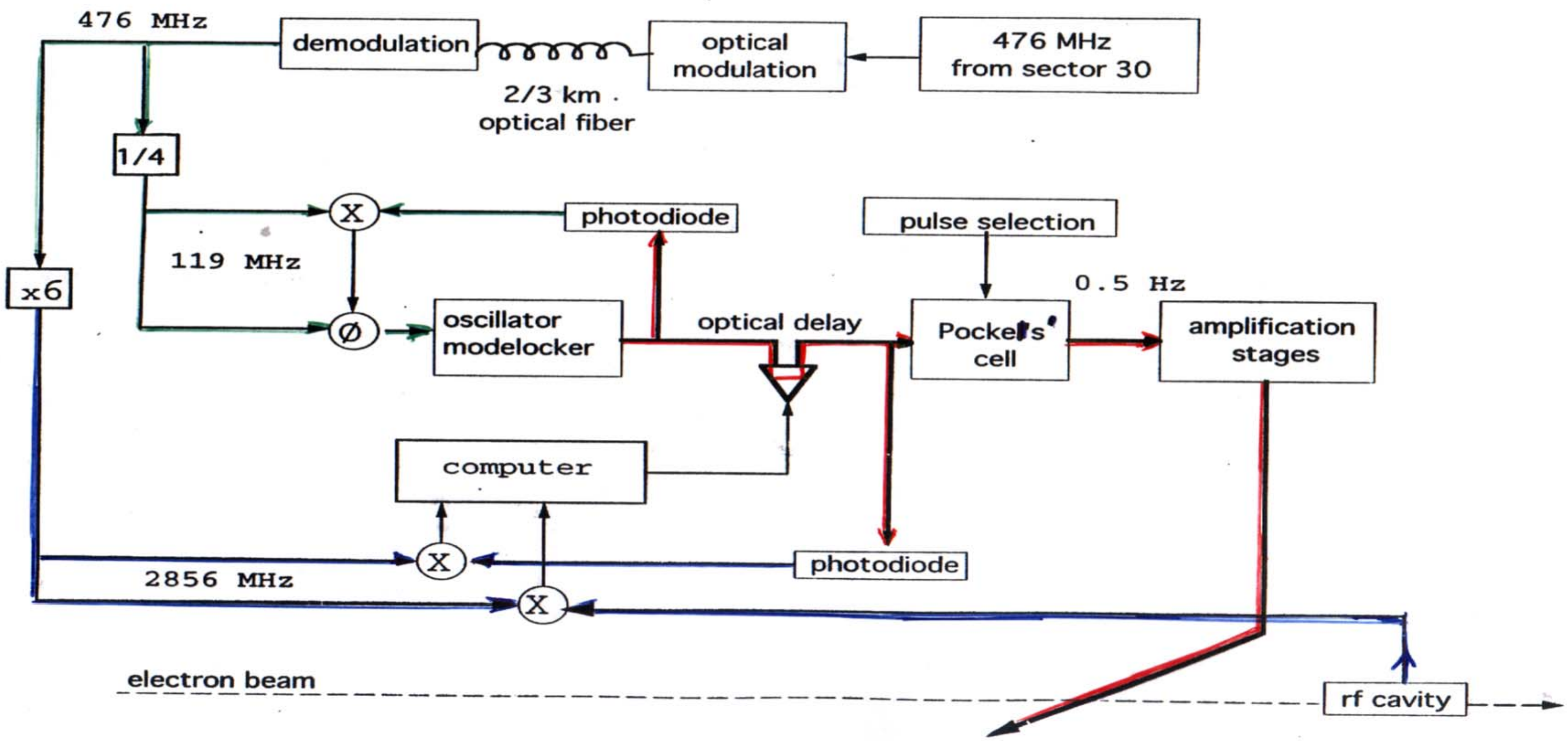
EXAMPLE: Using **colliding** x-ray beams from Free Electron Lasers

$\lambda = 0.1$ nm → $\hbar\omega = 12$ keV **If** $\sigma = 0.1$ nm, $\Delta t = 0.1$ fs

and $P = 4.5$ TW **30 e^+e^- pairs** are produced per pulse

LASER PULSE –ELECTRON BEAM SYNCHRONIZATION

Laser - electron synchronization
Goal: 1 ps



STRONG FIELD QED $E \geq E_c$

FIELD IN THE FOCUS OF AN INTENSE LASER BEAM

$$I_L = 10^{18} \text{ W/cm}^2 \quad \rightarrow \quad E_L = \sqrt{2Z_o I_L} = 2.75\times10^{10} \text{ V/cm}$$

But if a 50 GeV electron ($\gamma = \mathcal{E}_e / mc^2 = 10^5$) traverses the focus,

IN THE ELECTRON REST FRAME

$$E^* = 2\gamma E_L = 5.5\times10^{15} \text{ V/cm} \approx 0.4\, E_c$$

STRONG FIELDS ARE ALSO FOUND IN:

- **“ATOMS” WITH $Z \geq 137$**
- **HEAVY ION COLLISIONS**
- **CHANNELING OF RELATIVISTIC ELECTRONS**
- **ASTROPHYSICAL ENVIRONMENTS (MAGNETIC FIELDS)**

1929 Klein Paradox

1936 Heisenberg-Euler Lagrangian

1951 Schwinger Critical Field

A *virtual* e^+e^- pair travels a distance

$$\lambda_c = \hbar/mc$$

If the energy gained in that distance in a static electric field, equals the electron rest mass

$$eE\lambda_c = mc^2$$

The field will spontaneously break down into e^+e^- pairs

$$E_c = m^2c^3/e\hbar = 1.32\times10^{16}\ \mathrm{V/cm}$$

EM PROCESSES IN STRONG FIELD QED (Multiphoton Processes)

PERTURBATIVE Dimensionless Invariant Coupling (Instead of $e/\sqrt{\hbar c}$)

$$\eta = e\,(\sqrt{\langle A^\mu A_\mu \rangle})/mc = eE/\omega mc$$

A **classical** parameter (no ħ). It **diverges** as ω→0. When $\eta \geq 1$ relativistic effects are important. Processes involving n photons are proportional to η^{2n}

NON-PERTURBATIVE

$$Y = E^*/E_c = 2\gamma e E_L \hbar/(m^2c^3)$$

When $Y \geq 1$ **pair production** is dominant.

$$\text{Probability/V-T} = (\alpha E^2/\pi^2\hbar)\exp(-\pi/Y)$$