XXV International Baldin Seminar
on High Energy Physics Problems
Relativistic Nuclear Physics & Quantum Chromodynamics

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Non-linear processes in photon- and electron- laser interactions

Definition: non-linear processes are those that cannot be described in terms of perturbative QED

1. First hopes:

QED vacuum breakdown - spontaneous electron-positron pair creation

(Schwinger effect (previously predicted by Sautzer, Heizenberg&Euler and justified by Schwinger))

Probability of e^+e^- ***pair production***

$$W \propto \frac{\mathcal{E}_S}{\mathcal{E}} \exp[-\pi \frac{\mathcal{E}}{\mathcal{E}_S}]$$

with

$\mathcal{E}$ - ***electric field strength***

$$\mathcal{E}_S = \frac{m^2}{e} = 1.32 \times 10^{16}\ \mathrm{V/cm}$$

$$\mathcal{E}_{\mathrm{atom}} \sim \times 10^9\ \mathrm{V/m}$$

$$\mathcal{E}(\frac{\mathsf{V}}{\mathsf{cm}}) \simeq 19.4\sqrt{I(\frac{\mathsf{W}}{\mathsf{cm}^2})}$$

I - ***laser power***

$$I_{crit} \simeq 4.6 \times 10^{29}(\frac{\mathsf{W}}{\mathsf{cm}^2})$$ ***for optical laser***

compare with $10^{21} - 10^{22}(\frac{\mathsf{W}}{\mathsf{cm}^2})$ ***expected power***

2. Current status:

Non-linear multiphoton processes with (ultra) high power laser field:

Non-linear multiphoton processes with (ultra) high power laser field:

Non-linear Breit-Wheeler e^+e^- ***pair production***

$$\underset{(L)}{\gamma + n\gamma_L} \to e^+e^-$$

Non-linear Compton high energy photon production

$$e^- + \underset{(L)}{n\gamma_L} \to e^- + \gamma$$

Non-linear trident processes

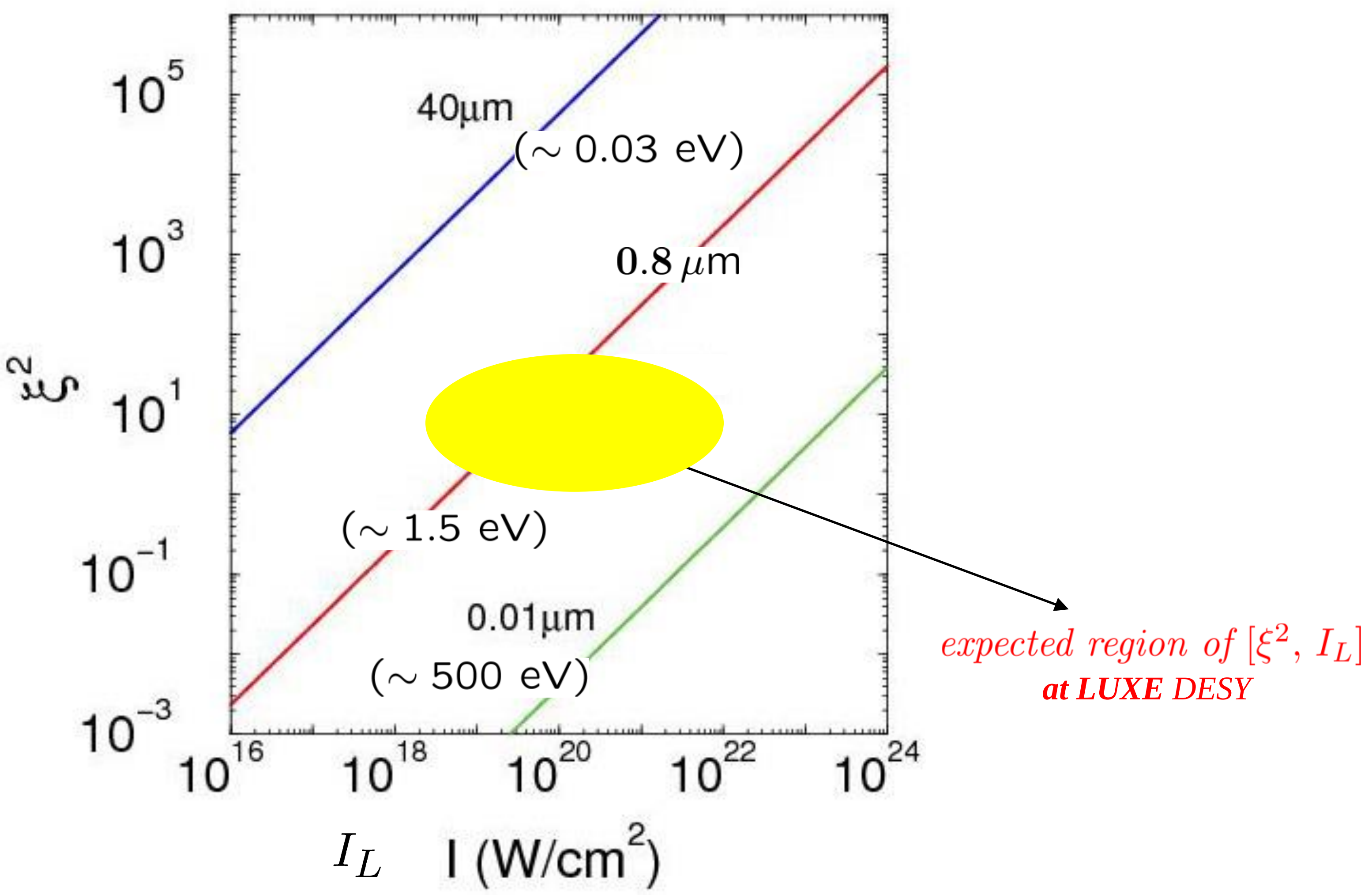
$$e^- + \underset{(L)}{n\gamma_L} \to e^- + e^+ + e^-$$

Reduced e.m. field intensity

$$\xi = \frac{e\mathcal{E}_{\mathrm{L}}}{m\omega_{\mathrm{L}}}$$

$$\xi^2 = \frac{0.56\, I[\mathrm{W/cm^2}] \times 10^{-18}}{(\omega_{\mathrm{L}}[\mathrm{eV}])^2}$$

Reduced field intensity ξ^2 *vs. laser intensity*



$$\xi^2 = \frac{0.56}{[\omega(\mathrm{eV})]^2} 10^{-18} I_L[\mathrm{W/cm}^2]$$

Original Breit-Wheeler process $\gamma' + \gamma \to e^+ e^-$

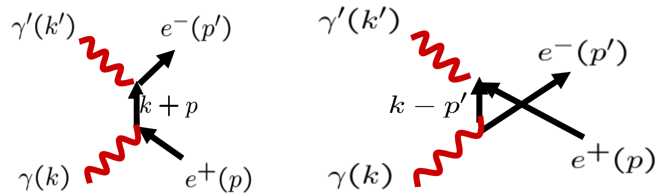
DECEMBER 15, 1934 PHYSICAL REVIEW VOLUME 46

Collision of Two Light Quanta

G. Breit* and John A. Wheeler,** *Department of Physics, New York University*

(Received October 23, 1934)

The recombination of free electrons and free positrons and its connection with the Compton effect have been treated by Dirac before the experimental discovery of the positron. In the present note are given analogous calculations for the production of positron electron pairs as a result of the collision of two light quanta. The angular distribution of the ejected pairs is calculated for different polarizations, and formulas are given for the angular distribution of photons due to recombination. The results are applied to the collision of high energy photons of cosmic radiation with the temperature radiation of interstellar space. The effect on the absorption of such quanta is found to be negligibly small.

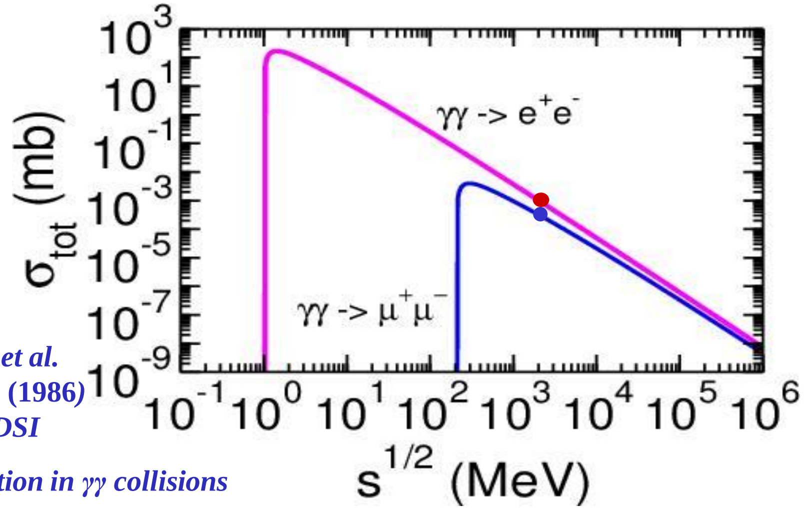


$$\sigma_{\text{tot}}^{BW} = \frac{4\pi\alpha^2}{s\gamma^4}\left\{(2\gamma^4+2\gamma^2-1)\,\text{arcsh}(\sqrt{1-\gamma^2}) - \gamma(1+\gamma^2)\sqrt{1-\gamma 2}\right\}\ , \quad \gamma^2 = \frac{s}{4m^2}$$

$\omega'_{\text{thr}} = m^2/\omega$

ω=1eV @ $\omega'_{\text{thr}} \simeq 250$ GeV

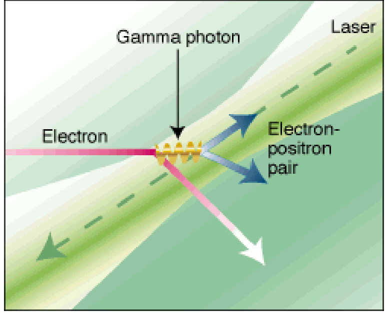
ω=1keV @ $\omega'_{\text{thr}} \simeq 250$ MeV



Courau *et al.*
NPB271 (1986)
Orsay, DSI

Lepton and pion pair production in γγ collisions

SLAC (E-144) experiment ***D. Burke et al., PRL 79 (1997)***



$\gamma' + L \to e^+ e^-$ ***generalized multi-photon process***

Kinematics of BW - process

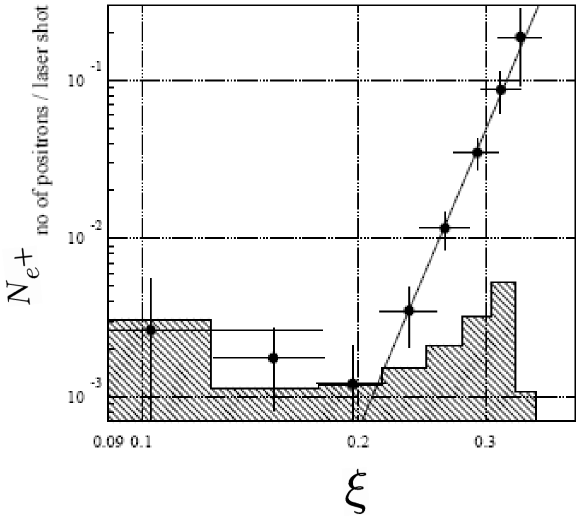
$$s_{thr}(\gamma'\gamma) = (k+k')^2 = 4\omega\omega' = 4m^2 \qquad \omega'_{thr} = \frac{m_e^2}{\omega} \simeq \frac{0.26 \cdot 10^{12}(eV^2)}{2.35\,eV\,(SLAC)} \simeq 111\ \text{GeV}$$

$$\omega'_{\text{SLAC}} \simeq 29\ \text{GeV} \implies \frac{\omega'_{thr}}{\omega'_{Bremmst}} \simeq 3.83$$

$$\gamma' + n\gamma \to e^+e^- \quad \to n_{\text{min}} \geq 4$$

$$I \sim 2 \times 10^{18}\ \text{W/cm}^2 \longrightarrow \quad 0.1 < \xi < 0.36$$

$(\omega = 2.35\ \text{eV})$



LUXE (Laser Und XFEL Experiment) at DESY

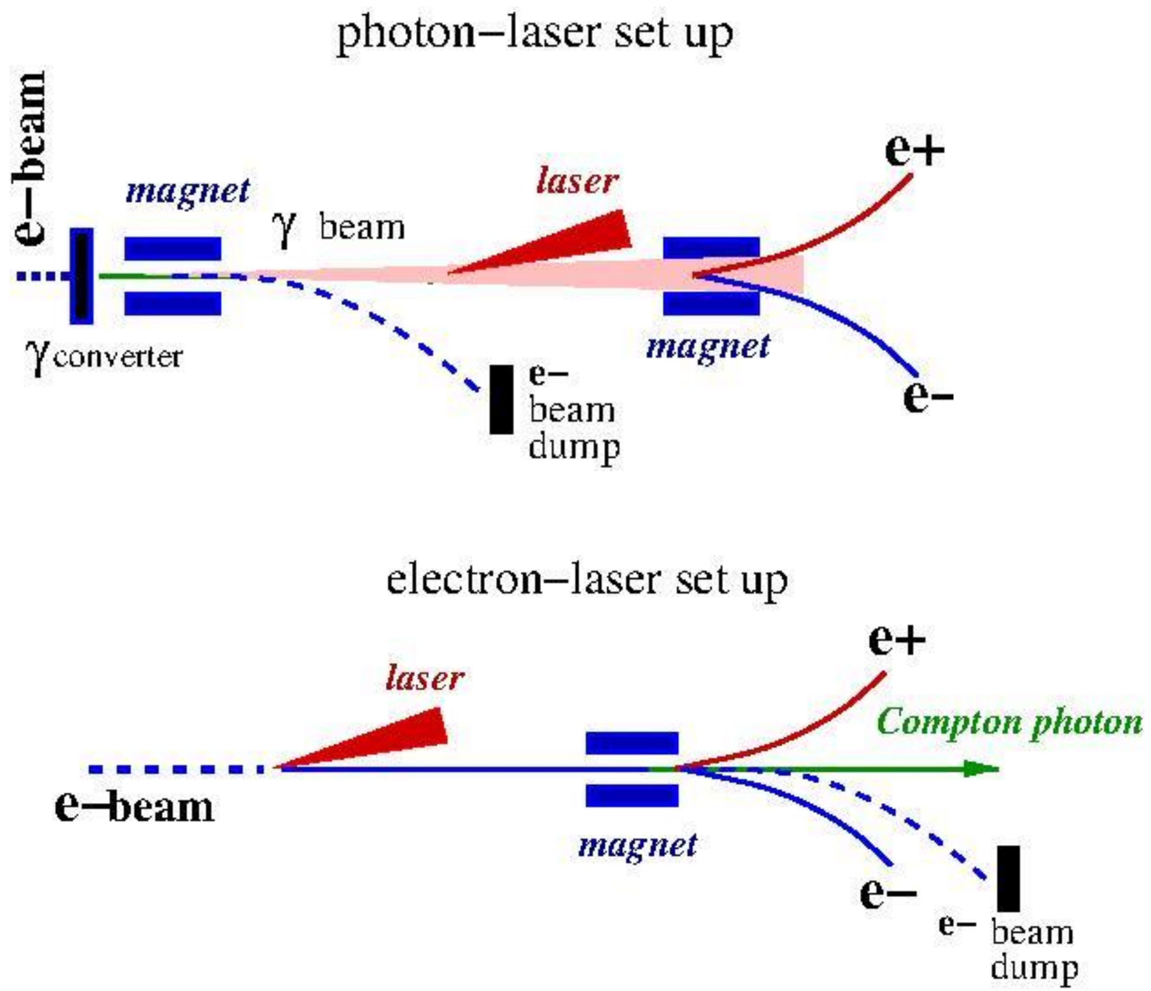
EPJST 230 (2021)

$E_e = 16.5$ GeV

ω_L =1.55 eV

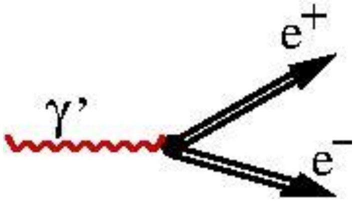
$0.5 \leq \xi \leq 6$

$I \sim 4.6 \times 10^{20}\ \frac{\mathrm{W}}{\mathrm{cm}^2}$



Interaction of charge particles with background field is considered in Furry picture

BW process $(originally\ \gamma' + \gamma \to e^+ + e^-)$



Compton scattering $(originally\ e^- + \gamma \to \gamma' + e^{-\prime})$

Volkov solution

$$\psi_p(\phi) = \left[1 + \frac{e(\gamma\cdot k)(\gamma\cdot A)}{2(k\cdot p)}\right]\frac{u_{p'}}{\sqrt{2p_0}}\mathrm{e}^{-ip\cdot x}\exp\left[-i\int\limits_{-\infty}^{\phi}\left(\frac{e(p\cdot A)}{(k\cdot p)} - \frac{e^2A^2}{2(k\cdot p)}\right)d\phi'\right]$$

$$A(\phi) - \ \textit{e.m. background field with}\ \phi = kx$$

$$S_{fi} = -ie\int d^4x\langle f|\gamma\cdot\varepsilon(k')|i\rangle\,\frac{\mathrm{e}^{-ik\cdot x}}{\sqrt{2\omega'}}$$

$$M_{fi}(kx) = \int\limits_{-\infty}^{\infty} d\ell\mathrm{e}^{-i\ell kx}\,M_{fi}(\ell) \Rightarrow S_{fi} = \int\limits_{\ell_{\min}}^{\infty} d\ell M_{fi}(\ell)\,\delta^4(k' + \ell k - p_{e^-} - p_{e^+})$$

$l\omega$ ***is the energy of the pulse involved into process***

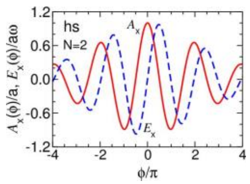
Non-linear BW process $\gamma' + L \to e^+ + e^-$

A.T., Kämpfer, PRL **108**(2013), EPJD **68** (2014), EPJD **74** (2020)

e.m. potential: $A = (0, \mathbf{A}),\ \ \mathbf{A}(\phi) = f(\phi)\,[\mathbf{a}\cos(\phi)]$ $\quad \mathcal{E} = -\frac{\partial \mathbf{A}}{\partial t}$ $\quad \phi = kx$ *- invariant phase,*

with $\mathbf{a} = \mathbf{e}_0 \frac{\xi m}{e}$

$f(\phi)$ *- envelope function*



$$\sum_{ss'} |S_{fi}|^2 \propto \int_{\ell=1}^{\infty} dl |M\left(\mathbf{e}_0, \mathbf{e}', k, k', \xi, f(\phi)\right)|^2 (2\pi)^4 \delta(\ell k + k' - q - q')$$

$$W \sim \int_{\ell=1}^{\infty} dl w_l = \int_{\ell=1}^{\infty} dl \left[\xi^2 u(\widetilde{A}_1(l)^2 - \widetilde{A}_0(l)\widetilde{A}_2(l)) - [|p\cdot e_i''\widetilde{A}_0(l) + ea\cdot e_i''\widetilde{A}_1(l)|^2]/m^2\right] \ ,$$

$$e'' = e' - k'(k\cdot e')/k\cdot k'$$

$$\widetilde{A}_m(\ell) = \frac{1}{2\pi}\int_{-\infty}^{\infty} d\phi f^m(\phi)\cos^m(\phi)\, \mathrm{e}^{i\ell\phi - i\mathcal{P}^{(lin)}(\phi)}$$

$$\mathcal{P}^{(lin)}(\phi) = \tilde{\alpha}(\phi) - \tilde{\beta}(\phi)\ ,$$

$$\tilde{\alpha}(\phi) = z\cos\phi_e \int_{-\infty}^{\phi} d\phi' f(\phi')\cos(\phi')\ ,$$

$$\tilde{\beta}(\phi) = \frac{u\ell\xi^2}{u_\ell}\int_{-\infty}^{\phi} d\phi' f^2(\phi')\cos^2(\phi')\ .$$

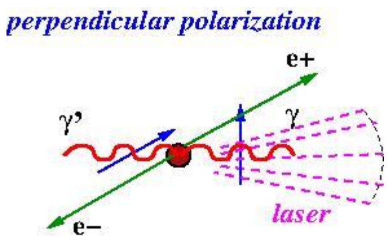
$$u = (kk')/4(kp)(kp'),\ u_\ell = \ell/\zeta,\ z = 2\ell\xi((u/u_\ell)(1-(u/u_\ell))^{1/2}$$

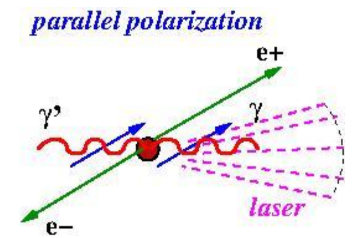
$$w(\ell) = w_\perp(\ell) + w_\parallel(\ell)$$

$$w_\parallel(\ell) = \xi^2(u-1)\left(|\widetilde{A}_1(\ell)|^2 - [\widetilde{A}_0(\ell)\widetilde{A}_2^*(\ell)\right) + (1+\tau^2)|\widetilde{A}_0(\ell)|^2,$$

$$w_\perp(\ell) = \xi^2\, u\, \left(\widetilde{A}_1(\ell)|^2 - [\widetilde{A}_0(\ell)\widetilde{A}_2^*(\ell)\right) - \tau^2|\widetilde{A}_0(\ell)|^2 \ ,$$

$$\tau^2 = (u_\ell/u - 1)\sin^2\varphi_e.$$

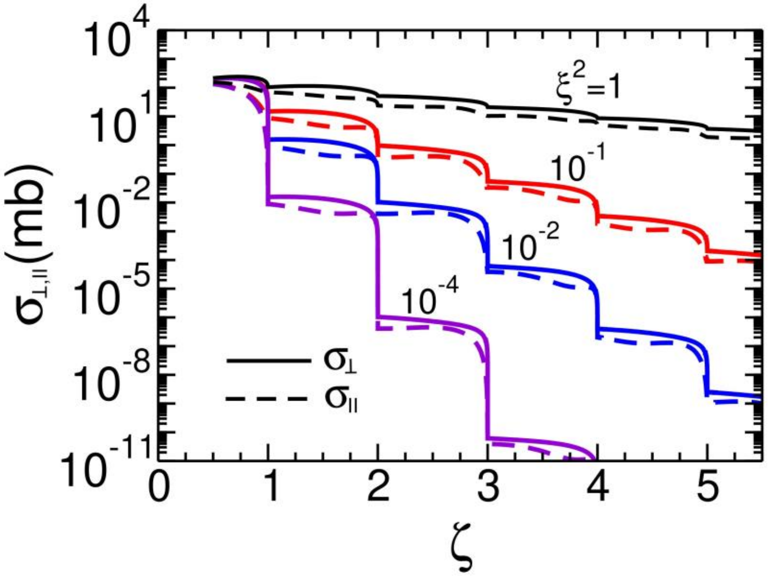


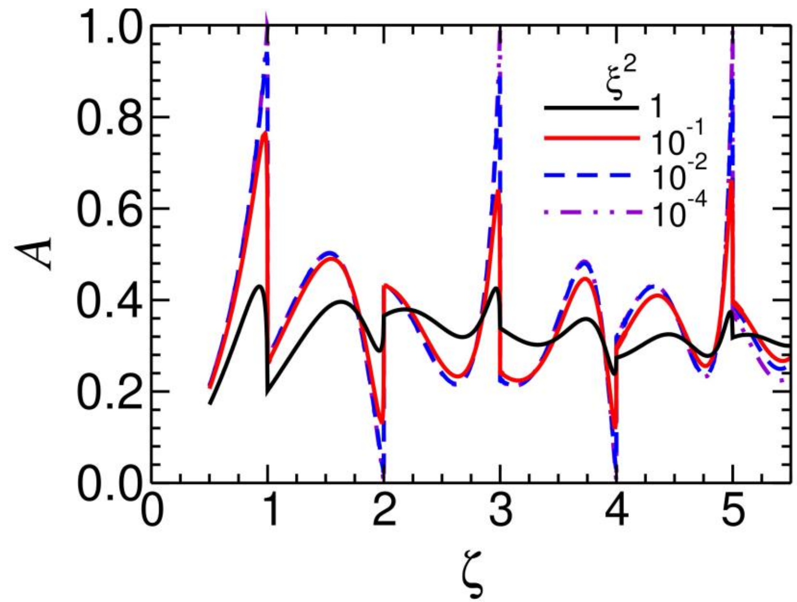


↓

$$\sigma_\perp,\ \sigma_\parallel, \quad \sigma_\perp > \sigma_\parallel$$

$$A = \frac{\sigma_\perp - \sigma_\parallel}{\sigma\perp + \sigma_\parallel}$$

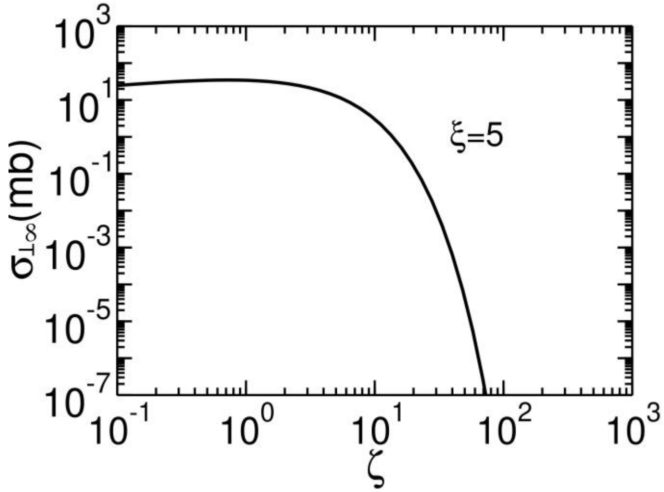


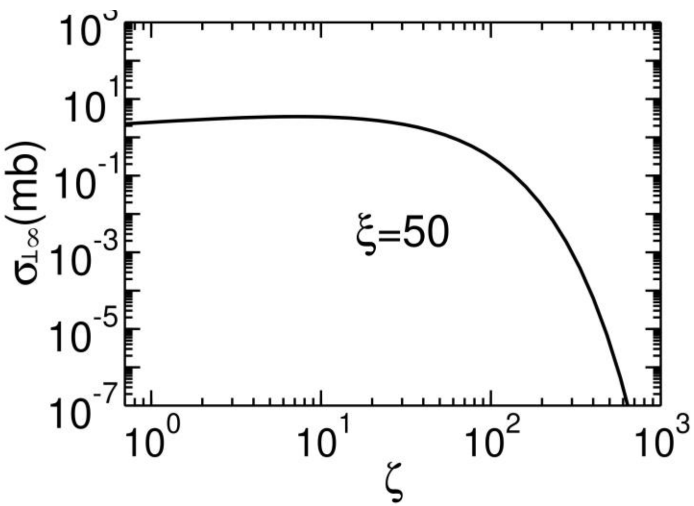


$\zeta = \frac{4m^2}{s}$ = **minimal number of laser photon involved in process**
an analog of "cumulative number"

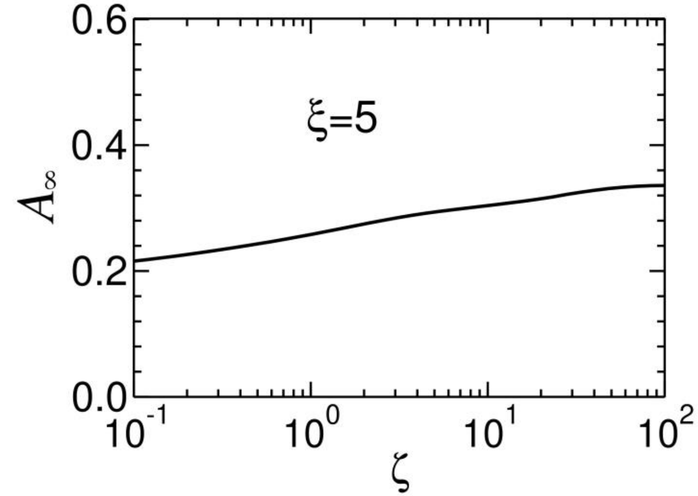
Ultra-high field intensity with $\xi \gg 1$

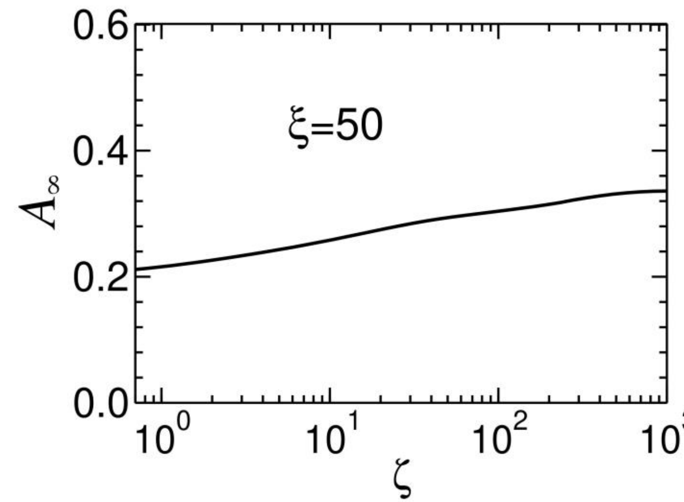
cross sections





asymmetries





Non-linear Compton scattering $e^- + L \to \gamma' + e^{-\prime}$

A.T., Kämpfer, Phys.Rev.A**103**(2021),
Phys.Part.Nucl.**47**(2016)
A.T., arXiv 2307.00621

Furry picture

$$M = \sum_{a=1,2} e'^{*}_{a} M_a \ ,$$

$e'_{1,2}$ *are the polarization vectors of* γ' *(linear polarization)*

$$\rho^f_{ab} = \frac{M_a M_b^*}{\sum\limits_a |M_a|^2}$$ *spin-density matrix*

$$\xi_3^f = \mathrm{Sp}\,(\rho\sigma_3)) = \frac{|\mathrm{M}_1|^2 - |\mathrm{M}_2|^2}{|\mathrm{M}_1|^2 + |\mathrm{M}_2|^2} = \mathcal{A}$$

Stoks parameter for intrinsic spin of recoil photon γ'

spin asymmetry $\mathcal{A}$ (or ξ_3^f) *shows direction and degree of* γ' *spin polarization*

$$\mathbf{e}'_1 = \frac{[\mathbf{k},\mathbf{k}']}{|[\mathbf{k},\mathbf{k}']|}, \qquad \mathbf{e}'_2 = \frac{|\mathbf{k}',\mathbf{e}'_1|}{|\mathbf{k}'|} \ , \quad \longrightarrow \quad \begin{aligned} \mathbf{e}'_1 &= -\mathbf{x}\sin\varphi + \mathbf{y}\cos\varphi \\ \mathbf{e}'_2 &= -\mathbf{x}\cos\theta\cos\varphi - \mathbf{y}\cos\theta\sin\varphi + \mathbf{z}\sin\theta \ . \end{aligned}$$

A.I.Ahiezer, V.B. Berestetsky. QED

$$d^2\sigma_1 = d\varphi d\omega' \mathcal{K} \sum_{l=1}^{\infty} [\xi^2\ \widetilde{A}_1^2 \sin^2\varphi + \xi^2 \frac{u^2}{4(1+u)} \left(\widetilde{A}_1^2 - \widetilde{A}_0\widetilde{A}_2\right)] \ , \qquad \textit{where} \quad \mathcal{K} = \frac{4\alpha^2}{\xi\chi m^2\ E_e}$$

$$d^2\sigma_2 = d\varphi d\omega' \mathcal{K} \sum_{\ell=1}^{\infty} [-\widetilde{A}_0^2 - \xi^2\,\widetilde{A}_1^2 \sin^2\varphi + \xi^2 \left(1 + \frac{u^2}{4(1+u)}\left(\widetilde{A}_1^2 - \widetilde{A}_0\widetilde{A}_2\right)\right)] \ .$$

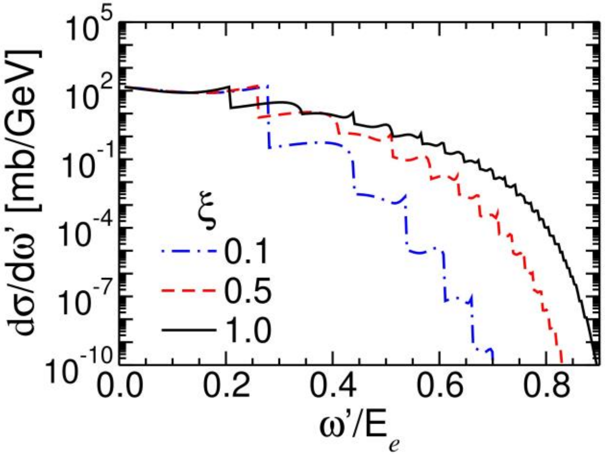
$$d^2\sigma = d^2\sigma_1 + d^2\sigma_2$$

$$\mathcal{A}(\varphi,\omega') = \frac{d^2\sigma_1 - d^2\sigma_2}{d^2\sigma} \ .$$

average asymmetry

$$\langle \mathcal{A}(\omega') \rangle_\varphi = \frac{1}{2\pi} \int_0^{2\pi} d\varphi\, \mathcal{A}(\varphi,\omega') \ ,$$

unpolarized cross sections

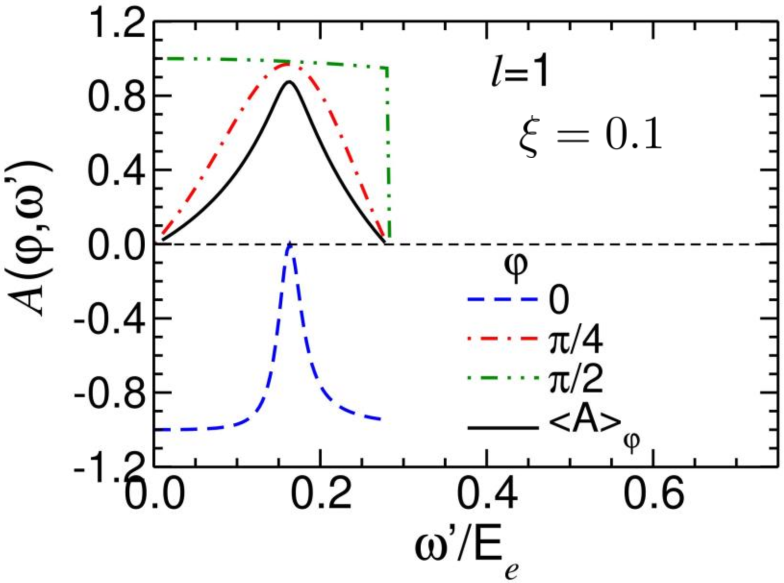


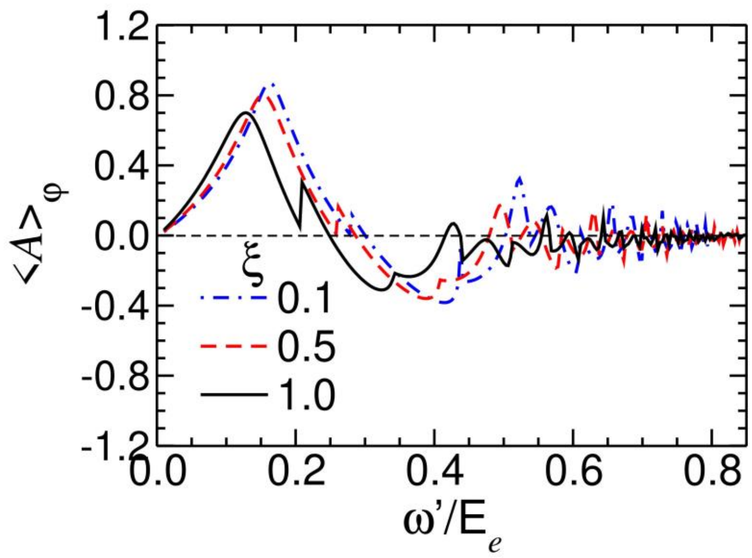
$E_e = 16.5\ \mathrm{GeV}$

$$\omega'_{\max}(\ell) = \frac{2\omega E_e}{2E_e|\cos\theta + \ell\omega(1-\cos\theta)}$$

*average asymmetry with all **l***

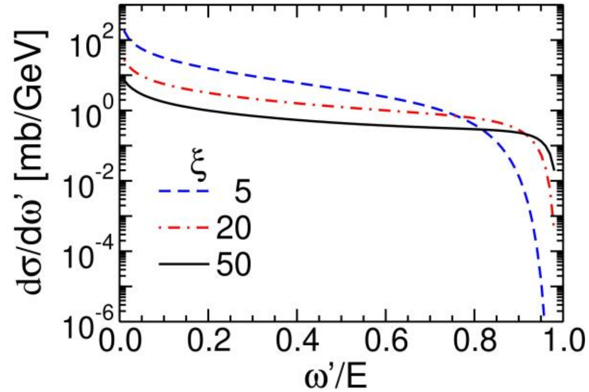
*asymmetry in range of first harmonic with **l=1***





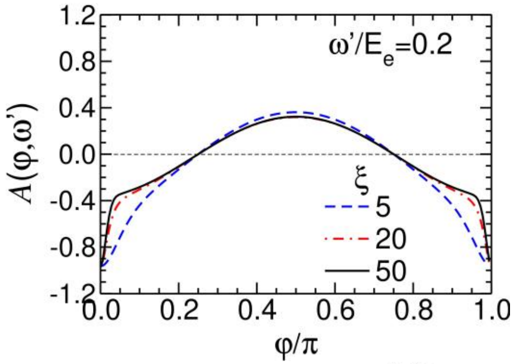
large and ultra-large field intensity $\xi \gg 1$

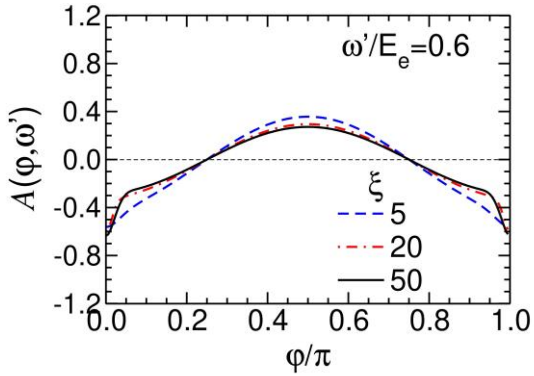
unpolarized cross sections



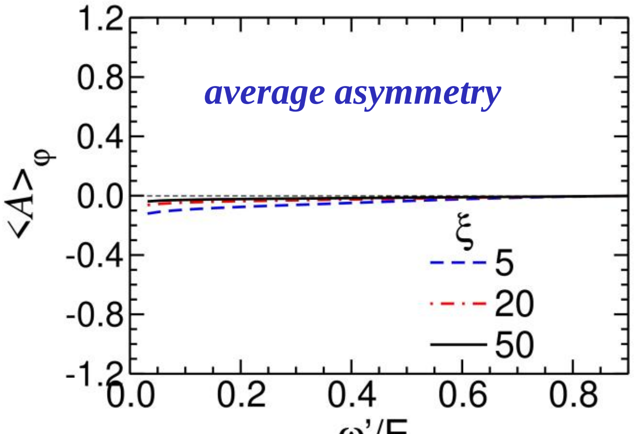
$E_e = 16.5$ GeV

dependence on azimuthal angle φ





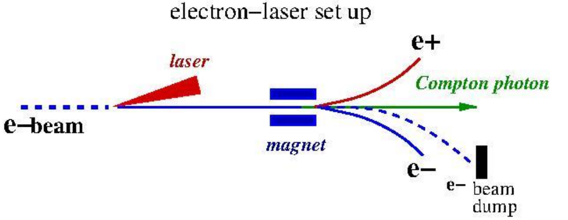
average asymmetry



Non-linear trident process

$$e^- + n\gamma_L \to e^- + e^+ + e^-$$

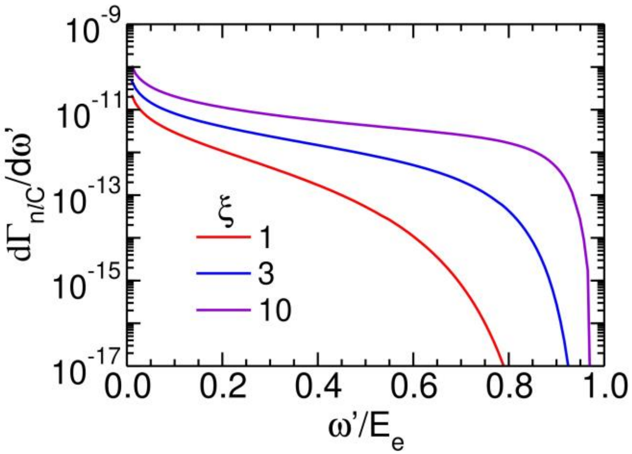
A.I. T., Acosta, Kampfer, PRA(104)2022
EPJST 230 (2021)

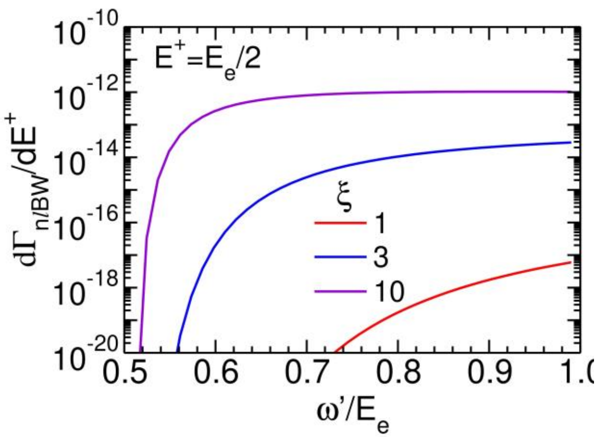


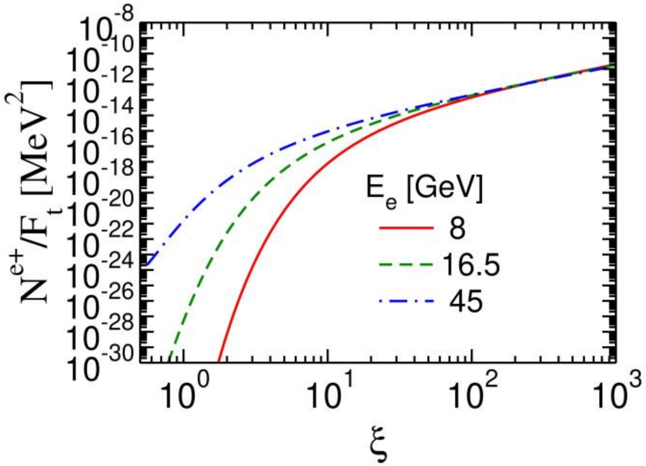
$$\frac{dN^{e^+}}{dE^+} = F_t \int_{E^+}^{E_e} d\omega' \frac{d\Gamma_{n\ell C}(\omega')}{d\omega'} \, \frac{d\Gamma_{n\ell BW}(\omega', E^+)}{dE^+}$$

$$F_t = \frac{1}{2}\left(\frac{2\pi}{\omega_{\rm L}}\right)^2 N_e \simeq 8.2\times 10^{21}\ {\rm MeV}^2$$

$$N_e = 10^9$$

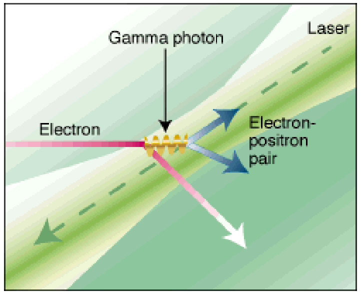


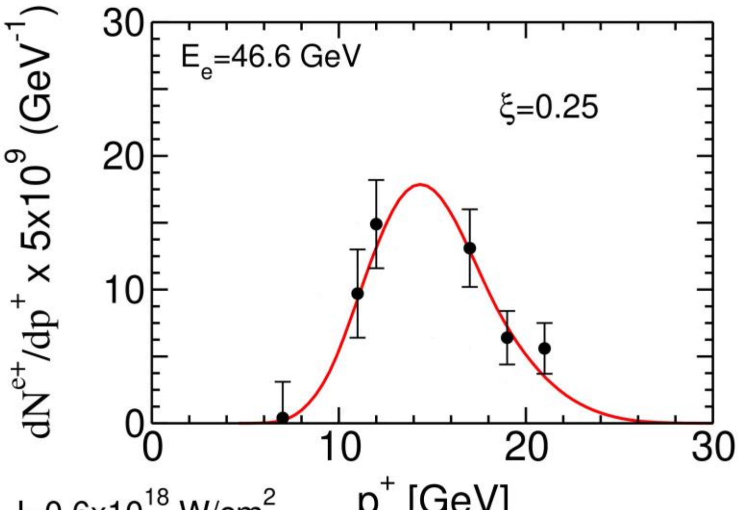




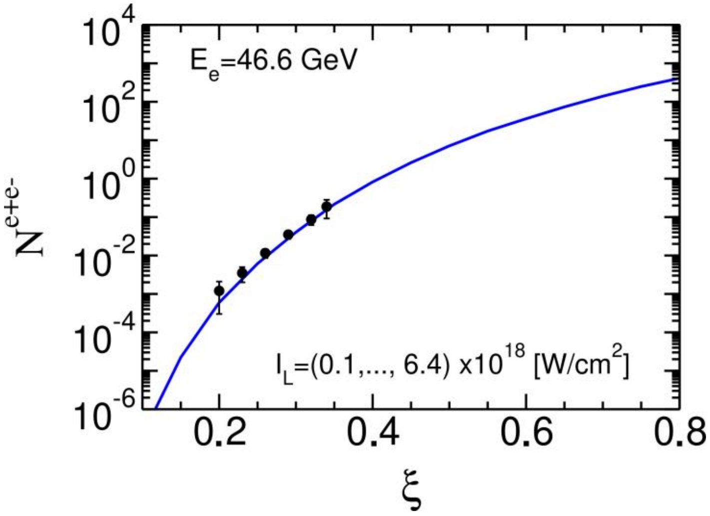
Checking model for E-144 experiment

low $\xi^2 \ll 1$





I=0.6x10^18 W/cm^2



Summary

1. We made predictions for unpolarized cross sections of non-linear BW and Compton processes in a wide region of e.m. field intensity

2. The main patterns of spin observables in BW and Compton scattering have been studied

3. The yield of electron-positron pairs at LUXE kinematic have been performed

4. The model was checked successfully for SLAC E-144 experiment

THE END

Thank you for attention !