

# COMPTON SCATTERING AT HIGH INTENSITIES

TOM HEINZL

ADVANCED QED METHODS FOR FUTURE ACCELERATORS

COCKCROFT INSTITUTE

03/03/2009

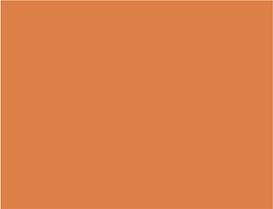


with: C. Harvey (UoP), A. Ilderton (Dublin), K. Ledingham (Strathclyde),  
H. Schworer (Stellenbosch), R. Sauerbrey and U. Schramm (FZD)

# Outline



1. Introduction
2. Nonlinear Compton Scattering: Overview
3. Nonlinear Compton Scattering: Results
4. Summary & Outlook



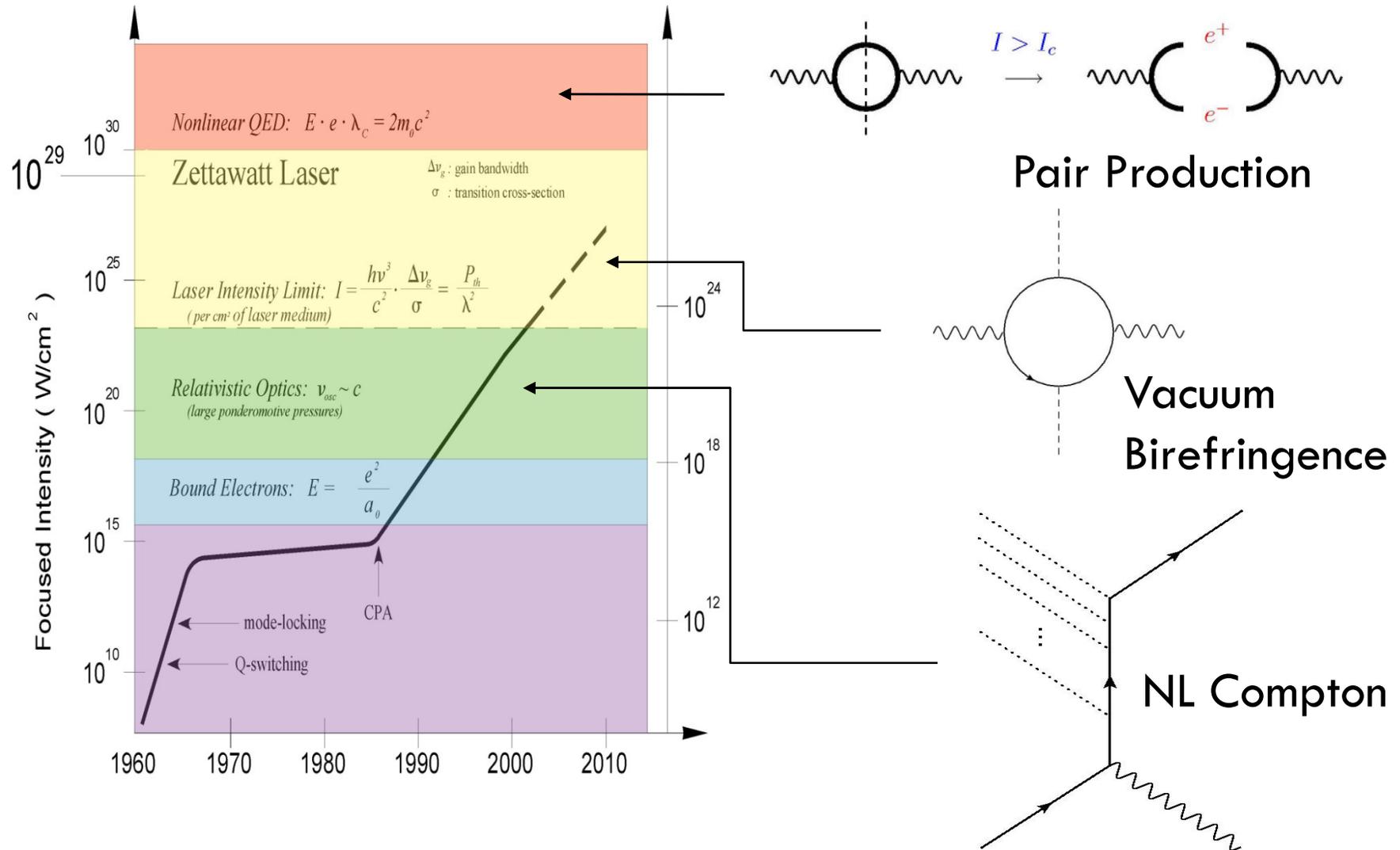
# 1. Introduction

# Strong field QED

- Strong (or intense) field QED = QED in presence of strong *external* electromagnetic field
- This talk: external field = **laser**
- Largest fields currently available in lab

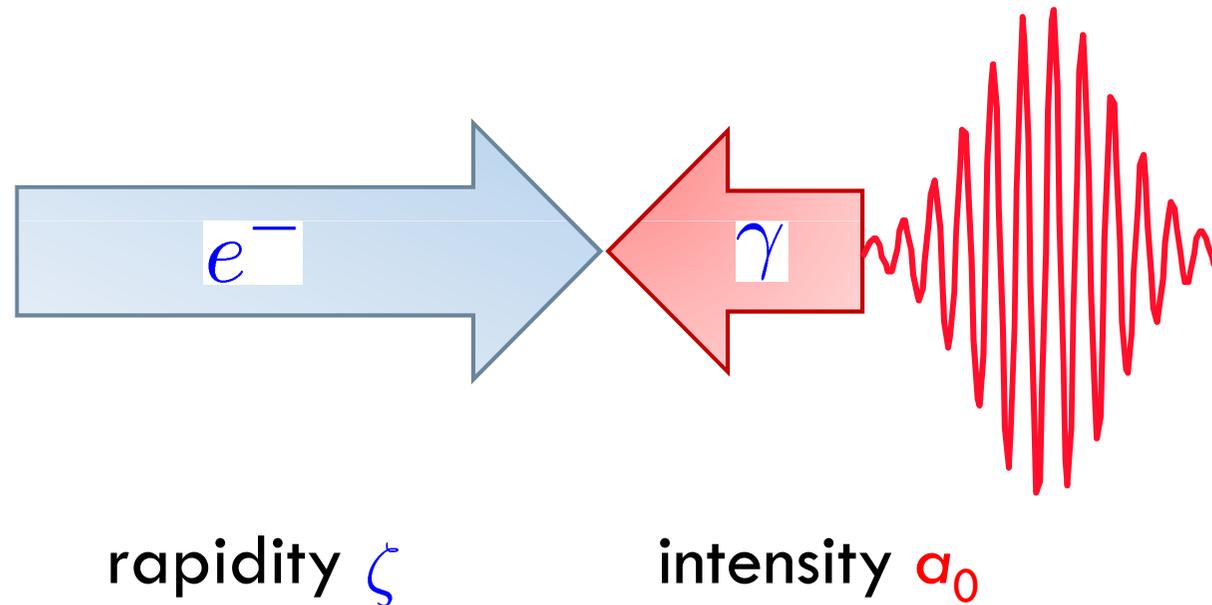
Power	$P \gtrsim 10^{15} \text{ W} \equiv 1 \text{ PW}$
Intensity	$I \gtrsim 10^{22} \text{ W/cm}^2$
Electric field	$E \gtrsim 10^{14} \text{ V/m}$
Magnetic field	$B \gtrsim 10^{10} \text{ G} \equiv 10^6 \text{ T}$

# Strong field QED processes



# Scenario

- Ultra intense laser pulse collides with electron beam



- **Q:** intensity effects on scattering process?

# Relevant parameter I

- 'dimensionless laser amplitude'

$$a_0 \equiv \frac{eE\lambda}{mc^2}$$

- (purely classical) ratio (no  $\hbar$ ):

$$\frac{\text{energy gain of } e^- \text{ in laser field } E \text{ across wave length } \lambda}{e^- \text{ rest energy}}$$

- NB:  $\lambda \equiv \lambda/2\pi$

# Relevant parameter II

- Lorentz and gauge invariant definition

(TH, A. Ilderton, Opt. Commun., 2009)

$$a_0^2 \equiv \frac{e^2}{m^2} \frac{\langle p_\mu T^{\mu\nu} p_\nu \rangle}{k \cdot p}$$

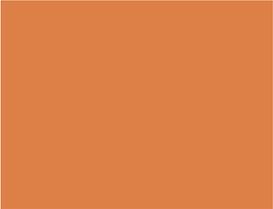
- with  $k$  and  $p$  4-momenta of  $\gamma$  and  $e^-$ , resp.
- $T^{\mu\nu}$  energy momentum tensor of laser field
- $\langle \dots \rangle$  = proper time average
- **NB:** in  $e^-$  rest frame,  $a_0^2 \sim \langle T^{00} \rangle \sim E^2$

# How large is $a_0$ ?

## □ Laser Facilities (Overview):

	XFEL (‘goal’)	FZD (150 TW)	VULCAN POLARIS (1PW)	VULCAN (10PW)	ELI HiPER
$I$ [W/cm <sup>2</sup> ]	$10^{27}$	$10^{21}$	$10^{22}$	$10^{23}$	$10^{26}$
$a_0$	10	20	70	200	$5 \times 10^3$

□ NB: Large  $a_0$  @ high power optical lasers



## 2. NLC: Overview

# Basic intensity effect

- Consider charged particle in plane e.m. wave ( $k^\mu$ )
- calculate average 4-momentum  $q^\mu \equiv \langle p^\mu(\tau) \rangle$   
where  $p^\mu(\tau)$  is solution of *classical* EoM
- Result: ‘**quasi**-momentum’ (longitudinal addition)

$$q^\mu \equiv p^\mu + \frac{a_0^2 m^2}{2 k \cdot p} k^\mu \equiv p^\mu + q_L^\mu$$

with  $q^2 = m^2(1 + a_0^2) \equiv m_*^2$

→ **mass shift** due to ‘quiver’ motion

(Sengupta 1951, Kibble 1964)

# Volkov solution

- Analytic solution of Dirac equation in plane e.m. wave  $A^\mu(\xi)$ ,  $\xi \equiv k \cdot x$

$$\Psi_p(x) = \exp \left\{ -ip \cdot x + \frac{1}{2ik \cdot p} \int^{k \cdot x} d\xi \left( 2ep \cdot A(\xi) - e^2 A^2(\xi) \right) \right\} \chi_P$$

- circular polarisation

$$A^\mu(\xi) = a_1^\mu \cos(k \cdot x) + a_2^\mu \sin(k \cdot x)$$

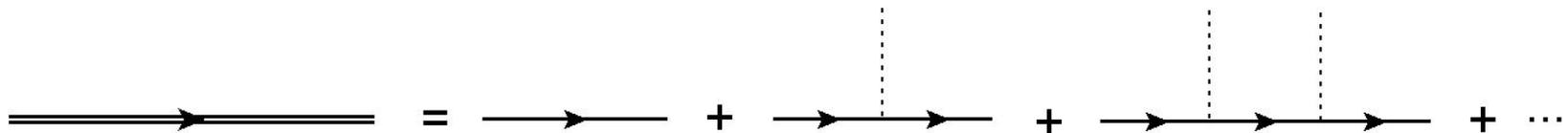
- yields Volkov solution (including **quasi**-momentum)

$$\Psi_p(x) = \exp \left\{ -iq \cdot x - ie \frac{a_1 \cdot p}{k \cdot p} \sin(k \cdot x) + ie \frac{a_2 \cdot p}{k \cdot p} \cos(k \cdot x) \right\} \chi_P$$

- Result:  $q_L^\mu$  from zero mode of  $A^2 \sim a_0^2$

# Furry picture

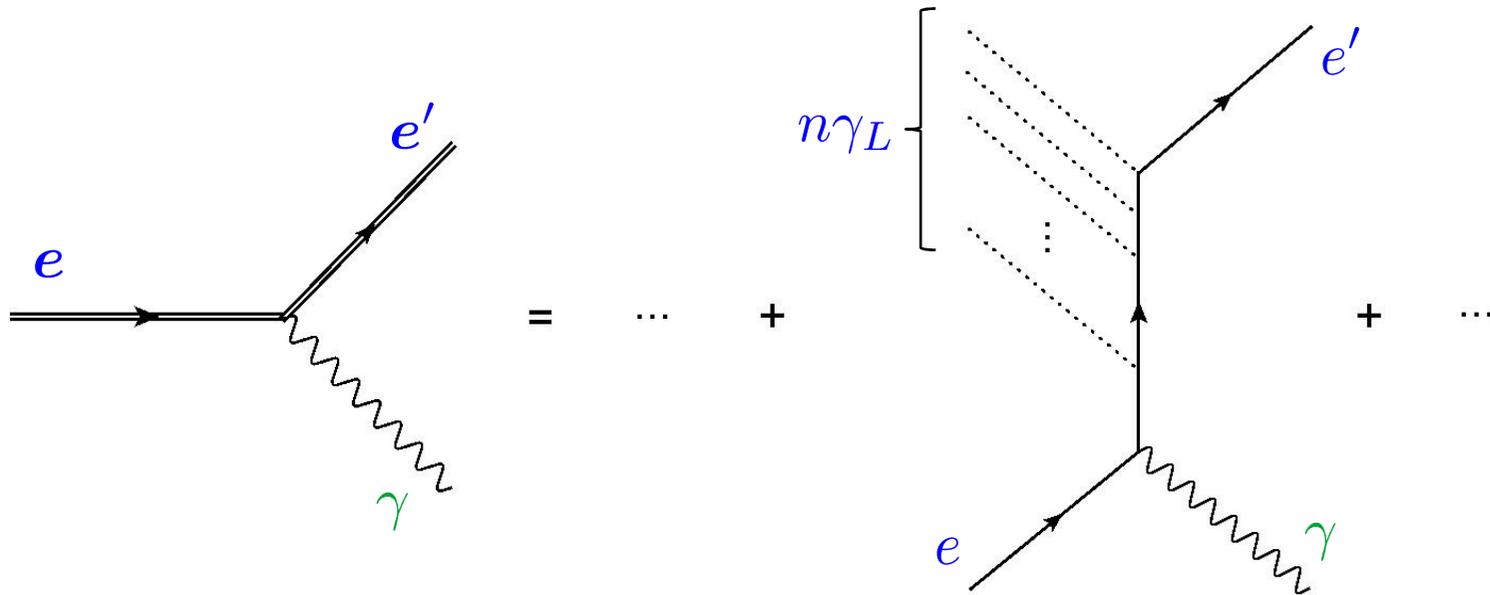
- In presence of *external* strong laser field  $A_\mu$
- Get additional interaction  $\mathcal{L}'_{\text{int}} = eA_\mu j^\mu$  (no  $F^2$ )
- Include into *free* Lagrangian  $\mathcal{L}'_0 \equiv \mathcal{L}_0 + \mathcal{L}'_{\text{int}}$
- Main effect in PT: replace free Dirac electrons  $\psi_p$  by **Volkov** electrons  $\Psi_p$
- Pictorially: ‘dressed’ (Volkov) electron line



- Continuous emission/absorption of laser photons (-----)

# NLC scattering

- Expand Furry picture diagram  $\rightarrow$
- Sum over all processes of the type  $e + n\gamma_L \rightarrow e' + \gamma$



Schott 1912; Nikishov/Ritus 1964,  
Brown/Kibble 1964, Goldman 1964

# NLC cont<sup>d</sup> (Landau/Lifshitz, Vol. 4)

- S-matrix element

$$S_{fi} \sim -ie \int \bar{\Psi}_{p'} A \Psi_p$$

- Sub-processes

$$e + n\gamma_L \rightarrow e' + \gamma$$

- Quasi-momentum conservation

$$q + nk = q' + k'$$

- Below: assume circular polarisation

- NB1:  $q = q(a_0)$

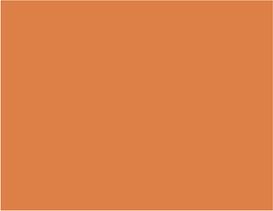
- NB2: 'nonlinear'  $\rightarrow n > 1$

- Observables:

- ▣  $e'$  spectrum: SLAC E-144  
(Bula et al. '96, Burke et al. '97)

- ▣  $\gamma$  spectrum:  
no quantitative analysis yet  
(plans at FZD & Daresbury)

- ▣ In particular:  
 $a_0$  effects in  $\gamma$  spectra?



# NLC: Results

# NLC formula

- Recall Compton formula (lab frame rapidity  $\zeta$ )

$$\omega' = \frac{\omega}{1 + (\omega/m - \sinh \zeta) e^{-\zeta} (1 - \cos \theta)}$$

- Quasi-momentum conservation yields modified (nonlinear,  $a_0$  dependent) Compton formula

$$\omega' = \frac{n\omega}{1 + \kappa_n e^{-\zeta} (1 - \cos \theta)}$$

with *total longitudinal momentum*

$$\kappa_n \equiv n\omega/m - \sinh \zeta + a_0^2 e^{-\zeta/2} \equiv |\mathbf{P}|/m$$

# Kinematic edge

- For backscattering ( $\theta = \pi$ ) and large  $\gamma = \cosh \zeta \gg 1$

- 'L'C:

$$\omega'_{\max} \simeq 4\gamma^2\omega$$

- Blue shift:  $\omega' > \omega$ , 'inverse Compton'

- NLC:

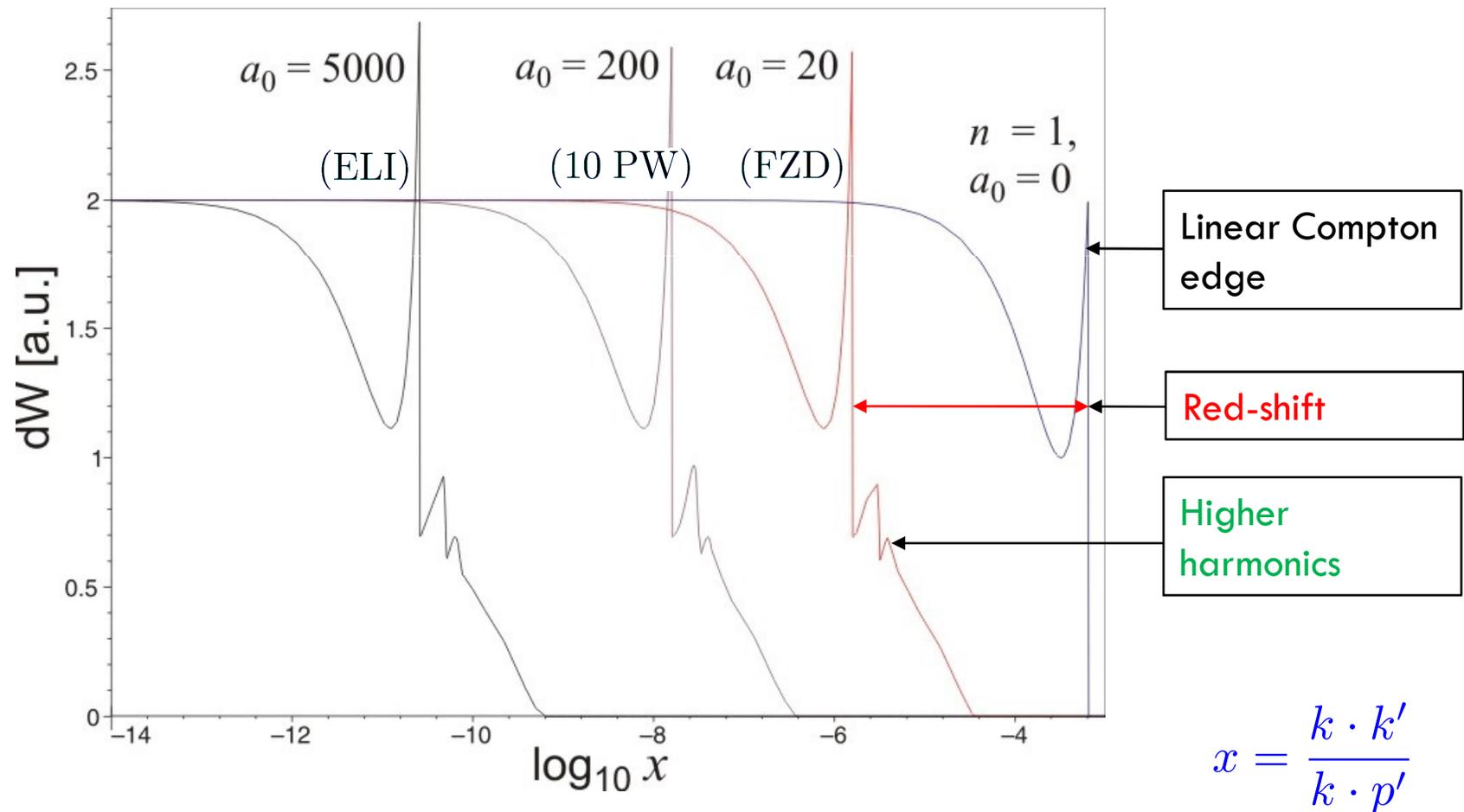
$$\omega'_{n,\max} \simeq 4\gamma^2 n\omega / a_0^2 \quad (a_0^2 \gg 1)$$

- Blue-shift (inverse Compton) as long as  $a_0 \lesssim 2\gamma$

- Red-shift of  $n=1$  edge compared to LC

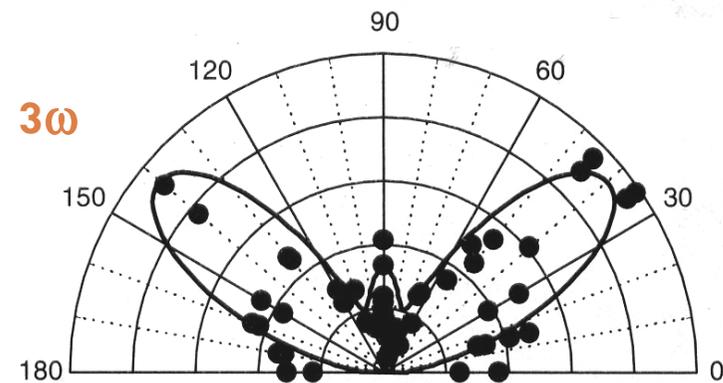
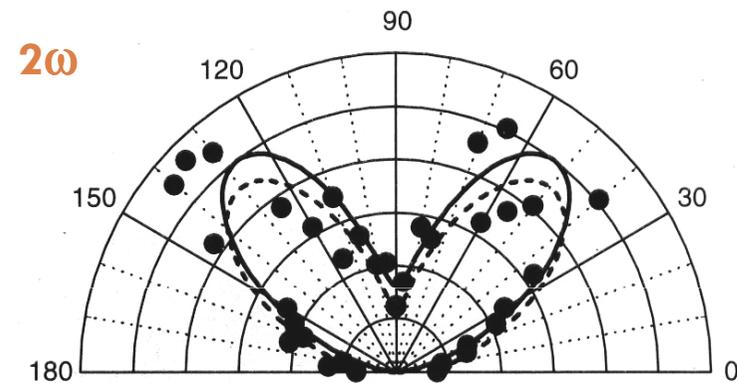
$$\omega'_{\max} \simeq 4\gamma^2\omega \longrightarrow 4\gamma^2\omega / a_0^2$$

# Main $a_0$ effects



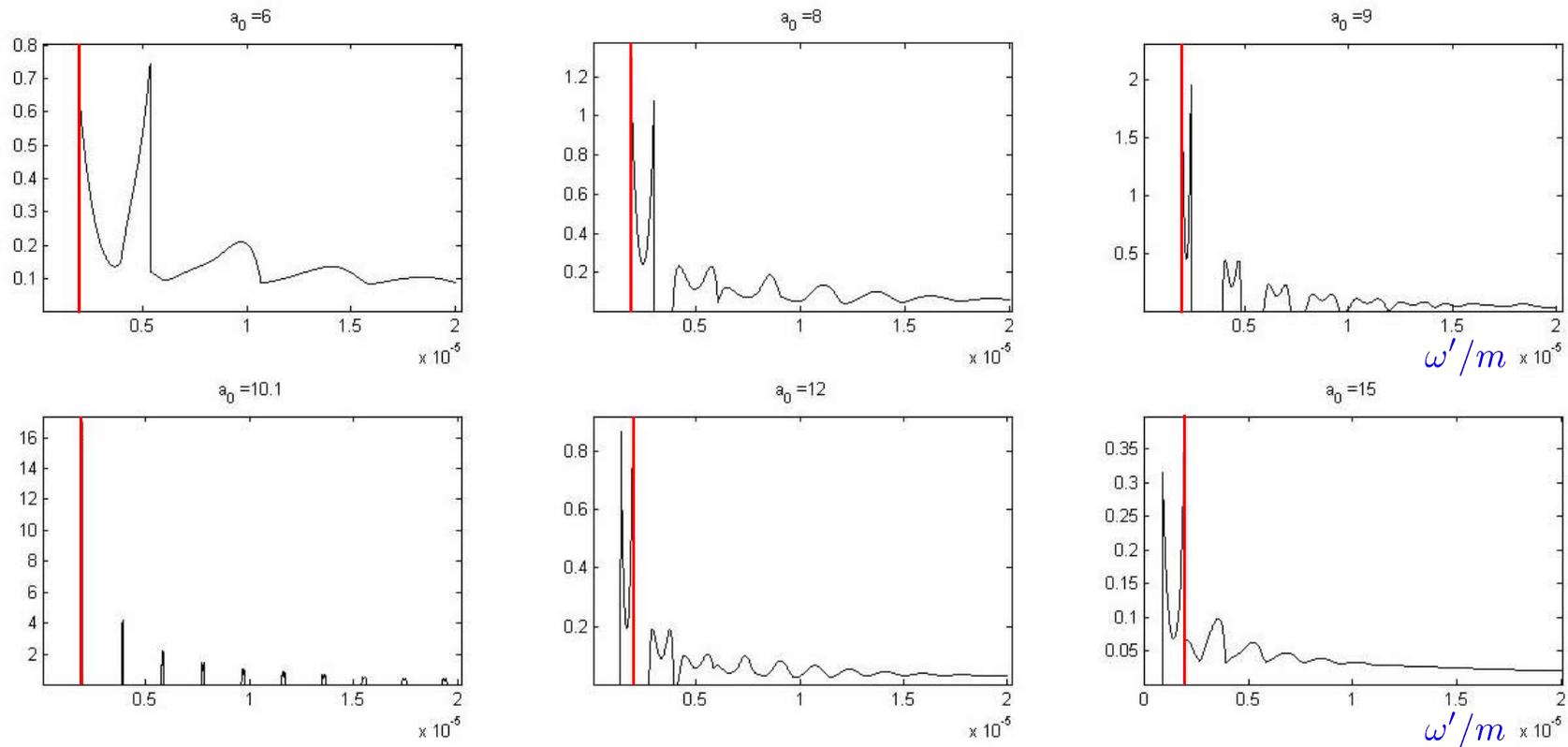
# Aside: Higher harmonics

- Harmonics  $n=2$  and  $n=3$  observed in ‘relativistic Thomson scattering’ using *linearly* polarised laser ( $a_0=1.88$ )
- Signal: quadrupole and sextupole pattern in angular distribution  
(Chen, Maksimchuk, Umstadter, Nature, 1998)



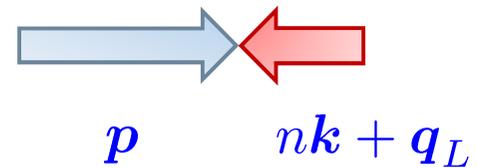
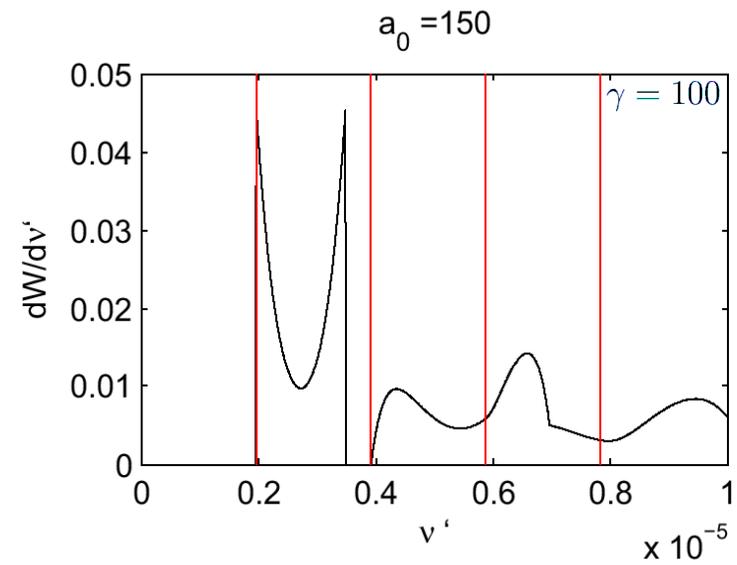
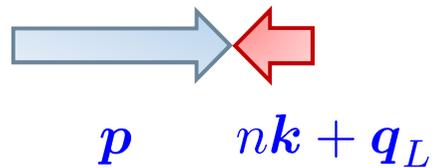
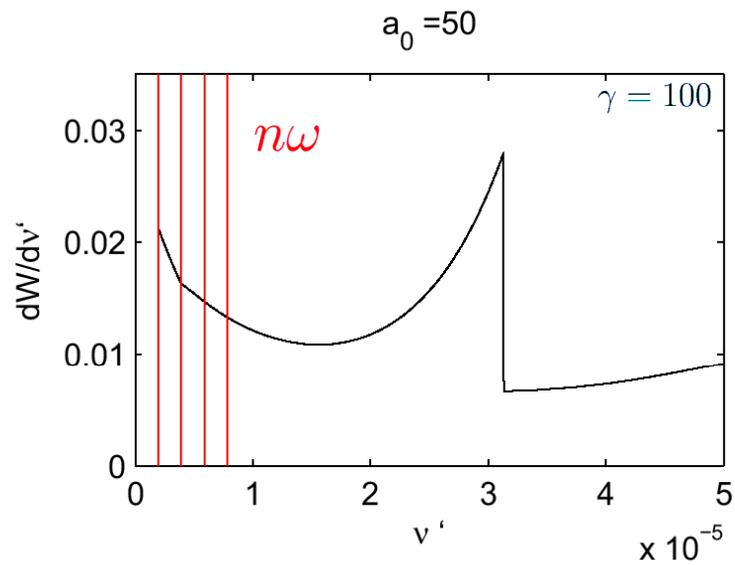
$$\theta = 90^\circ$$

# $a_0$ dependence (lab)



Tuning  $a_0$  similar to changing frame: when  $a_0 = a_{0c} \simeq 2\gamma$   
'inverse' Compton  $\rightarrow$  Compton

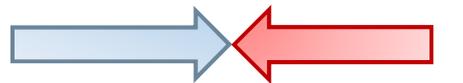
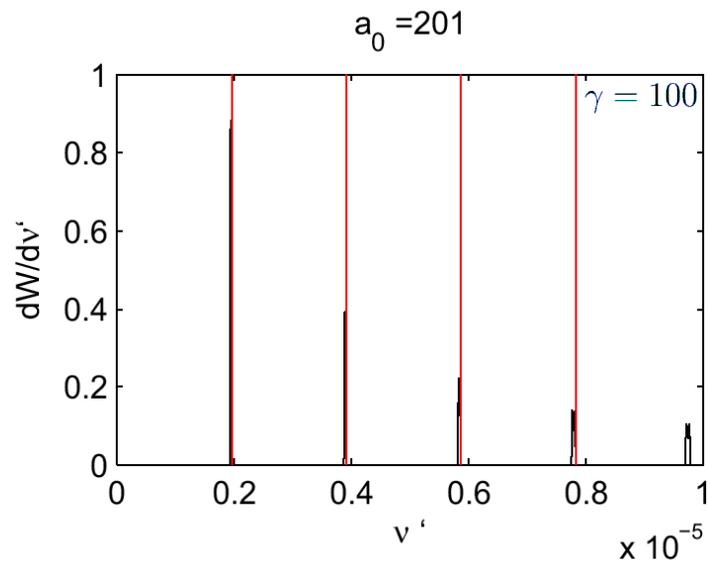
# $a_0$ dependence (lab)



'inverse' Compton  $\omega'_n > n\omega$

$$a_0 < a_{0c} \simeq 2\gamma$$

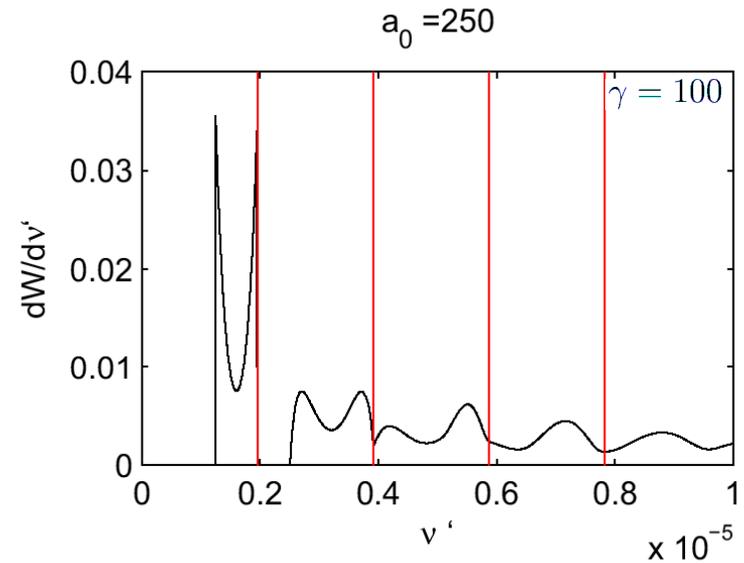
# $a_0$ dependence (lab)



$$p = -(nk + q_L)$$

$$a_0 = a_{0c} \simeq 2\gamma$$

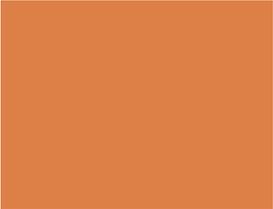
CM frame



$$p \quad nk + q_L$$

$$a_0 > a_{0c} \simeq 2\gamma$$

Compton



## 4. Summary & Outlook

# NLC: Summary

□ process:  $e + n\gamma_L \rightarrow e' + \gamma$

□  $a_0$  effects on  $\gamma$  spectra

▣ red-shift of Compton edge

$$4\gamma^2\omega \rightarrow 4\gamma^2\omega/a_0^2$$

▣ Higher harmonics generation (HHG) for large  $a_0$  ?

□ lab frame:

▣ at 'critical'  $a_0 = a_{0c} \simeq 2\gamma$ , spectrum 'collapses' to line spectrum

▣ Boundary between 'inverse' Compton ( $\omega' > \omega$ ) and Compton ( $\omega' < \omega$ )

# NLC: Outlook

## □ Theory requires testing:

- Establish Furry picture
- Quasi-momentum?
- Mass shift?

## □ Applications include:

- X-ray generation  
e.g. T-REX @ Livermore
- Polarized gamma beams
- Utilise for probing vacuum birefringence?

