

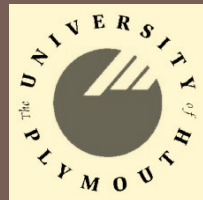
COMPTON SCATTERING AT HIGH INTENSITIES

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ADVANCED QED METHODS FOR FUTURE ACCELERATORS

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Outline



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



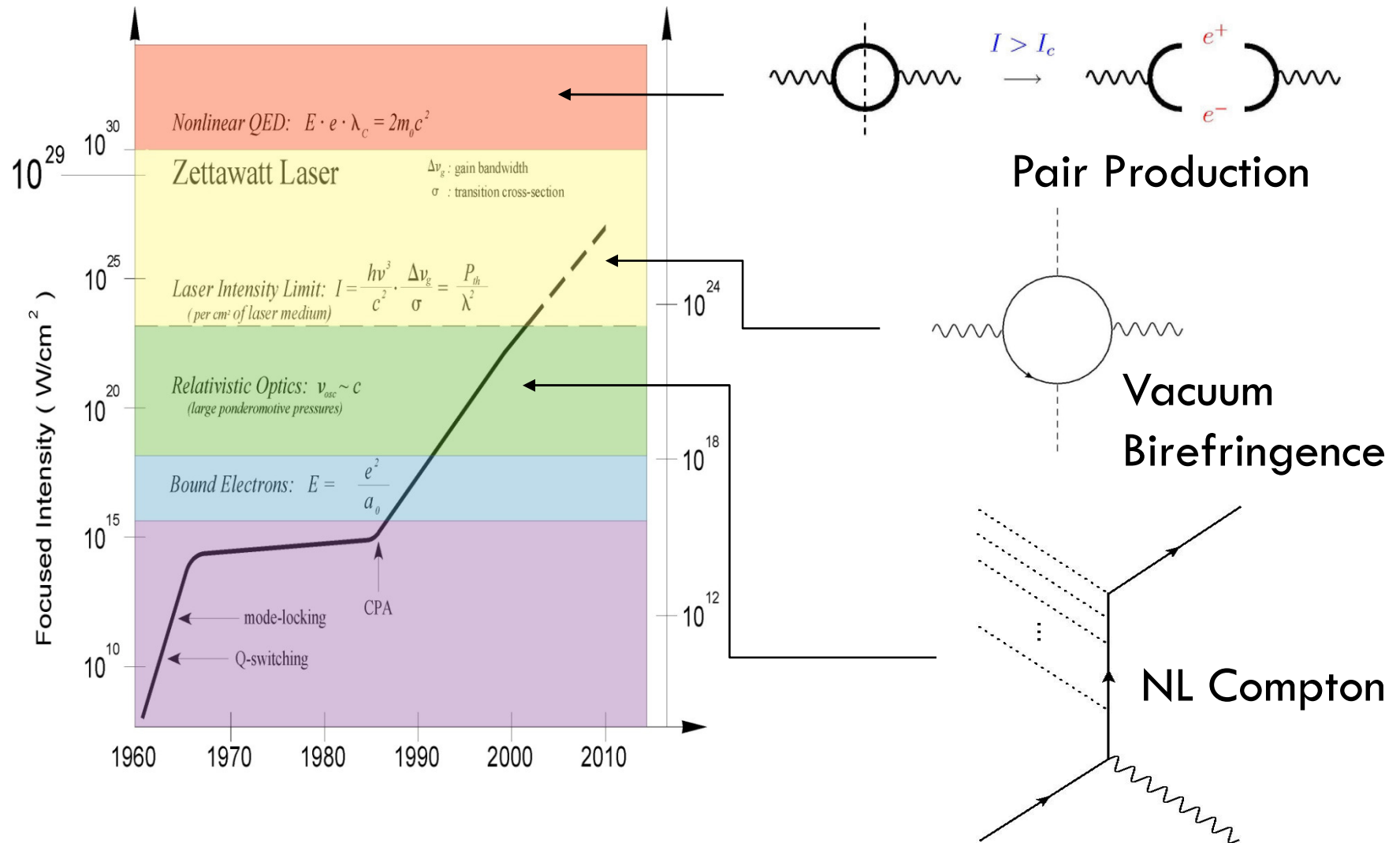
1. Introduction

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

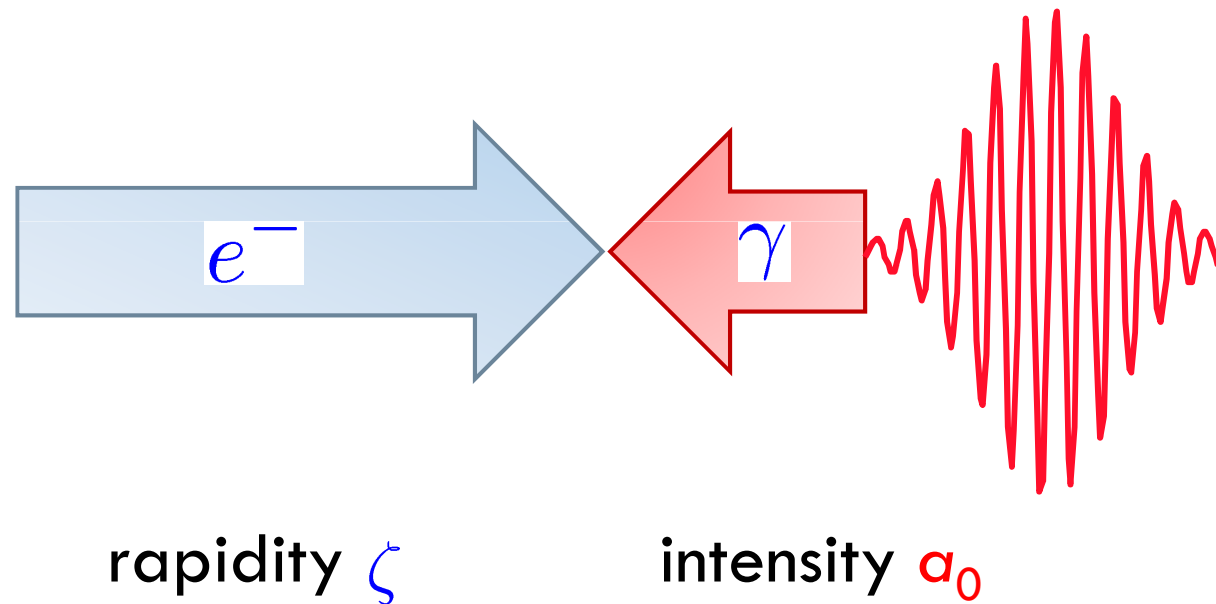
Power	$P \gtrsim 10^{15} \text{ W} \equiv 1 \text{ PW}$
Intensity	$I \gtrsim 10^{22} \text{ W/cm}^2$
Electric field	$E \gtrsim 10^{14} \text{ V/m}$
Magnetic field	$B \gtrsim 10^{10} \text{ G} \equiv 10^6 \text{ T}$

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 γ 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 ²]	10^{27}	10^{21}	10^{22}	10^{23}	10^{26}
a_0	10	20	70	200	5×10^3

□ NB: Large a_0 @ high power optical lasers



2. NLC: Overview

Basic intensity effect

- Consider charged particle in plane e.m. wave (k^μ)
- 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

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

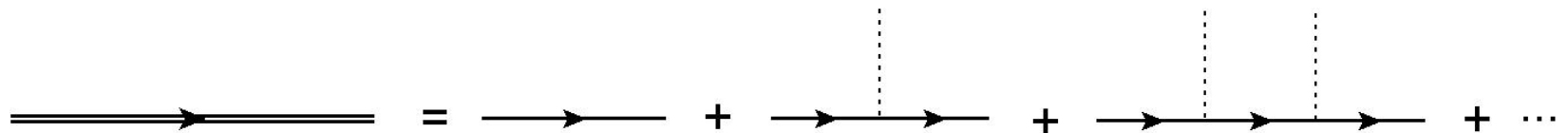
- yields Volkov solution (including quasi-momentum)

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

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

Furry picture

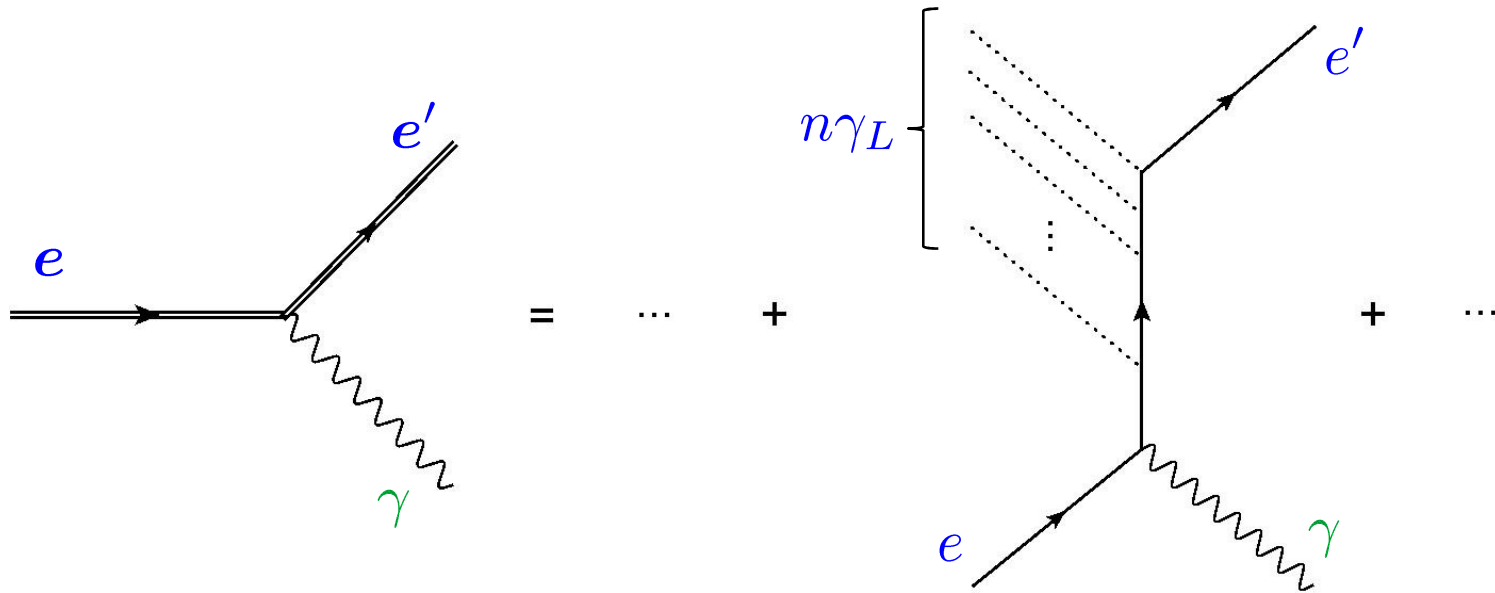
- In presence of *external* strong laser field A_μ
- Get additional interaction $\mathcal{L}'_{\text{int}} = eA_\mu j^\mu$ (no F^2)
- Include into *free* Lagrangian $\mathcal{L}'_0 \equiv \mathcal{L}_0 + \mathcal{L}'_{\text{int}}$
- Main effect in PT: replace free Dirac electrons ψ_p by **Volkov** electrons Ψ_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^d (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)

- ▣ γ spectrum:
no quantitative analysis yet
(plans at FZD & Daresbury)

- ▣ In particular:
 a_0 effects in γ spectra?



NLC: Results

NLC formula

- Recall Compton formula (lab frame rapidity ζ)

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

- 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:

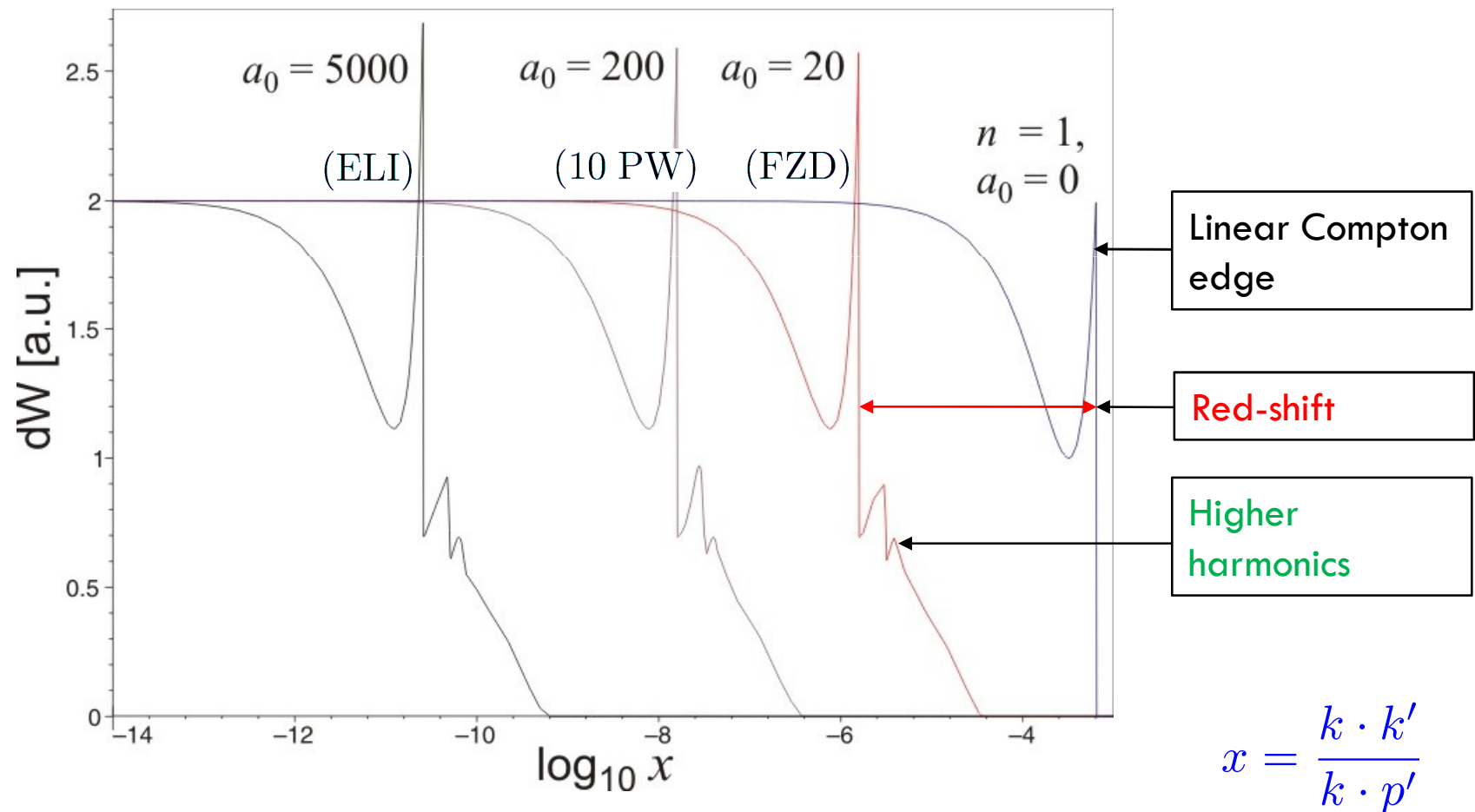
$$\omega'_{n,\max} \simeq 4\gamma^2 n\omega / a_0^2 \quad (a_0^2 \gg 1)$$

- 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

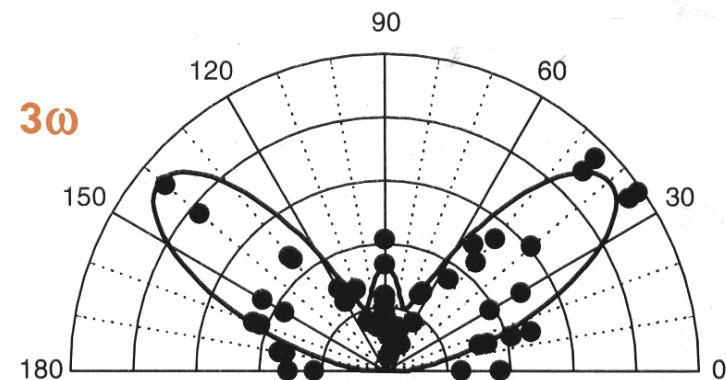
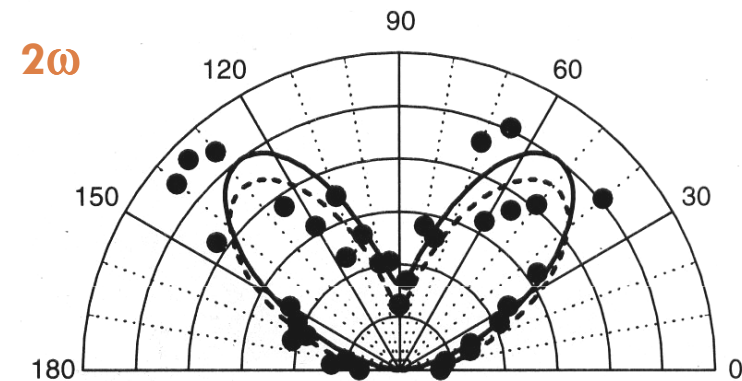


Aside: Higher harmonics

- Harmonics $n=2$ and $n=3$ observed in 'relativistic Thomson scattering' using *linearly* polarised laser ($a_0=1.88$)

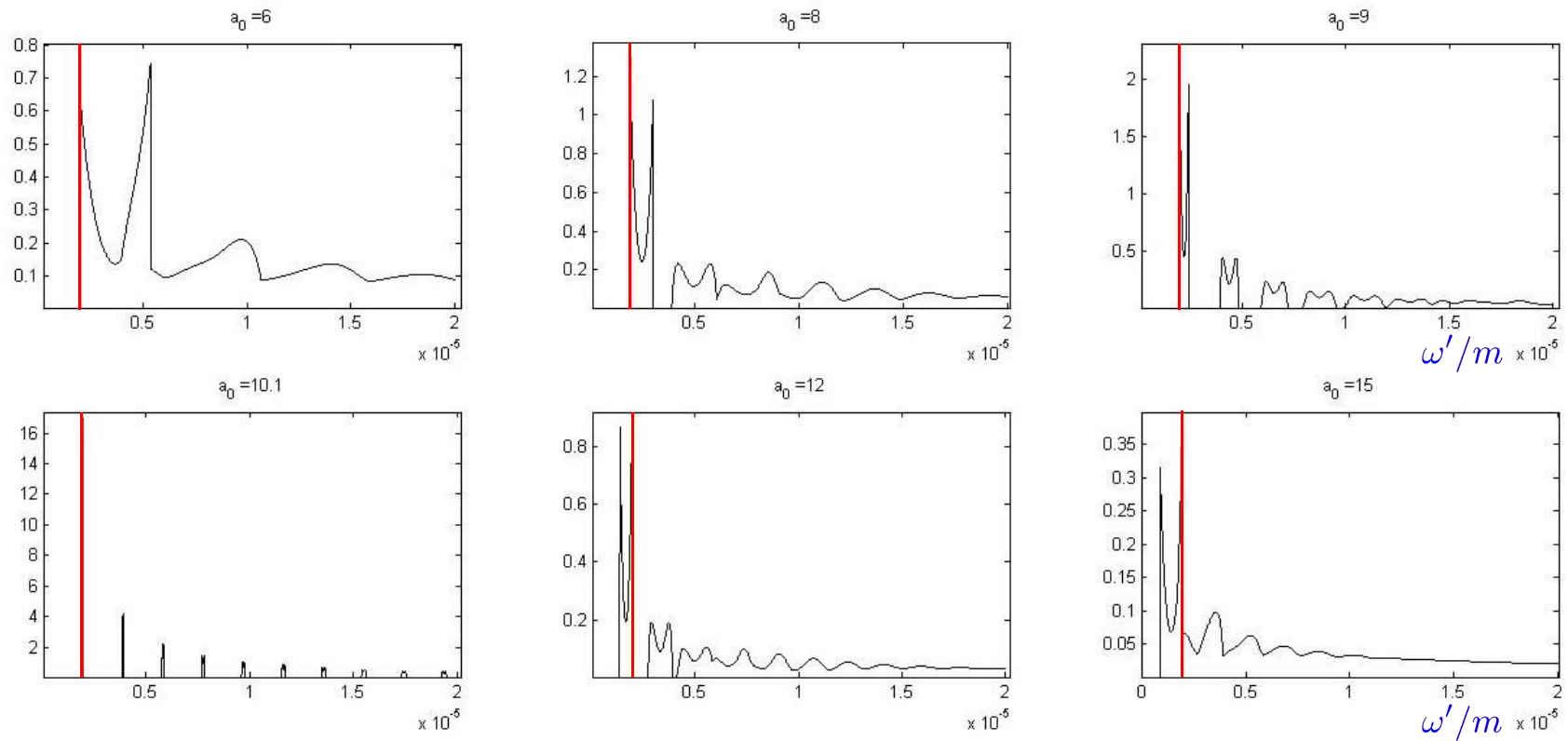
- Signal: quadrupole and sextupole pattern in angular distribution

(Chen, Maksimchuk, Umstadter, Nature, 1998)



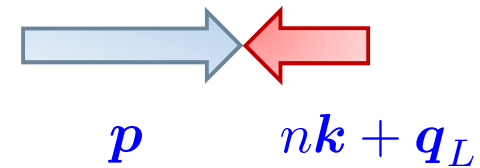
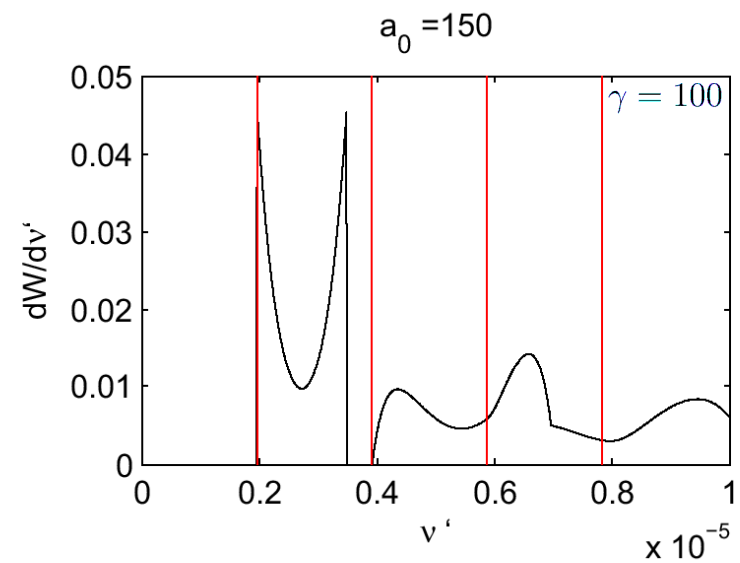
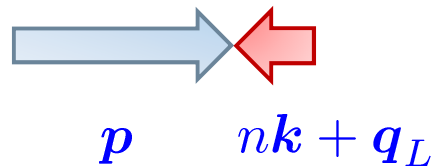
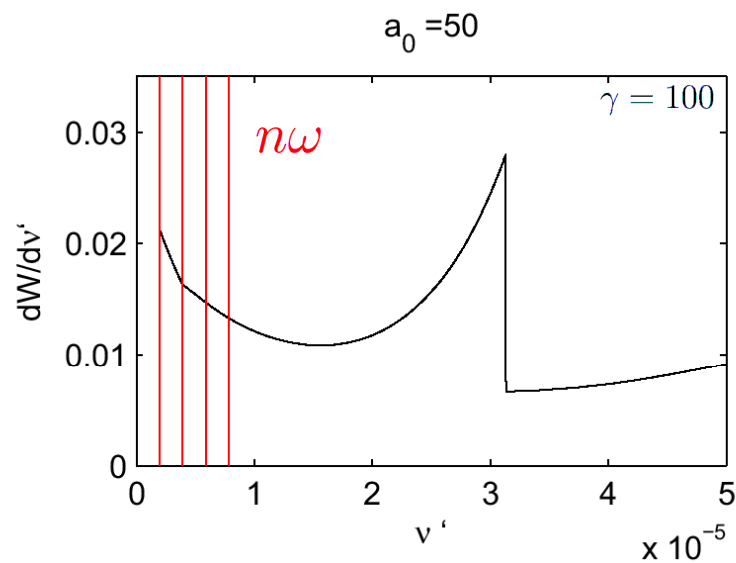
$$\theta = 90^\circ$$

a_0 dependence (lab)



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

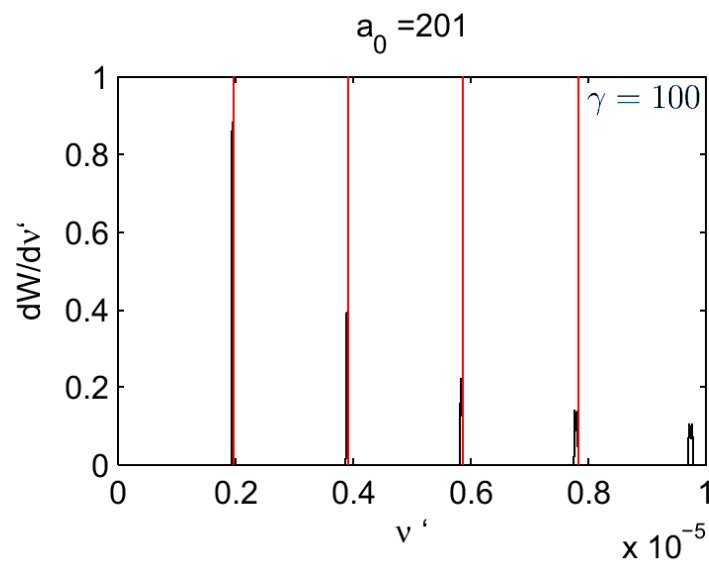
a_0 dependence (lab)



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

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

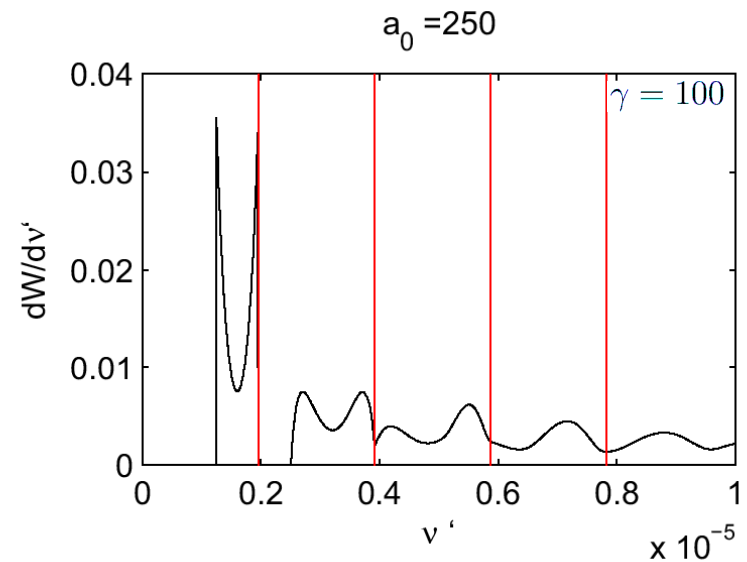
a_0 dependence (lab)



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

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

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 γ 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?

