Testing strong field QED with a laser on the electron beam at ILC/CLIC

Stefano Porto

with Anthony Hartin and Gudrid Moortgat-Pick

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Universität Hamburg
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Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

DESY

Outline

1. Strong field QED
2. SLAC Experiment 144 and proposal at ILC/CLIC
3. Testing Zel'dovich quasi-levels and the Unruh effect
4. Conclusions and outlook

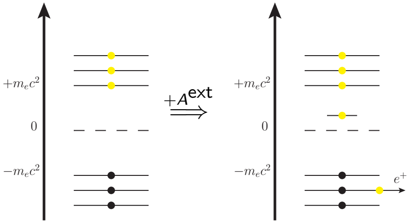
See also Tony Hartin's talk at the working group RD9.

QED in strong external electromagnetic fields

Klein, Sauter, Schwinger:

$$E_{\rm cr} = \frac{m_e^2}{e} = 1.3 \cdot 10^{18}\ \ \mathrm{V/m}$$

$$B_{\rm cr} = \frac{m_e^2}{e} = 4.41 \cdot 10^{9}\ \ \mathrm{T}$$



Schwinger critical field: vacuum polarization. Ex. laser $I \sim 10^{30}\ \mathrm{W/cm^2}$.

Can develop on magnetars, heavy ions collisions, and . . . linear colliders.

- $\Upsilon \equiv \frac{e}{m_e^3}\sqrt{|(F_{\mu\nu}p^\nu)^2|}\ \sim\ \gamma\frac{E}{E_c}$ or $\gamma\frac{B}{B_c}$.

  'Intensity' of the external field. Vacuum is polarized at $\Upsilon \sim 1$.

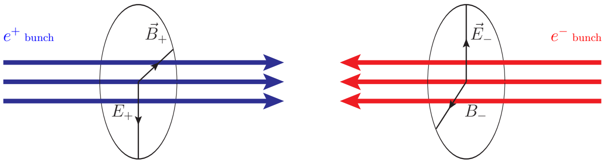
- $\eta = \frac{e}{m_e}\sqrt{|A_\mu A^\mu|}$.

  Describes the multiplicity of photons from the external field in the initial states.

Strong fields at linear colliders

High luminosity: $\mathcal{L} = f \frac{n_1 n_2}{4\pi \sigma_x \sigma_y}$

needs squezeed bunches (small σ_x, σ_y) $\Longrightarrow$ large $\Upsilon \sim \frac{1}{\sigma_x + c\,\sigma_y}$



Intense charge bunches $\longrightarrow$ strong field associated

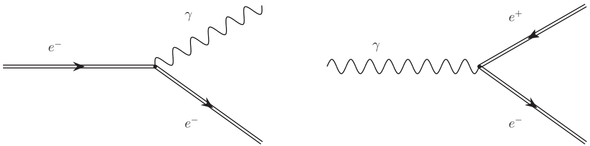
Machine	LEP II	SLC	ILC-1TeV	CLIC-3TeV
Energy (GeV)	94.5	46.6	500	1500
$\Upsilon_{average}$	0.00015	0.001	0.27	3.34

e^- sees 2 *almost* anticollinear **constant crossed fields**: $|\mathbf{E}| = |\mathbf{B}|$, $\mathbf{E} \cdot \mathbf{B} = 0$, **static**.

★ high density of photons + wavefunction overlap $\Rightarrow$ external field $\sim$ classical field.

Strong fields at linear colliders

Beamstrahlung; coherent pair production [Chen, Telnov '89]; incoherent pair production. Implemented in `CAIN` [Yokoya] and `GUINEAPIG` [Schulte].



Need to consider all the processes in the strong field [SP, Hartin, Moortgat-Pick '13].

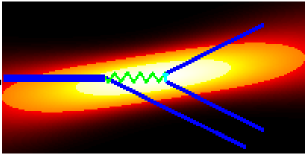
- Generalized Dirac equation: Furry picture [Furry '51]
- Classical electron motion: Quasi-classical operator approach [Baĭer & Katkov '51]

Strong Fields/Nonlinear QED to be considered in $\gamma\gamma$ interactions [Reiss '51], in particular:

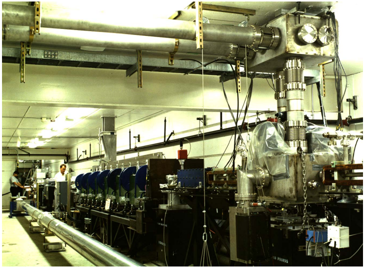
- $\gamma\gamma$-colliders [Ginzburg et al '81], [TESLA TDR].
- Laser physics ...

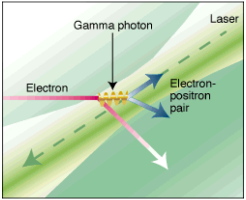
SLAC Experiment 144

E144
cranked beyond the limit



www.slac.stanford.edu/exp/e144/

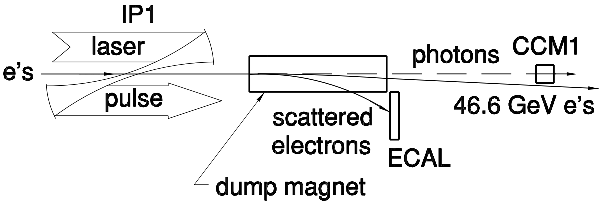




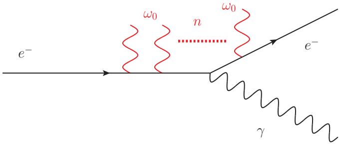
- SLC Final Focus Test Beam (FFTB): 46.6 GeV
- Laser peak intensities: $\approx 0.5 \cdot 10^{18}$ W/cm^2
- Few weeks of operations

[Bamber *et al.* '99].

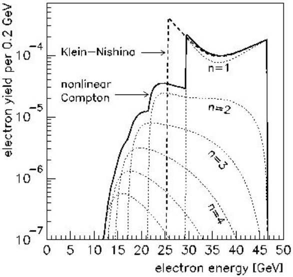
E144: set up for Nonlinear Compton scattering, $e^- + n\omega_0 \to e^- + \gamma$



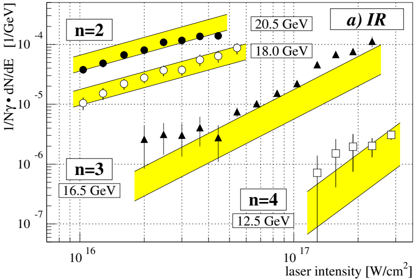
- $I = \frac{1}{377\Omega} E^2_{\mathrm{lab}}, \qquad I_{\mathrm{max}} \approx 0.5 \cdot 10^{18}\ \mathrm{W/cm^2}$
- $\eta^2 = 3.7 \cdot 10^{-19}\, I\, \lambda^2, \qquad \eta_{\mathrm{max}} \sim 0.4$
- $\Upsilon_e = \eta \frac{p \cdot k}{m^2 c^4}, \qquad \Upsilon_{e,\,\mathrm{max}} \sim 0.27$
- Terawatt pulses at $\lambda_{IR} = 1053$ nm and $\lambda_g = 527$ nm, circular/linear polarized laser beams.



The rates are important, not the bad defined cross sections [Nikishov & Ritus '64].
Observed dependence on the number n of absorbed γs.

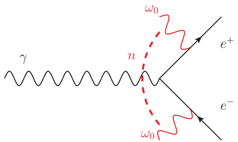


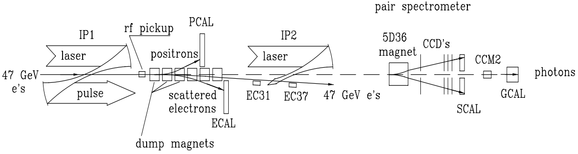
Adapted from [McDonald '98], [Bamber et al. '99].



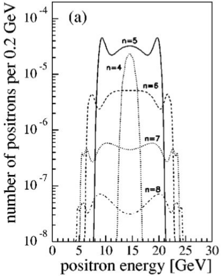
Rate at order $n \propto I^{n-1}$

Multiphoton Breit-Wheeler pair production at E144, $\gamma + n\omega_0 \to e^+e^-$





Theory: [Nikishov & Ritus '64-'65]. Dependences on the number n_γ and on Υ.



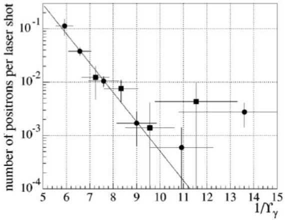


FIG. 49. Number of positrons per laser shot as a function of $1/\Upsilon_\gamma$. The circles are the 46.6 GeV data whereas the squares are the 49.1 GeV data. The solid line is a fit to the data.

Adapted from [McDonald '98], [Bamber et al. '99].

Proposal to repeat E144 at ILC/CLIC

Today and next future:

- Daresbury, FZD: 10 MeV-e^- and high intensity ($\eta \sim 10$).
- Future very high intensities: XFEL 10^{27} W/cm^2, ELI 10^{26} W/cm^2.

No high energy physics.

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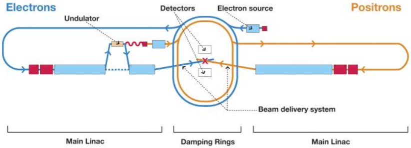
No high energy physics. Next linear collider?

Powerful electron beams 175-500 GeV: with similar laser as E144, $\Upsilon \gtrsim 1$:



Physical case for

- pair production
- vacuum polarization

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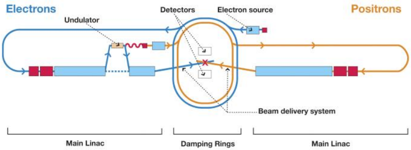

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Possibilities: **ADD-ON! no (compelling) DESIGN CHANGES**

- Exploiting the polarimeter laser or a specific laser on the beam dump.
- Exploiting Test-beam or parasitically the electron beam.
- Performing the same experiment on the positron beam (dump or not).

Side effect: electron mass-shift

The effective mass of an electron in an electromagnetic wave [Brown and Kibble '64], [Kibble '64]

$$\overline{m} = m\sqrt{1+\eta^2}, \qquad \eta = \frac{eE}{m\omega_0 c}$$

and the correspondent quasi-momentum $q_\mu = p_\mu + \frac{\eta^2 m^2}{2k\cdot p} k_\mu$ is such that $q^2 = \overline{m}^2$.

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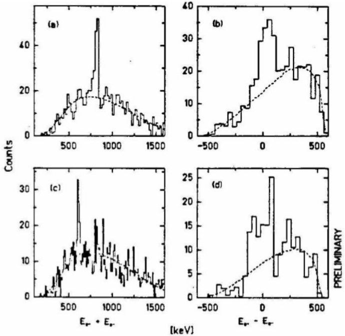
Searching structures in the e^+e^- invariant-mass spectrum.

Darmstadt [Schweppe et al '83] and CERN-NA-046 [Bassompierre et al. '91] picks?



$$\overline{M}^2 = (q_1^2 + q_2^2) \propto \sqrt{n}$$

Complications because of $\overline{m}$.

$$1 + \frac{\Delta}{1+\eta^2} \leq \frac{M^2}{4m^2} \leq 1 + \Delta$$

No decisive evidence for the mass shift at E144 [Bamber et al. '98].

Observed in Rochester [Meyerhofer et al. '95].

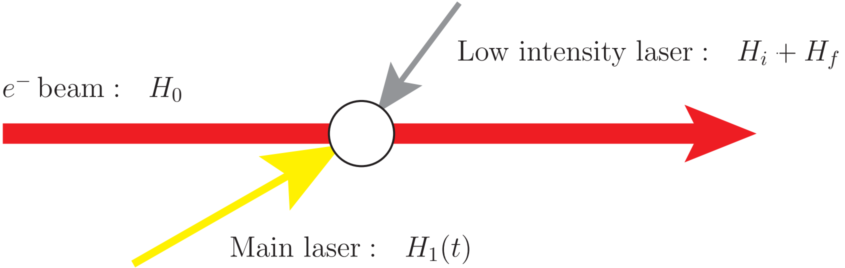
Radiative transitions between Zel'dovich quasi-levels in a laser

System H_0 interacting with em field $H_f + H_i$ under a T-periodic force $H_1(t)$: **NEW!**

$$H = H_0 + H_1(t) + H_f + H_i$$

$\Rightarrow$ quasi-levels spectra with energy gaps $m \cdot \hbar\omega = \hbar 2\pi / T$ [Zel'dovich '67].

Transitions and radiations $m' \cdot \hbar\omega$ from **ground state** to **excited state** and viceversa due to H_1.



Low I laser to the IP, frequency-tuned to stimulate quasi-levels transitions.

Outlook: probing the Unruh effect

A gravity accelerated observer out of a black hole sees Hawking radiation [Hawking '74]:

$$T = \frac{\hbar g}{2\pi ck}$$

Equivalence $\Longleftrightarrow$ Principle

An accelerated observer in a region without gravity feels a radiation with a thermal bath [Fulling '72, Davies '75, Unruh '76]:

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An electron observer Thomson-scatters with the Unruh termal bath photons.

Unruh radiation:

$$\frac{dU_{\text{Unruh}}}{dt} = \frac{\hbar r_e^2 \left(\frac{eE}{m}\right)^4}{90\pi c^6} = \frac{\hbar r_e^2 a^4}{90\pi c^6} \propto T^4$$

Larmor radiation:

$$\frac{dU_{\text{Larmor}}}{dt} = \frac{\hbar 2 e^2 a^2}{3c^3}$$

$\frac{dU_{\text{Unruh}}}{dt} \sim \frac{dU_{\text{Larmor}}}{dt}$ at $\sim 100 \cdot E_{\text{cr}}$. With 500 GeV electrons we would need:

$$E_{\text{lab}} \sim 10^{13}\ \text{V/m}, \quad I_{\text{laser}} \sim 10^{19}\text{-}10^{20}\ \text{W/cm}^2$$

Large background. Can be observed at all?

Debate still open [Akhmedov, Singleton '07], [Martín-Martínez, Fuentes, Mann '11], [Ford, O'Connell '05].

Conclusions and outlook

- Strong external fields affect the motion and the states of particles (nonlinear QED).
- E144 studied the effect of a laser on a HE electron beam, in particular nonlinear Compton scattering and pair production.
- Next LC: opportunity to repeat E144, at **higher energy** and **statistics**.
  It would be important to discuss it **SOON**.
- Possibility of performing the same experiment on the positron beam.
- Studying mass-shift effects.
- Testing Zel'dovich quasi-levels theory.
- Check whether is possible to detect the Unruh radiation.

Invitation to PIF2013

DESY, Hamburg 9th-11th July 2013

Topics: Strong field QED/QFT in

- LCs
- LASERS
- Crystals
- Heavy ion collisions etc.

Chair: Tony Hartin

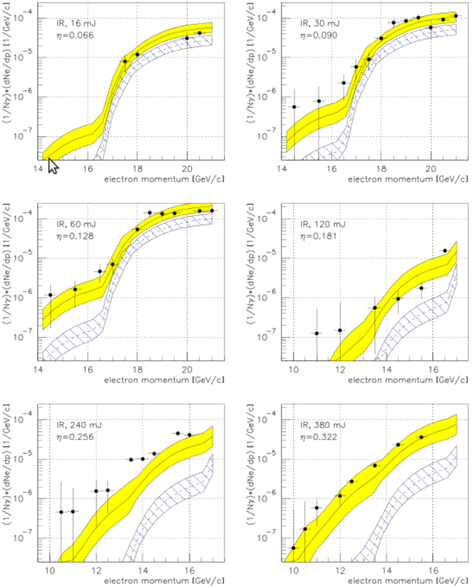
Registration deadline: 28th June

(Abstracts deadline: 31st May)

https://indico.desy.de/event/pif2013

Thanks!

Backup: Compton scattering at E144

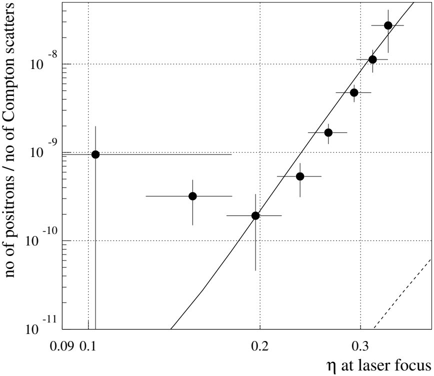


Scattering rates observed at E144 in terms of electron energy.

$n_\gamma = 2, 3$-edges.

[McDonald '98]

Backup: Pair production at E144



[McDonald '98]

Backup: Observation of relativistic mass-shift effects

[Meyerhofer et al. '95]

Electrons (up to 175 keV) from the ionization of Kr by a laser:

- Laser: $\lambda = 1053$ nm, 1 ps, $I_{\text{peak}} \simeq 10^{18}$ W/cm^2
- Relativistic mass-shift associated with the electrons quiver motion is apparent;
- Electron trajectory obtained without considering the mass-shift disagrees with the experimental observations.