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Observation of Nonlinear QED Effects in Electron-Laser Collisions

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(for the E-144 collaboration)

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Outline

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- Summary and Outlook

Tests of QED

QED is extensively tested in the weak field regime.

- Nonlinear Optics:

  Test of QED at moderately strong fields.

  ⇒ Fields of order 10^8 V/cm are produced by focused laser beams and their interaction with atomic systems is investigated.

- E-144:

  Test of QED in fields comparable to the critical field strength of QED and in the realm where multiphoton interactions are important.

  ⇒ Study of interactions between 46 GeV electrons and photons at the focus of a Terawatt laser.
  In the rest frame of the electron, the field reaches 10^{15} - 10^{16} V/cm.

Multiphoton Interactions

- Coherent interaction of an electron with n field photons at a single space-time point.
- They become important when the parameter

$$\eta = \frac{eE_{rms}}{m\omega_o c} = \frac{e}{mc^2}\sqrt{A_\mu A^\mu} \longrightarrow 1$$

⇒ accessible in low amplitude, low frequency fields

Classical Picture

- A free electron in a circularly polarized field undergoes transverse circular motion with angular frequency ω_0 and velocity $\beta_\perp = v_\perp / c$ given by

$$\eta = \gamma_\perp \beta_\perp, \qquad \text{with} \quad \gamma_\perp = (1 - \beta_\perp^2)^{-1/2}$$

⇒ weak field or non-relativistic limit: $\eta \simeq \beta_\perp$

- As η approaches unity, the classical radiation spectrum of an accelerating electron includes the *n*th harmonic of the wave frequency ω_0 (multipole radiation).

  The emission rate of the *n*th order multipole is

$$Rate \propto \eta^{2n} \propto I^n$$

$\Rightarrow$ nonlinear for $n > 1$

Quantum Mechanical Picture

- The electron absorbs n wave photons and emitts a single high energy photon.

$$e + n\,\omega_o \longrightarrow e' + \omega$$

Mass Shift

- The transverse motion increases the electrons energy, leading to an effective mass

$$\overline{m}^2 = m^2(1+\eta^2)$$

- In QM picture, the effective mass of electrons in a strong field arises due to "dressing" by continual absorption and re-emission of wave photons.

$\Rightarrow$ This effect is identifiable as a shift in the kinematic edge (minimal electron energy) of Compton scattering.

Ponderomotive Potential

- In nonuniform fields, the effective mass is called the ponderomotive potential, which describes the forces on a charged particle as it enters and exits the wave:

$$U = \overline{m}c^2 \approx mc^2 + \frac{1}{2}mc^2\eta^2$$

$$\Rightarrow \quad F = -\nabla U \approx -\frac{1}{2}mc^2\nabla\eta^2$$

The Critical Field of QED

- At the critical field, the voltage drop across a Compton wave length is equal to the electron rest mass:

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

- At the critical field, the vacuum "sparks" into e^+e^- pairs.

  ⇒ Expect copious e^+e^- pair production.

- The electric field in the rest frame of a high energy electron is

$$E_{rest} = (1+\beta)\gamma\, E_{lab} \simeq 2\gamma\, E_{lab}$$

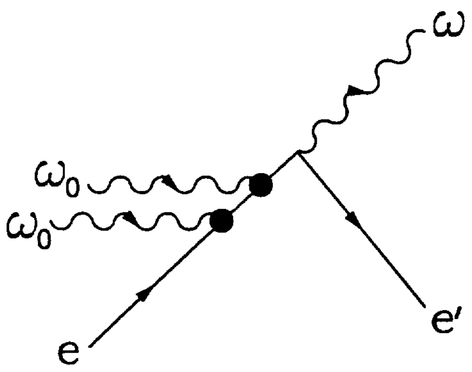
  ⇒ In the rest frame of 46 GeV electrons ($\gamma = 9 \times 10^4$), the critical field strength can be reached with a focused laser pulse of

$$E_{lab} = 7 \times 10^{10}\ \mathrm{V/cm}$$

- Field strength are characterized by Schwinger parameter

$$\Upsilon = \frac{E_{rest}}{E_{crit}} = 2\gamma\, E_{lab}\frac{e\hbar}{m^2c^3}$$

Nonlinear Compton Scattering



e + $n\omega_0$ -> e' + ω

Kinematics

The maximum energy of scattered gammas is

$$\omega_{max} = \frac{2n\gamma^2\omega_o(1+\cos\theta)}{1+\frac{2n\gamma\omega_o}{m}(1+\cos\theta)+\eta^2}$$

⇨ dependent on n, η and crossing angle θ

Cross Section

Closed form for circularly polarized wave field (Narozhnyi, Nikishov, Ritus):

$$\frac{d\sigma_n}{dy} = \frac{2\pi r_o^2}{x}\left\{-\frac{4}{\eta^2}J_n^2(z) + \left(2+\frac{u^2}{1+u}\right)\left[J_{n-1}^2(z) + J_{n+1}^2(z) - 2J_n^2(z)\right]\right\}$$

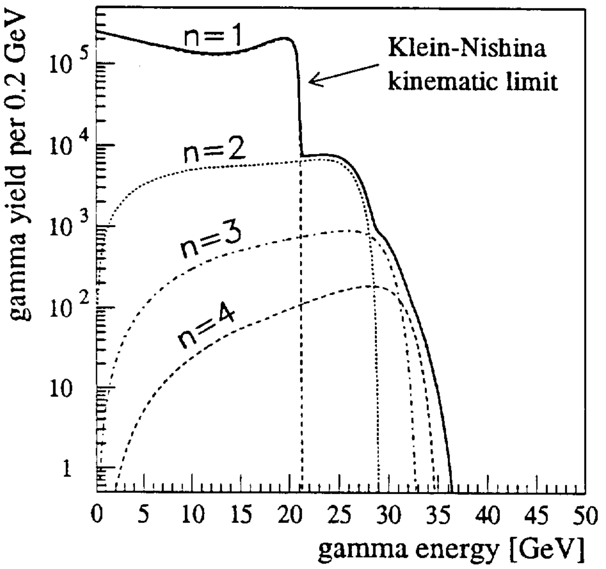
$$x = \frac{4\omega_o E_e}{m^2}, \quad y = \frac{\omega}{E_\epsilon}, \quad u = \frac{y}{1-y}, \quad z = \frac{2\eta}{x}\sqrt{nux - u^2(1+\eta^2)}$$

⇨ reduces to Klein-Nishina formula for n = 1 and η -> 0

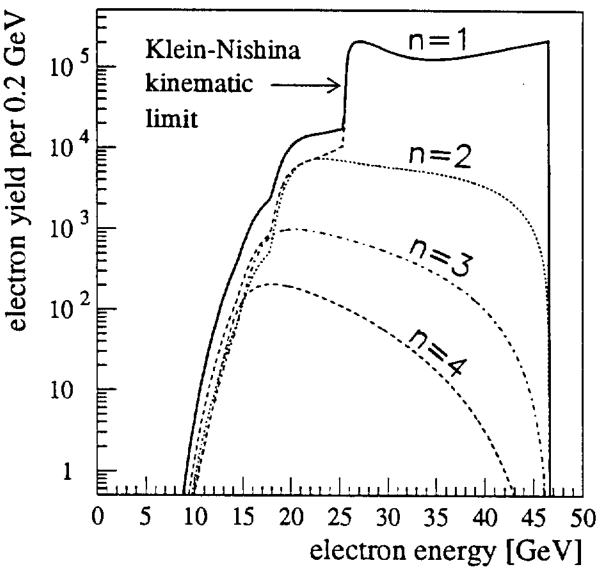
Spectra for E-144 Configuration

- IR laser ($\lambda = 1054$ nm)
- Intensity at laser focus 10^{18} W/cm^2 ($\eta = 0.64$)

gamma spectrum



electron spectrum

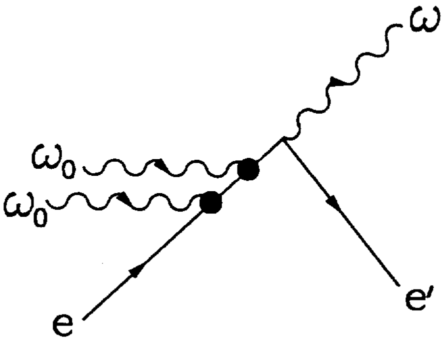


Experimental Program

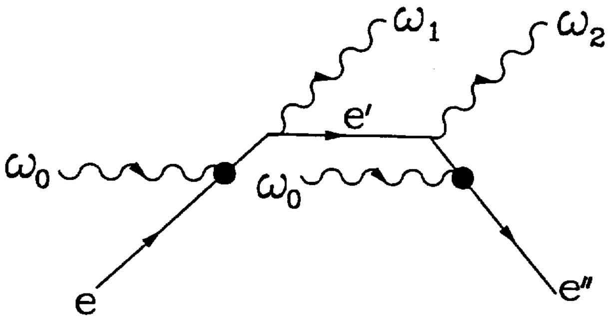
- Measure electron spectrum beyond the linear Compton edge.
- Test nonlinear dependence of cross section on laser intensity for $n > 1$
- Confirm shift of linear Compton edge in gamma spectrum due to increased effective electron mass.
- Note: Process also provides γ-beam for light-by-light scattering.

Coherent Multiphoton Absorption vs Incoherent "Multiple Scattering"

- Nonlinear Compton (coherent)



- Multiple Linear Compton (incoherent)



- Kinematics of the final state electrons are identical.
- Both processes are nonlinear in laser intensity.
- Spectra of final-state electrons are similar.
- Rates for E-144 configuration are comparable.

⇒ Hard to distinguish by measuring final state electrons. Gamma spectrum is free from this ambiguity.

Beamstrahlung

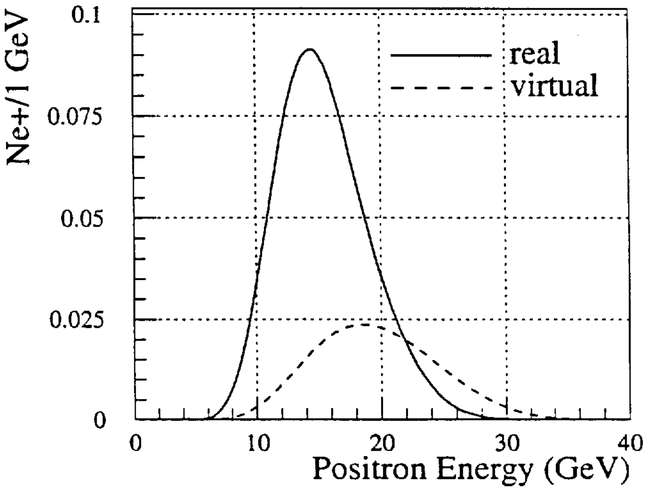
- Field strength at laser focus is comparable to field of bunch at future e^+e^- collider.

  ⇒ $e + n\,\omega_0$ interactions with large n are similar to beamstrahlung.

- $e + n\,\omega_0 \rightarrow e'\, e^+e^-$ is close analog of important pair production background in future colliders.

- Two processes contribute to pair production:
  - multi-photon Breit-Wheeler (real photon)
  - trident (virtual photon)

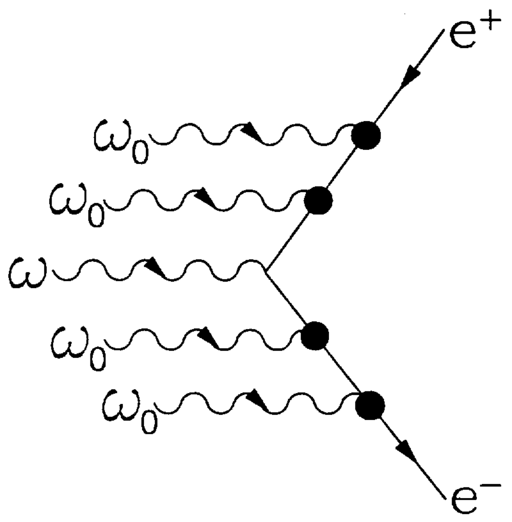
- Calculated positron spectra for E-144 configuration:



  - green laser (λ = 527 nm)
  - $Y \cong 0.4$

- Measure cross section and energy spectrum of positrons produced at electron-laser interaction point.

Multi-Photon Breit-Wheeler Process



"light-by-light" scattering with real photons

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

Experimental Program

- Measure pair production cross section.
- Measure e^+e^- invariant mass spectrum and search for anomalous structures in the low mass region (< 2 MeV/c^2).
    - The structure of the observed e^+e^- invariant mass spectrum in heavy ion collisions (Darmstadt) is still not completely understood.

⇨ E-144 offers excellent opportunity to study this spectrum without the complications of strong interactions.

More Exotic Motivations

Low Emittance Positron Source

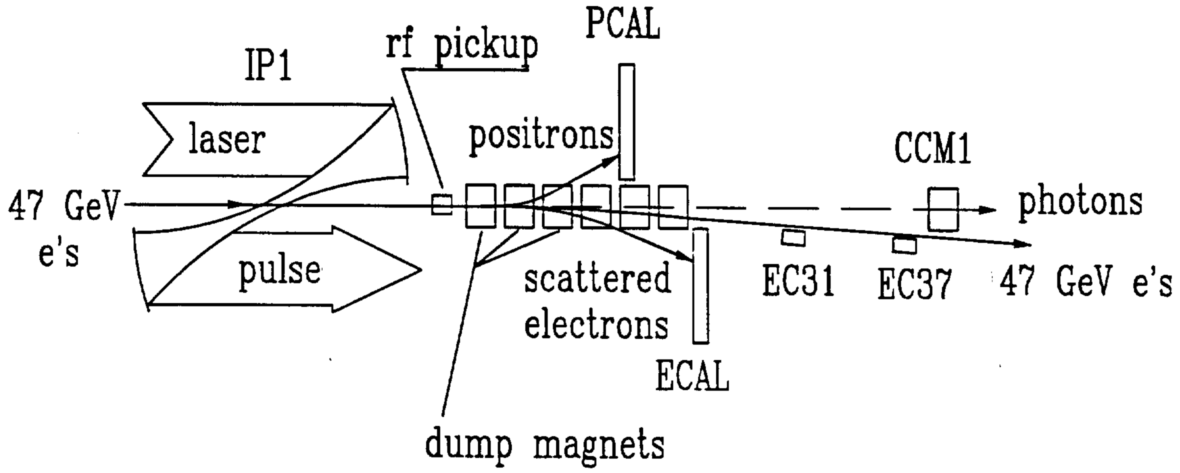
- Pair Production in electron-laser collisions could be excellent low emittance positron source for future colliders (no Coulomb scattering in laser target).

Electron-Laser Technology

- Electron-laser collision technology of E-144 is precursor of e–γ and γ–γ colliders.

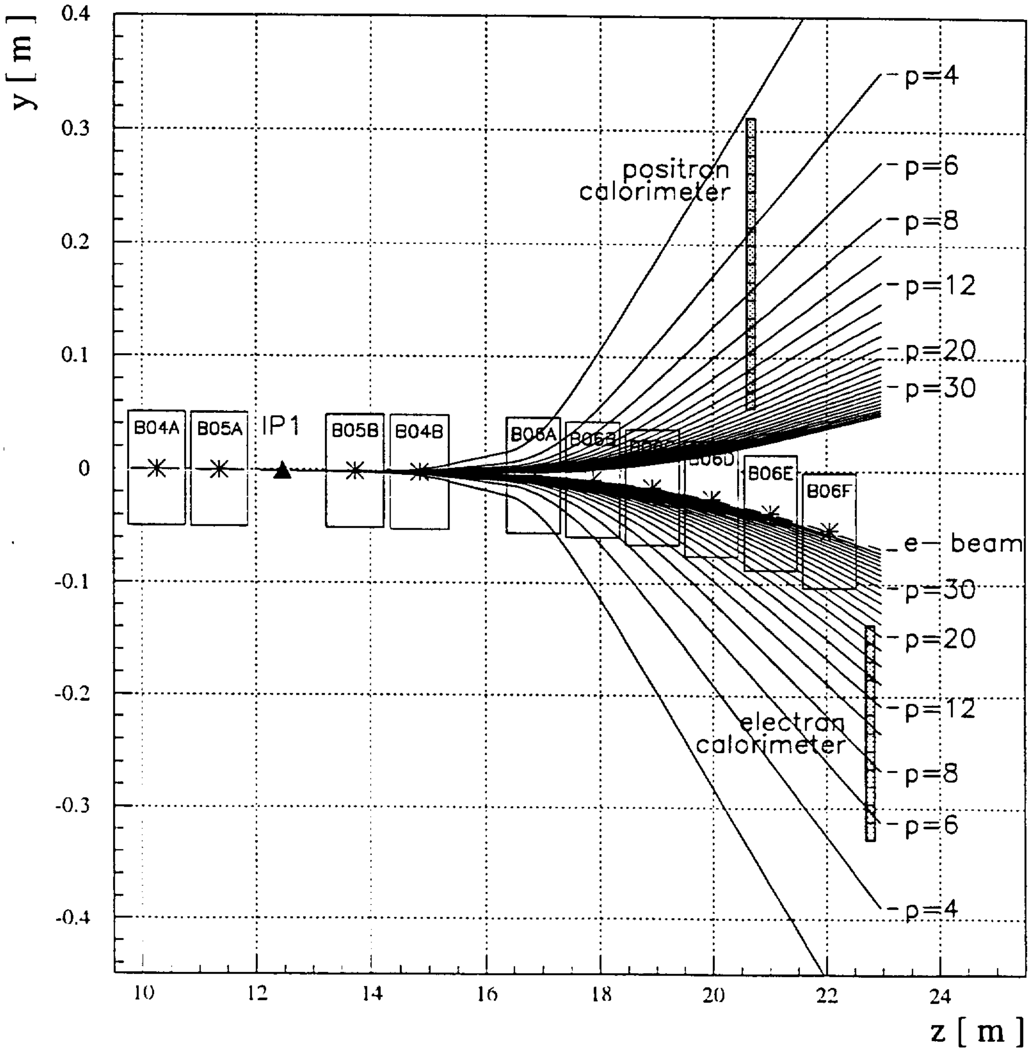
Experimental Setup (Phase I)

- Experiment is set up at the Final Focus Test Beam (FFTB) at SLAC.
- In a first phase, we study nonlinear Compton scattering and beamstrahlung.
- Measure rates of electrons, gammas and positrons produced at the electron-laser interaction point.
- Use FFTB dump magnets as spectrometer.



IP1 Spectrometer

- Consists of 6 permanent magnets with 0.45 Tesla.
  ⇒ transverse kick of ~ 0.8 GeV/c
- Calculate trajectories of charged particles in dump line to obtain correlation between momentum and impact position at ECAL and PCAL.
- ECAL is on vertically movable stage in order to intercept different parts of the electron spectrum.

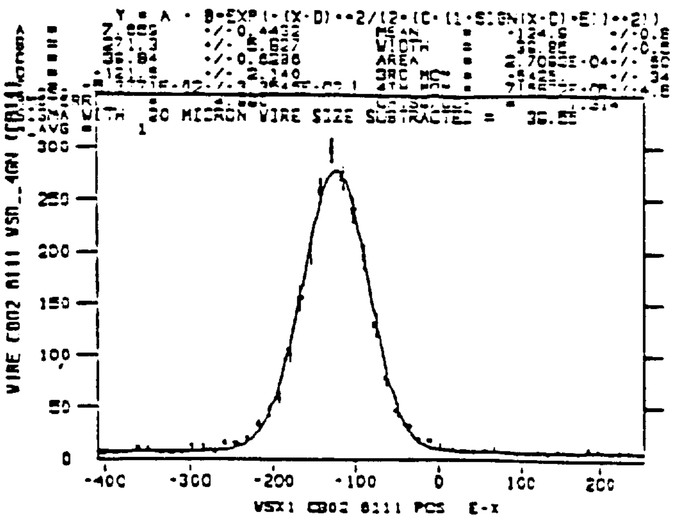


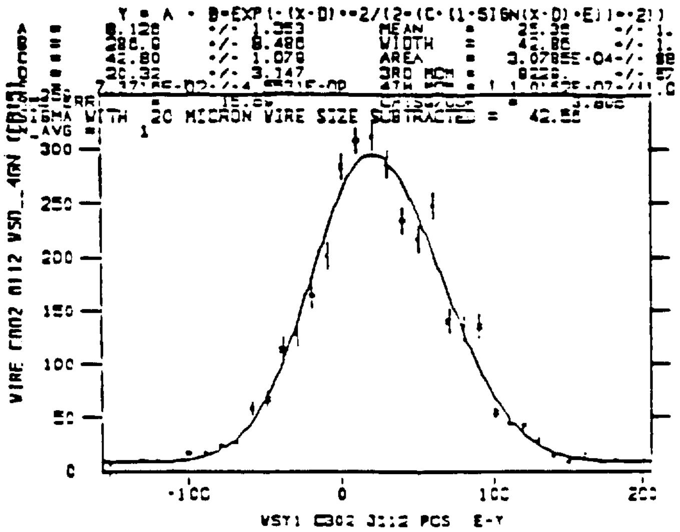
Electron Beam

- FFTB is prototype for the electron focusing system at the interaction point of the Next Linear Collider (NLC).
- The E-144 electron-laser interaction point is 12 m downstream of the final focus.

Beam Parameters at E-144 IP

- Energy: 46.6 GeV
- Charge: 5×10^9 e^- per bunch
- Bunch length: $\sigma_z \cong 870\ \mu m$ => $FWHM(t) \cong 7$ psec
- Spot size: $\sigma_x \cong 40\ \mu m$, $\sigma_y \cong 40\ \mu m$
- Wire Scans at IP:





Laser System

- Table-top terawatt (T^3) laser.
- Phase locked to Linac RF.
- Principal: chirped pulse amplification.

  ⇒ Stretch pulse, then amplify and compress.

- Design parameters:
  - energy per pulse: 1 Joule for green (λ = 527 nm)
  - pulse duration: 1.0 psec FWHM
  - focal spot area: 15 μm^2 for green
  - repetition rate: 1/2 Hz

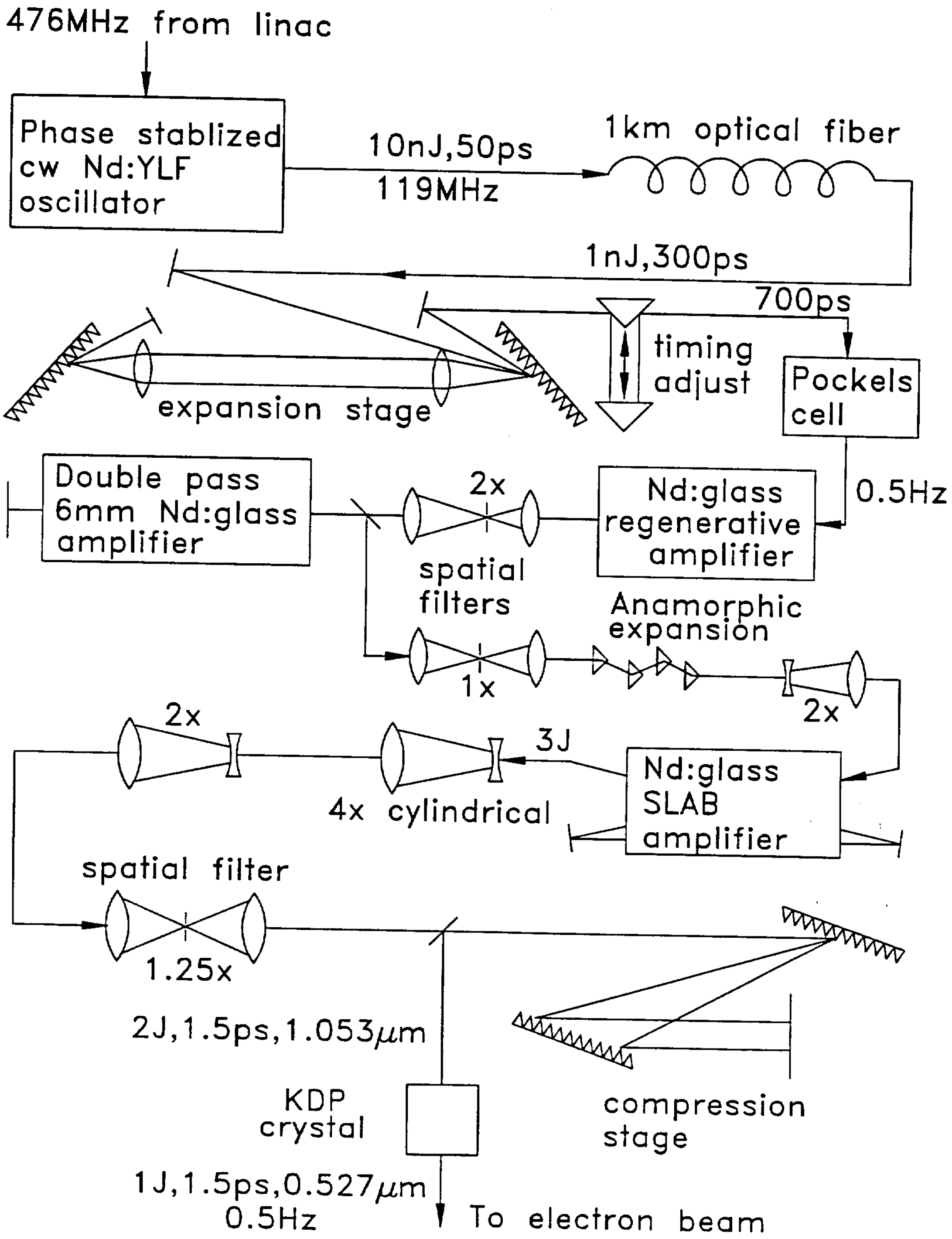
⇒ Field strength in LAB frame: 7.3×10^{10} V/cm

⇒ Field strength in rest frame of 46.6 GeV electron: 1.3×10^{16} V/cm = E_{crit}

⇒ Photon density at the laser focus in ~ $10^{27}/cm^3$

⇒ Radiation length of of this "photon solid" is
X_o ~ 0.1 mm (Pb: X_o = 5.6 mm)

Schematic of Terawatt Laser System

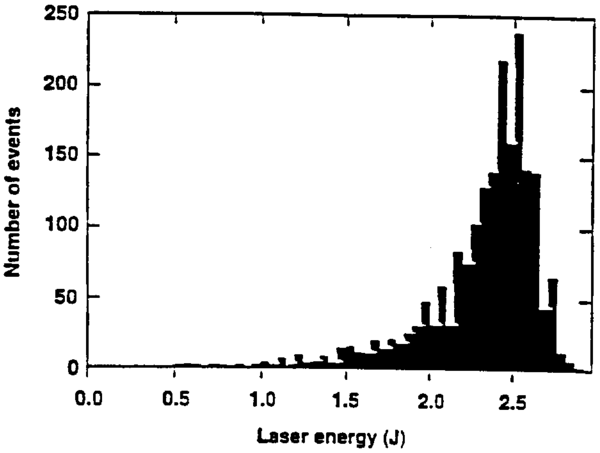


Christian Bula, Princeton University *June, 1996*

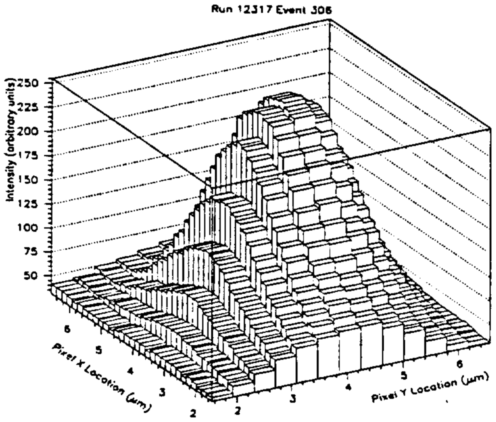
Intensity Measurement

- The laser intensity I at the focus is obtained by measuring the energy E, focal area A and pulse width τ at each shot:
  $\Rightarrow I = E/(A \cdot \tau)$

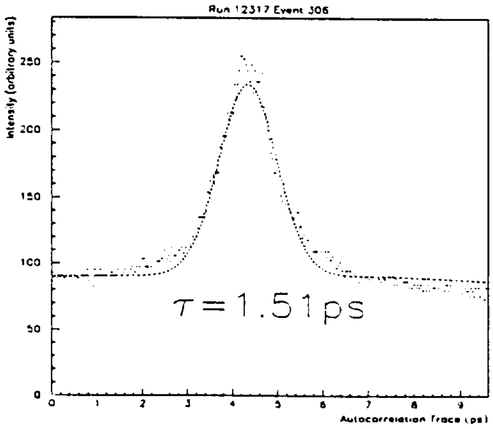
- **Energy:**
  Measured with pyroelectric Joulemeter.



- **Focal Area:**
  Intensity profile is measured with CCD camera in "equivalent target plane".



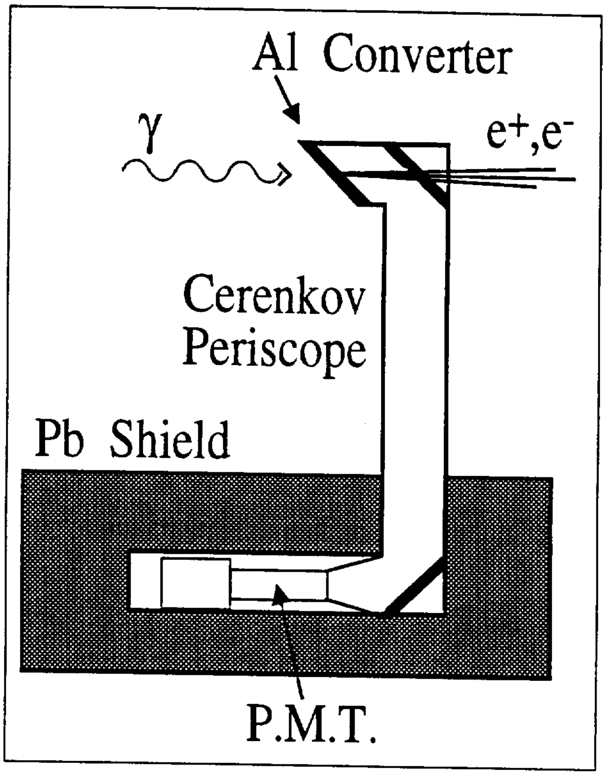
- **Pulse Width:**
  Output of single shot autocorrelator measured with linear CCD array.

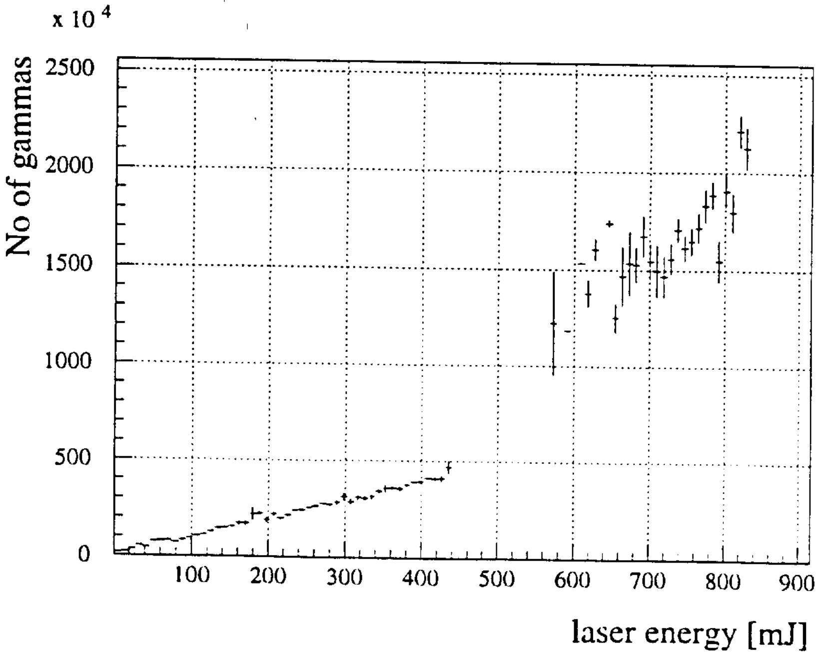


Detectors

Gas Cerenkov Counter CCM1

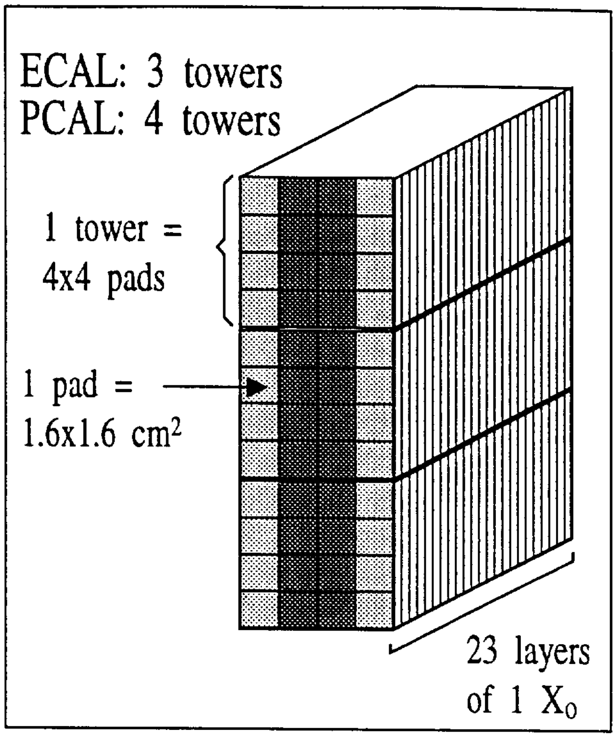
- Monitors the backscattered gamma rate (~ linear Compton rate).
- Primary measure of electron-laser overlap.
- Used to normalize the nonlinear signal.
- 10 % uncertainty in calibration.
- Signal to first order proportional to laser energy:





Silicon-Tungsten Calorimeters ECAL and PCAL

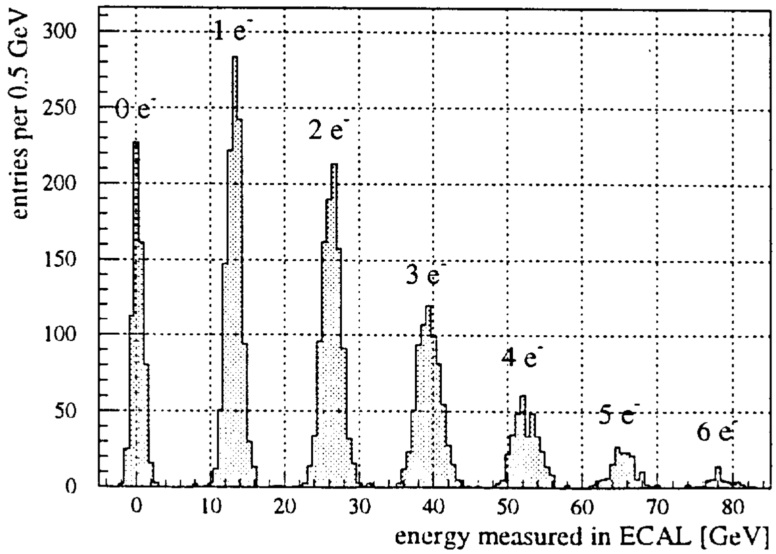
- 23 layers of Si and 1 X_0 of Tungsten.
- 12 (16) rows and 4 columns of 1.6 x 1.6 cm^2 pads.
- Layers for each pad are ganged into 4 longitudinal segments.
- Signal is in center pads.
- Outer pads are used for background subtraction.



- Calibrated with FFTB test beam (6 - 25 GeV).

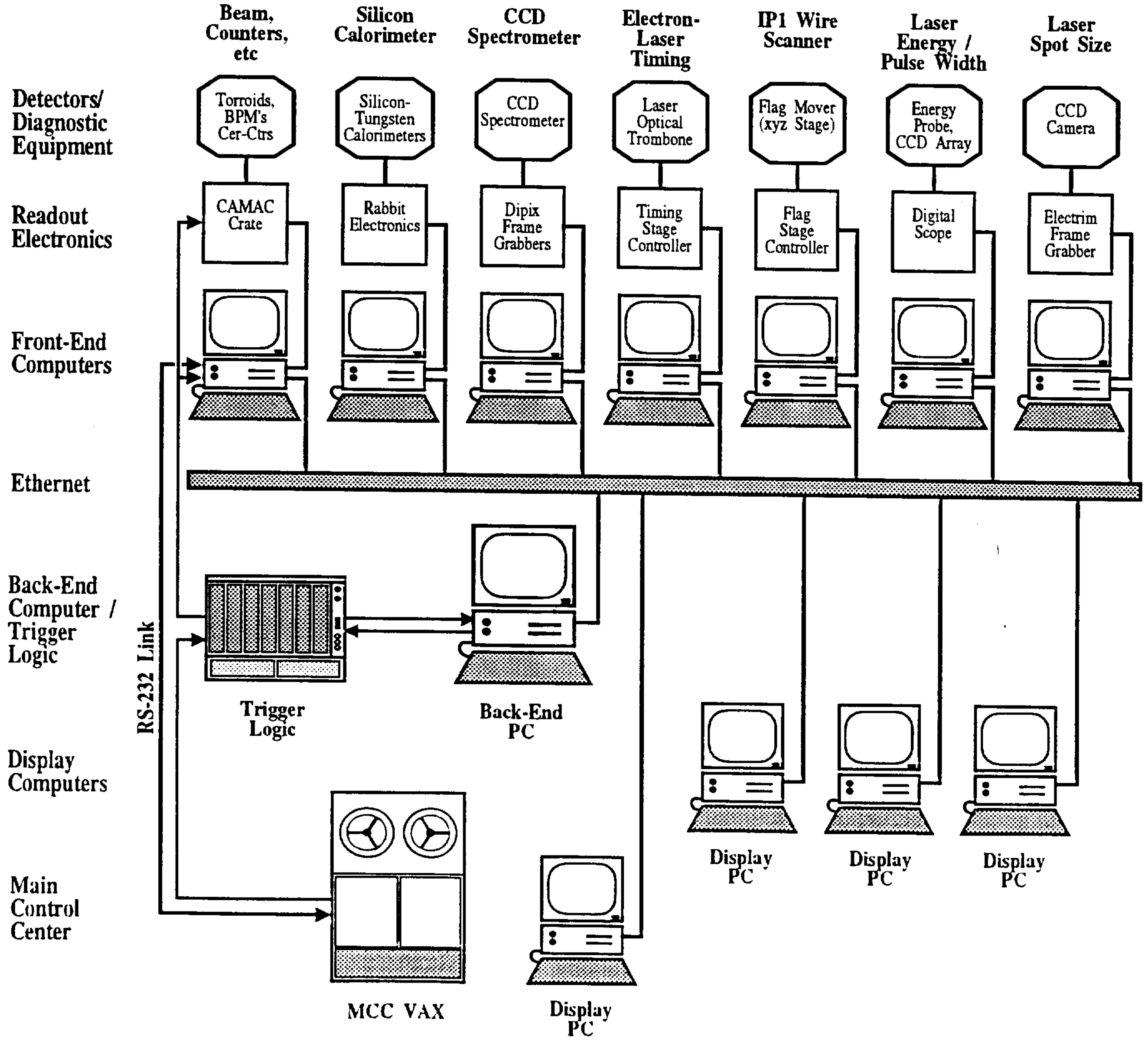
⇒ Resolution: $$\frac{\Delta E}{E} = \frac{0.19}{\sqrt{E}} + \frac{0.4}{E}$$

- ECAL response to 13 GeV test beam



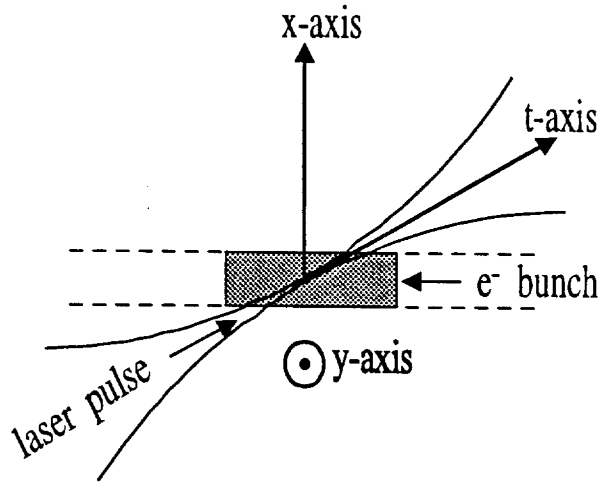
Data Acquisition

- Is based on PC's, connected by local Ethernet.
- Modular, easy adaption to new detector configurations.
- Inexpensive, built with "off the shelf" components.
- Made possible by moderate event rate.

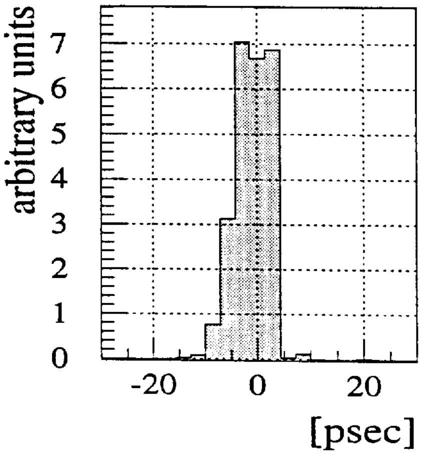


Laser Electron-Beam Overlap

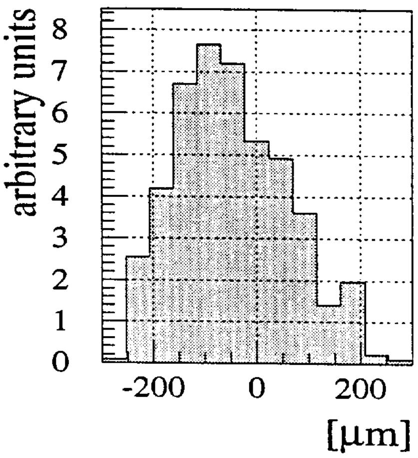
- Scan laser focus across e^- beam in space and time.
- Monitor linear (CCM1) and nonlinear (Ecal) Compton-scatter rates.



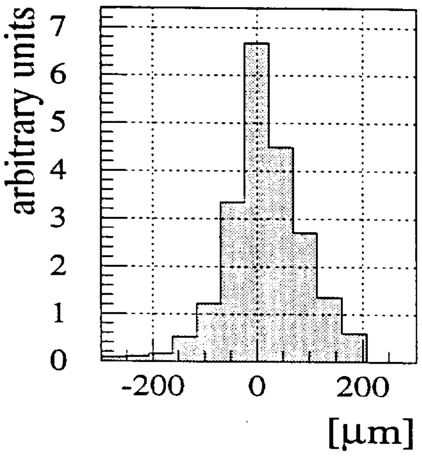
time scan



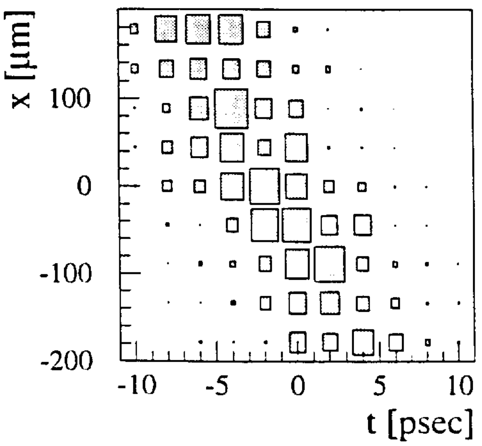
x scan



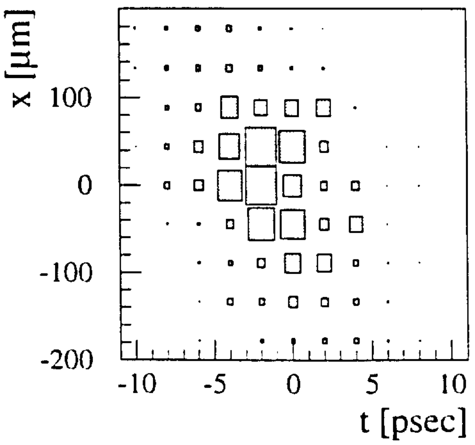
y scan



xt scan, linear rate



xt scan, nonlinear rate



Timing Jitter

- Jitter of electron-laser timing is of same order as "overlap" time:

$$\sigma^2_{\text{jitter}} \sim \sigma^2_{\text{overlap}} \simeq \frac{1}{2}\left(\sigma^2_{\text{laser}} + \sigma^2_{\text{e-beam}}\right)$$

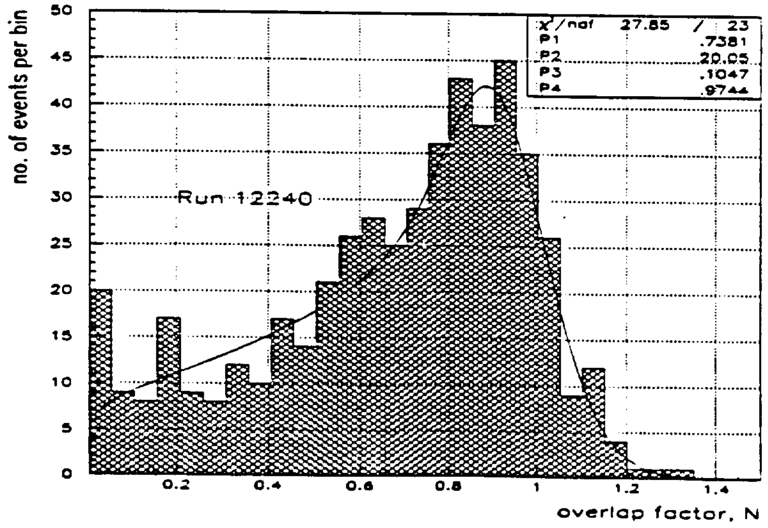
- Various measurements of timing jitter gave

$$\sigma_{\text{jitter}} \simeq 2 \text{ psec}$$

- This value is confirmed by data analysis:

$\Rightarrow$ Distribution of "overlap factor" N = Nγ(obs)/Nγ(sim) can be parameterized as:

$$f(N) = \frac{R}{\sqrt{\pi}} \frac{N^{R^2-1}}{\sqrt{\ln(1/N)}}, \qquad \text{with} \quad R = \frac{\sigma_{\text{overlap}}}{\sigma_{\text{jitter}}}$$

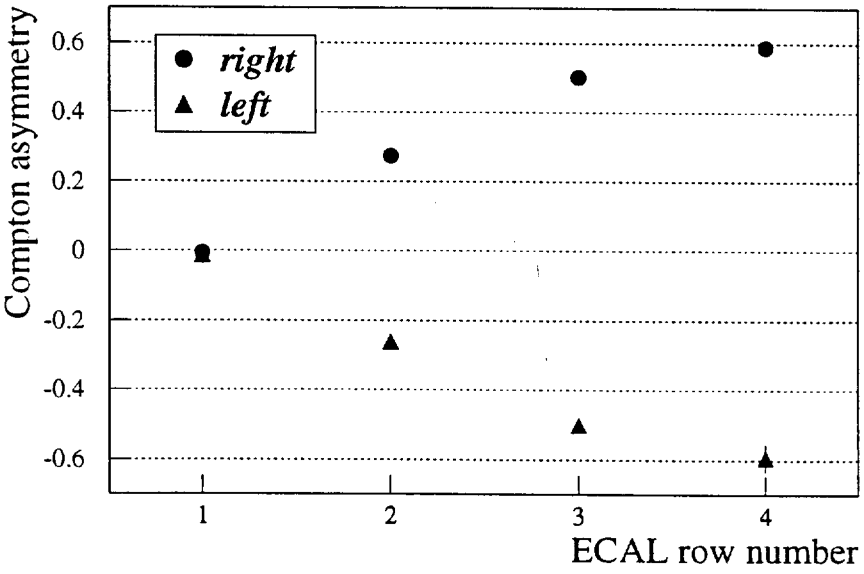


Beam Polarization

- Measure Compton scattering rate asymmetry in top 4 ECAL rows for longitudinaly polarized electron beam and circularly polarized laser.
- Fit to measured polarization asymmetry in 4 momentum bins of ECAL yields:

  $P_e P_{laser} = 0.81 +- 0.01$
- Laser polarization $P_{laser} > 96$ %

$\Rightarrow$ Beam polarization $P_e = 0.81^{+0.04}_{-0.01}$



Measured polarization asymmetries in top 4 ECAL rows for left and right circularly polarized laser.

The top row was centered at 25.6 GeV, the zero crossing of the Compton asymmetry.

Nonlinear Compton Scattering

- Cross section depends on laser intensity, which varies in space and time.

  ⇒ Invariant cross section cannot be defined.

- From energy measured in ECAL row, we obtain the number of incident electrons per momentum interval:

$$\frac{dN}{dp} = \frac{E}{\langle p \rangle \Delta p}$$

- Normalize with gamma rate to form normalized yield:

$$\frac{1}{N_\gamma}\frac{dN}{dp} \simeq \frac{1}{\sigma_{\mathrm{T}}}\left\langle \frac{d\sigma}{dp} \right\rangle$$

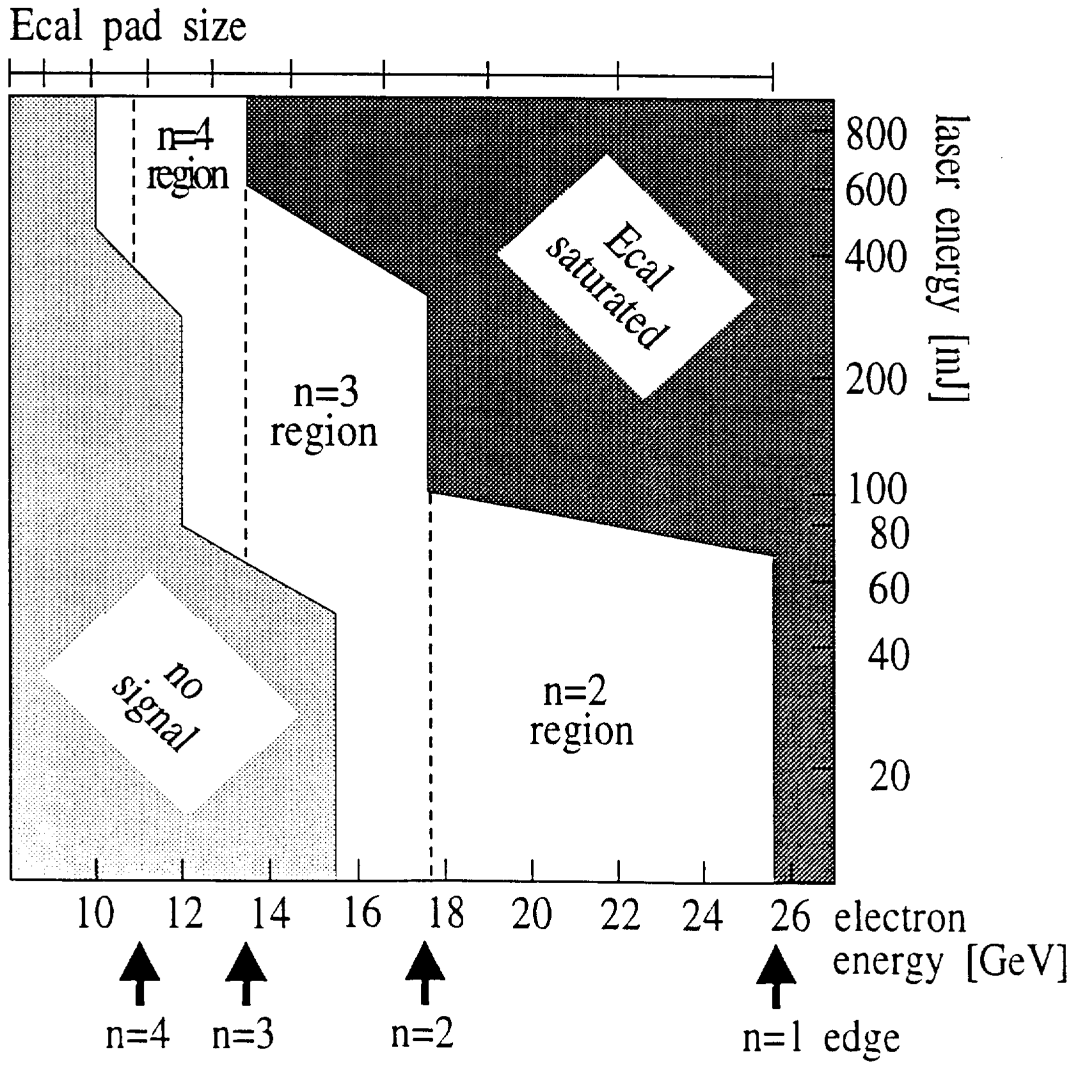
  ⇒ Effects of timing jitter, errors in electron beam parameters cancel to 1. order.

- Comparison with theoretical predictions by numeric integration of $\frac{1}{\sigma_{\mathrm{T}}}\left\langle \frac{d\sigma}{dp} \right\rangle$ over space and time for each event.

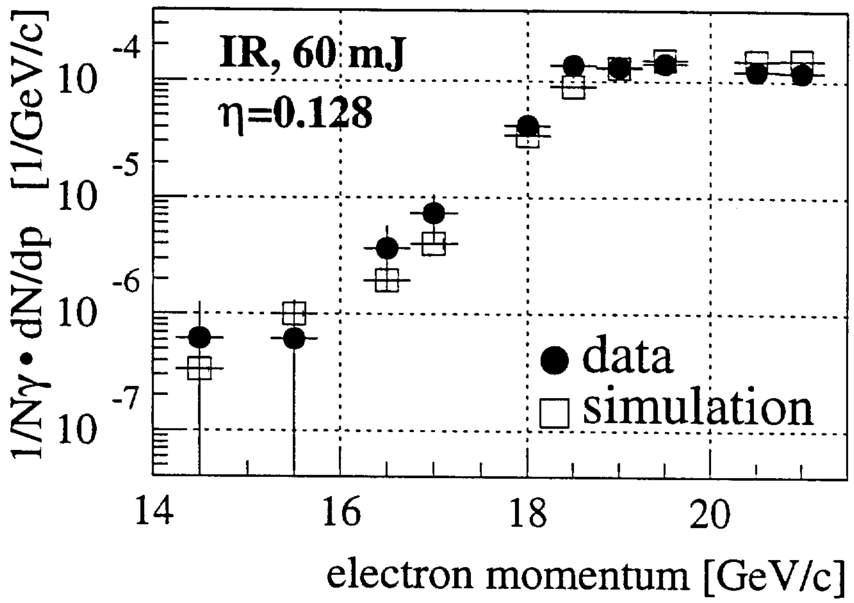
- Simulation takes into account:
  - correct interaction geometry,
  - nonlinear and multiple Compton scattering and combinations of the two.

Data Collection Strategy

- Fast drop of electron rate for momenta beyond the linear Compton edge.
- ECAL saturates at ~ 10 TeV per pad.
- Dynamic range of ECAL is limited to ~ 100 by
  - electromagnetic shower spreading,
  - n = 1 'backsplash",
  - electronic crosstalk.
- Measure electron rates for n = 2, 3, 4 seperately, with adjusted ECAL position.



Normalized Yield vs Recoil Electron Momentum



- Error bars include:
  - statistical error (dispersion of entries in bin)
  - uncertainty in ECAL reconstruction (corrections for shower spreading, "backsplash", ...)

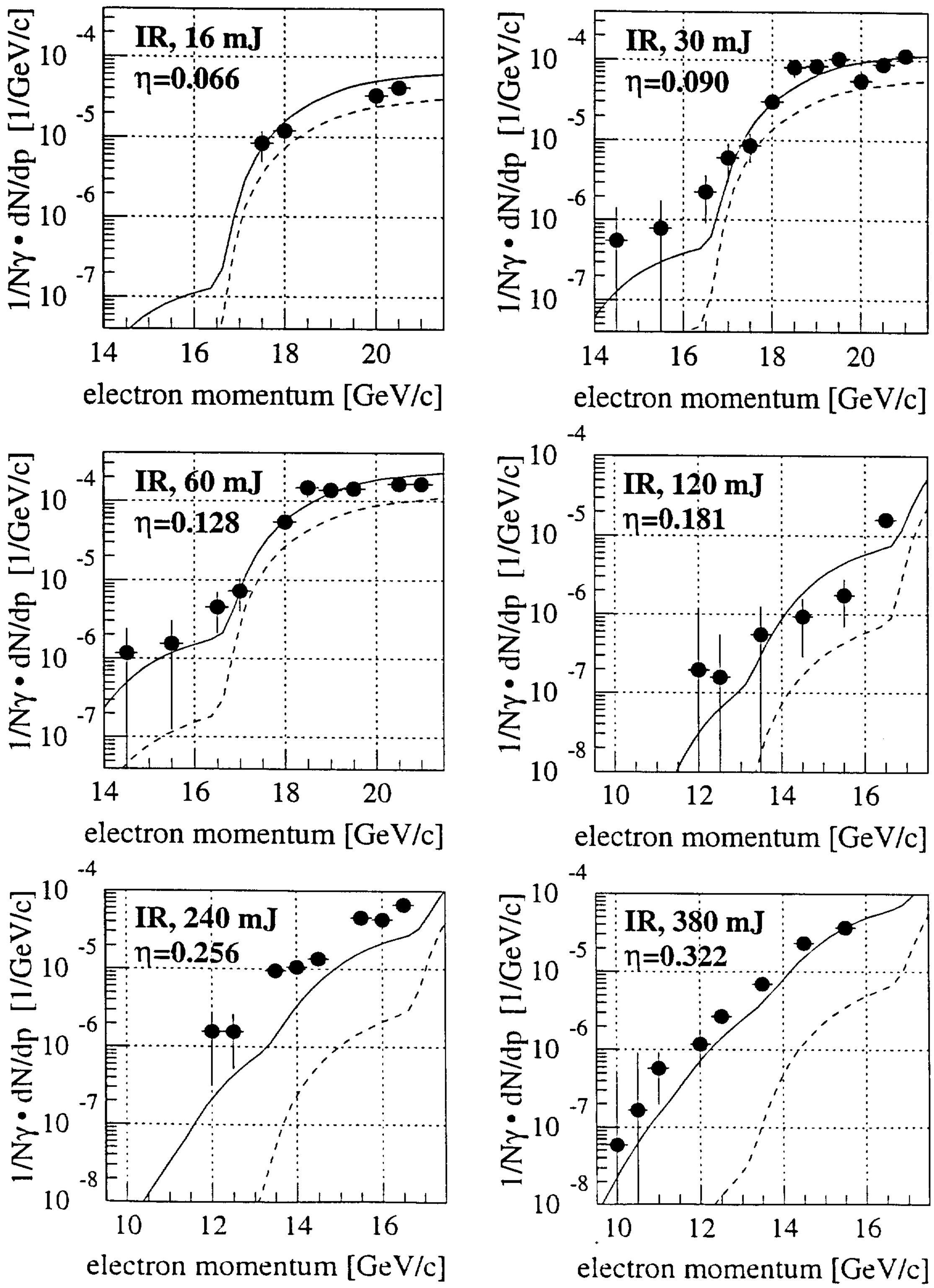
Scaling to Standard Interaction Parameters

- Compensate for small variations in interaction parameters by scaling data (bin by bin) with ratio of simulated rates at measured and standard electron/laser spot dimensions.

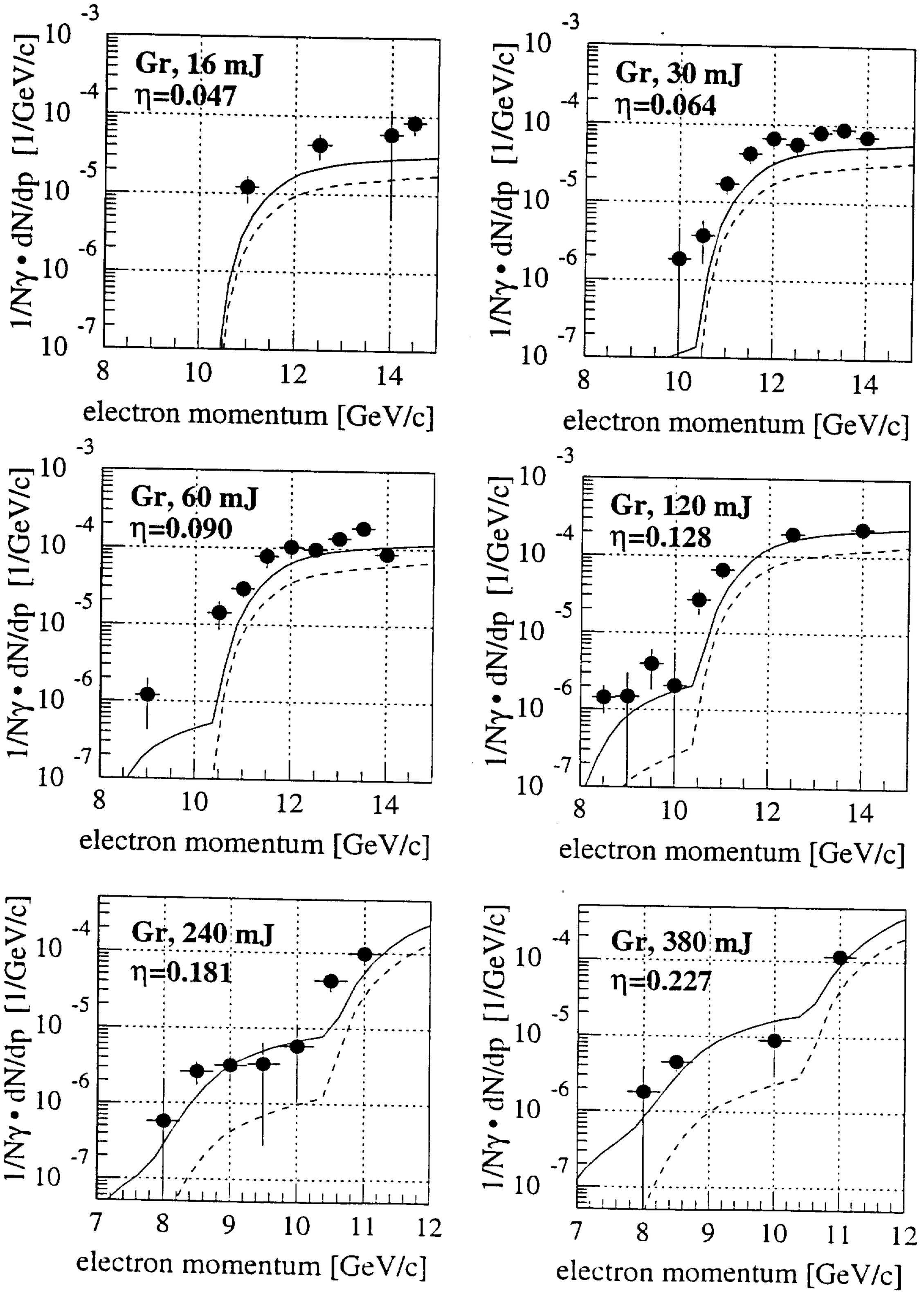
  ⇒ Simulation can be shown as continuous line.

  ⇒ Simulation uncertainties are added to data errors.

IR, Circularly Polarized Laser



Green, Circularly Polarized Laser

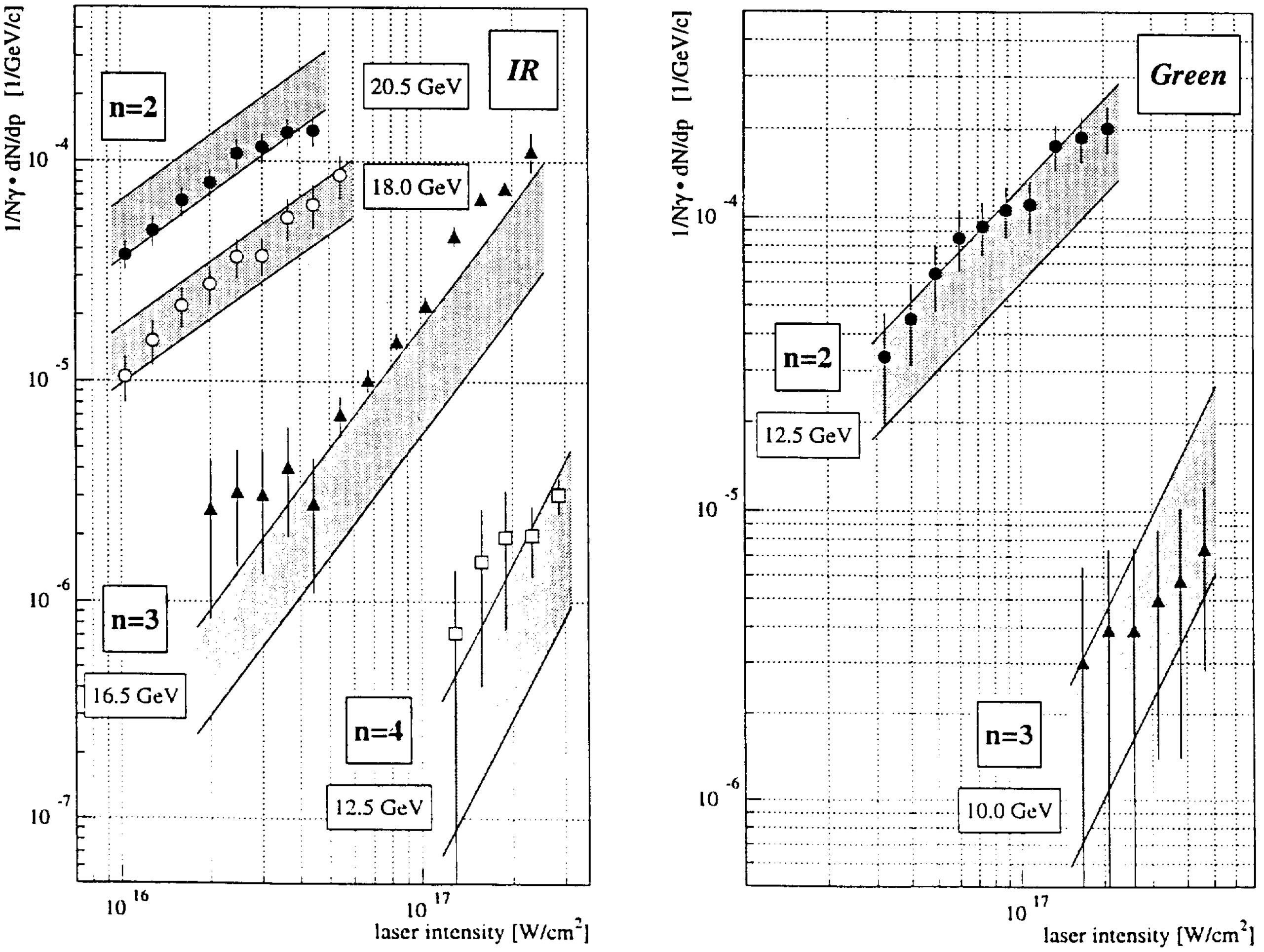


Dependence on Laser Intensity

- In 1. order approximation we expect

$$\frac{1}{N_\gamma}\frac{dN}{dp} \propto \eta^{2(n-1)} \propto I^{n-1}$$

- The shaded bands represent the simulation, including an uncertainty in laser intensity of
  - +/– 30 % for IR,
  - +50 / –30 % for green.

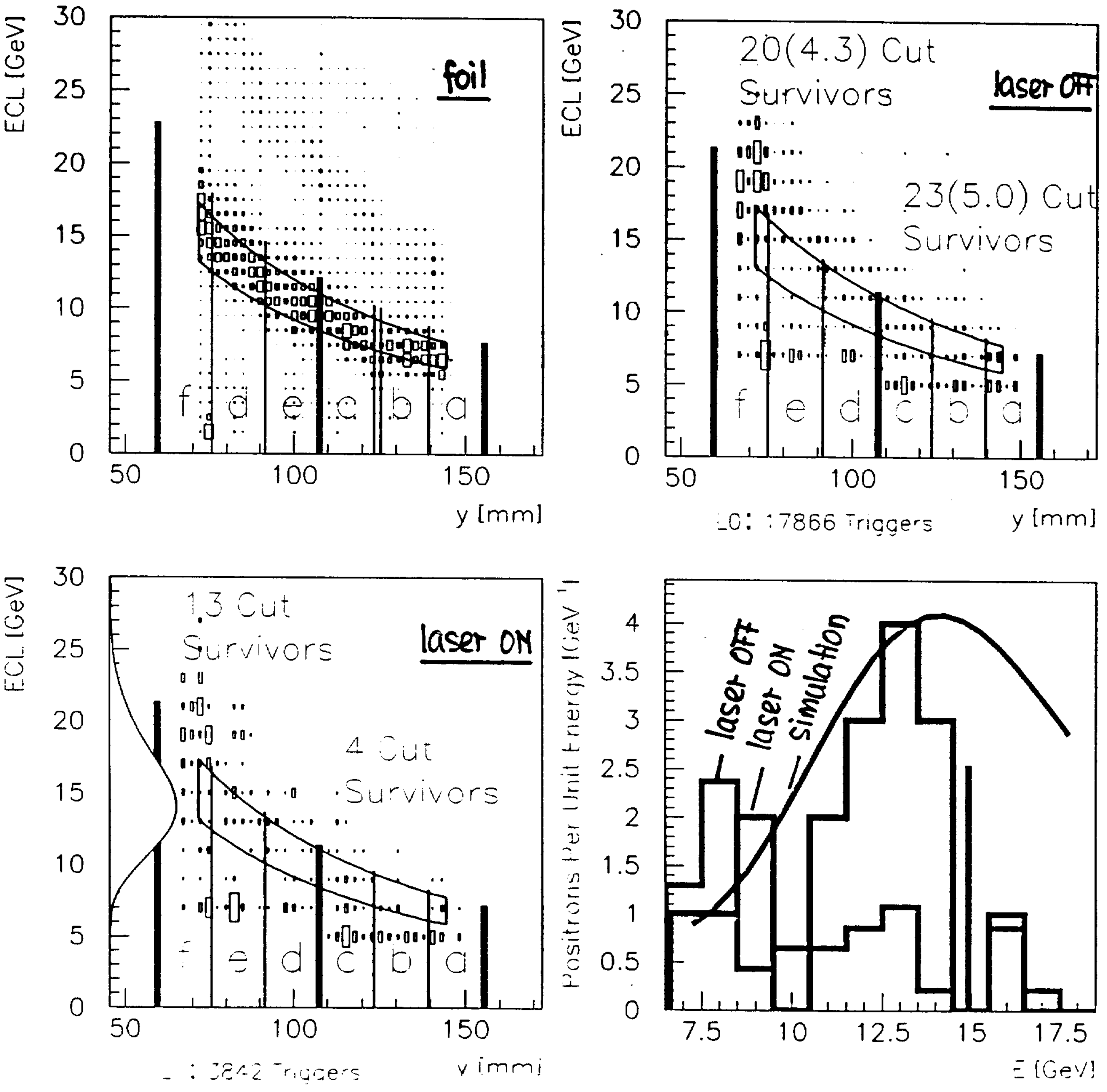


Positron Production at IP1

- Process: $e + n\omega_0 \to e' \, e^+e^-$ with intermediate photon (real or virtual).
- Green laser is favorable, since $\gamma + n\omega_0 \to e^+e^-$ with gammas from (linear) Compton scattering needs
  - $n >= 4$ for green and
  - $n >= 8$ for IR.
- Weak signal: with electron / laser parameters achieved, expect ~ 1 e^+e^- pair in 100 laser shots.
- Search for single positron hits in PCAL.
  ⇒ cluster analysis (E_{clu}, Y_{clu})
- Measure background with laser OFF events.
- Suppress background by comparing cluster energy E_{clu} with nominal momentum $P_{clu} = P(Y_{clu})$:
  - IP1 positrons: $E_{clu} / P_{clu} \cong 1$
  - upstream positrons: $E_{clu} / P_{clu} > 1$
- Results from two run periods:
  - September 94
  - December 95

September 94 Data

Green laser, ~3800 shots



	laser ON	laser OFF
→ Rows d,e,f (signal):	13	4.3
Rows a,b,c :	4	5

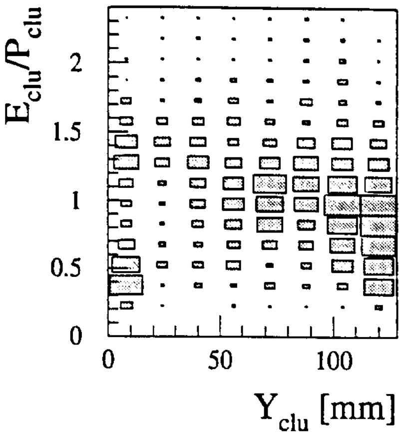
→ Probability that excess in signal rows is due to background fluctuation is $< 10^{-3}$

December 95 Data

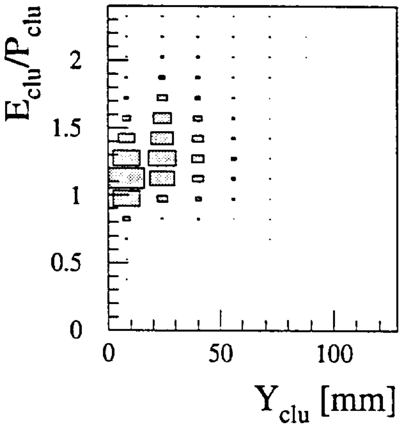
- **Electron beam:** huge backgrounds due to wire mesh in beam.
  - ⇒ lots of beam tuning, unstable conditions.
  - ⇒ large spot at IP1: ~ 150 x 50 μm^2
- **Laser:** Green, 700 - 800 mJ, very stable.
- **Data Sample:** ~ 13'800 laser shots (after cuts).
- **Analysis:** increased background made different approach necessary:
  - ⇒ 2 assumptions:
    - same background in laser ON and OFF events
    - positrons from IP1 are produced by real photons (Breit-Wheeler spectrum)
  - ⇒ extract signal by fitting laser ON data with signal shape obtained by Monte-Carlo simulation and background shape measured with laser OFF events.

Fit Procedure

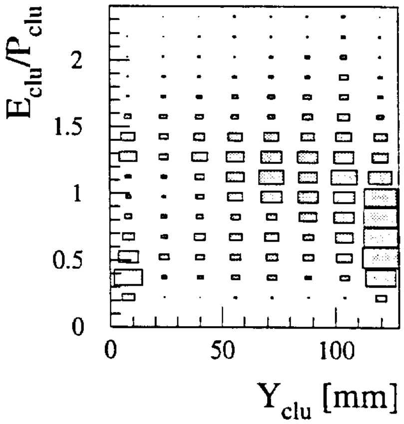
- **Data D(i,j):**
  - clusters from laser ON events



- **Signal Shape SS(i,j):**
  - simulate PCAL response to single e+ hits with Breit-Wheeler spectrum
  - add background from laser OFF events
  - use reconstruced Monte-Carlo hits
  - normalize: $\sum$ SS(i,j) = 1



- **Background Shape BS(i,j):**
  - clusters from laser OFF events
  - normalize: $\sum$ BS(i,j) = 1



- **Least-Squares fit with:**

$$\chi^2 = \sum_{i,j} \frac{[D(i,j) - \alpha\, SS(i,j) - \beta\, BS(i,j)]^2}{D(i,j)}$$

$\Rightarrow$ α: "signal" estimate, i.e. excess of clusters in laser ON sample.

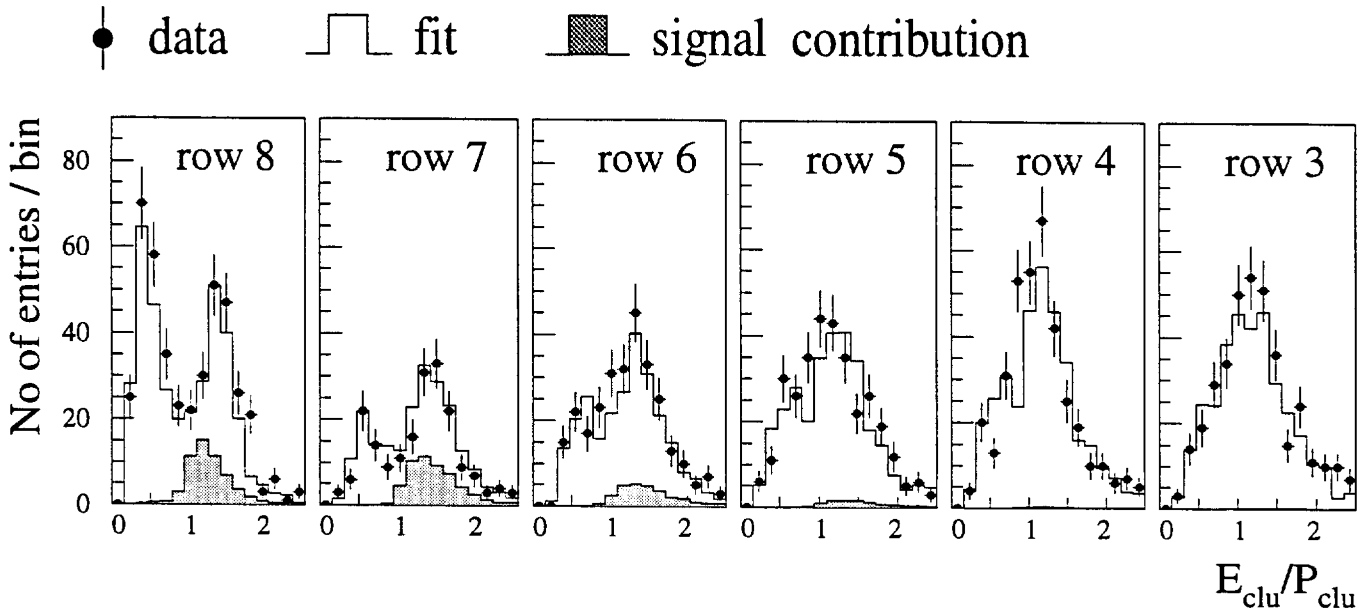
β: "background" estimate.

Result

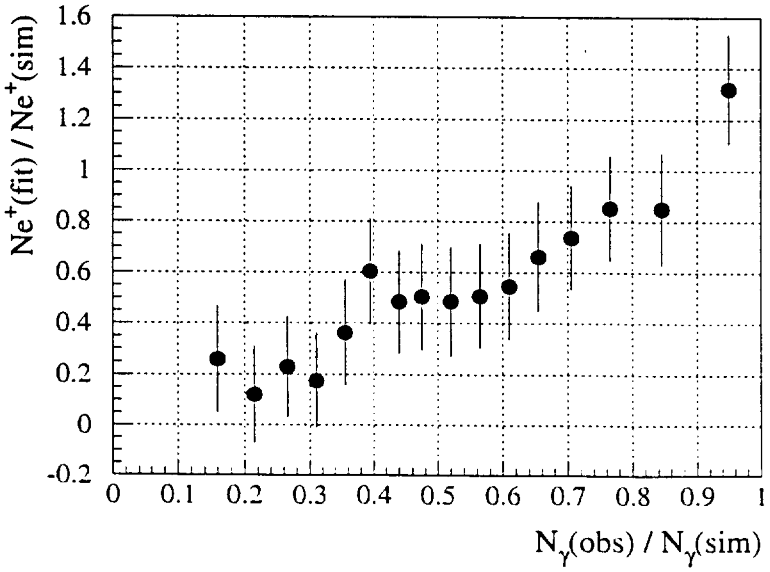
- Signal α: 133 +- 22 pairs

  ⇒ ~ 1 pair / 100 laser shots

  ⇒ ~ 6 sigma effect



Signal Dependence on Overlap



Summary

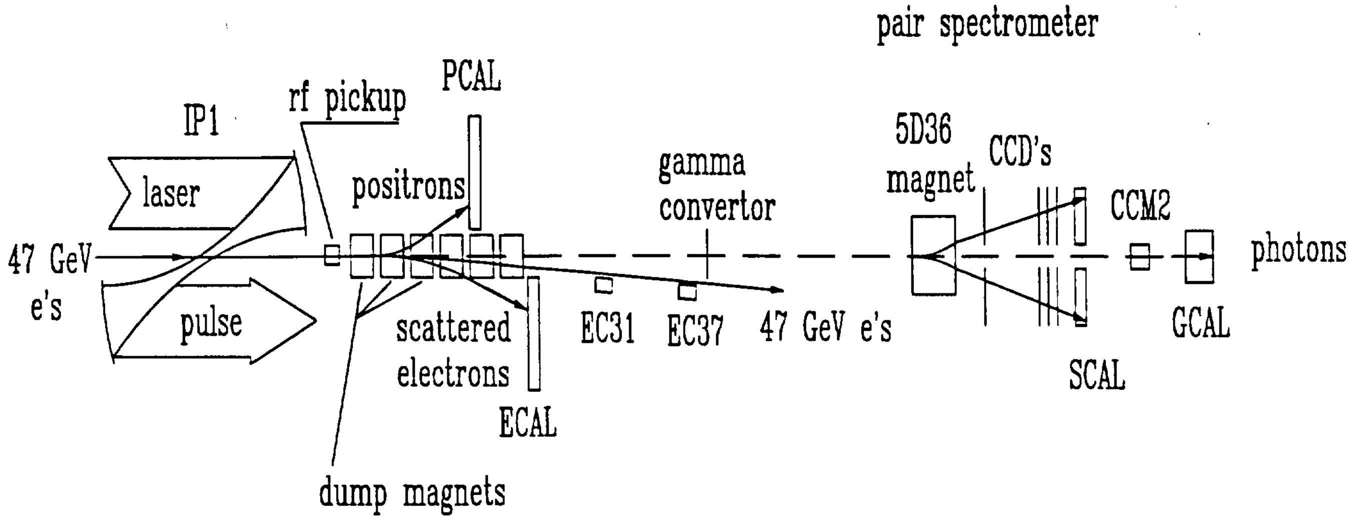
- Beam Polarization (April 94)
  - Measured electron beam polarization Pe = $0.81^{+0.04}_{-0.01}$, in good agreement with SLC/SLD measurements.
- Nonlinear Compton Scattering (March 95)
  - Observed clear nonlinear signal in electron spectrum.
  - Measured electron rates in n = 2, 3 and 4 region.
  - Dependence of scattering rates on electron momentum and field intensity is in good agreement with theoretical calculations over 3 orders of magnitude.
- Positron Production
  - Sept 94: Found 13 positron candidate events in data sample where 4.3 background events were expected.
  - Dec 95: Assuming a Breit-Wheeler energy spectrum, we found an excess of 133 +/- 22 positron candidates in laser ON sample.

Outlook

Near Future (August 96)

- Positron production at IP1:
  - smaller beam spot: 25 x 25 μm^2
  - 1000 times less background compared to Dec 95
  - signal to noise improvement of 10^3 to 10^4

- n = 2 signal and mass shift effect in gamma spectrum (CCD spectrometer).



Far Future

- "Light-by-Light" scattering with real photons at IP2
  - pair production cross section
  - pair invariant mass spectrum