HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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Photon-Photon Scattering at the high-intensity frontier

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TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

Outline

1. Scattering Formalism
   - Classical Electrodynamics
   - Quantum Electrodynamics
     - Optical Photons
     - Hard X-Rays
2. Scientific Studies
   - Photon Emission
   - Multiphoton Pair Production

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1. Scattering Formalism
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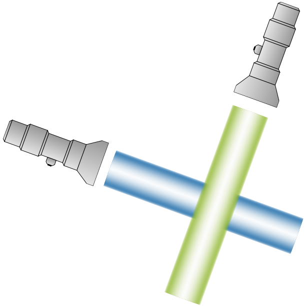
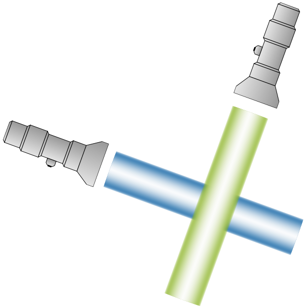
Vacuum

Classical Light-by-Light Scattering



Classical Light-by-Light Scattering



- Flashlights as light source
- No scattering observed

Classical Lagrangian

$$\mathcal{L}_{\text{class}} = \mathcal{L}_{\text{int}} + \mathcal{L}_{\text{kin}} = -A_\mu J^\mu - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \tag{1}$$

- Field strength tensor
- Background field
- Source term
- Interaction term $-A_\mu J^\mu$
- Kinetic term $-\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
- Equations of motion → inhomogeneous Maxwell equations

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Field Strength Tensor

$$F_{\mu\nu}(x) = \partial_\mu A_\nu - \partial_\nu A_\mu, \qquad [A_\mu, A_\nu] = 0 \tag{2}$$

- Fields do not interact directly with each other!
- Photon-photon scattering is impossible in classical electrodynamics
- Equations of motion → homogeneous Maxwell equations

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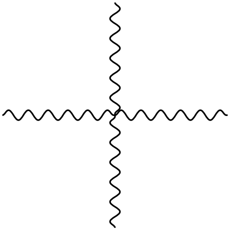
Feynman Diagram



- Photons $\rightarrow$ curly lines
- $[A_\mu, A_\nu] = 0$
- No interaction $\rightarrow$ no scattering $\rightarrow$ lines pass each other

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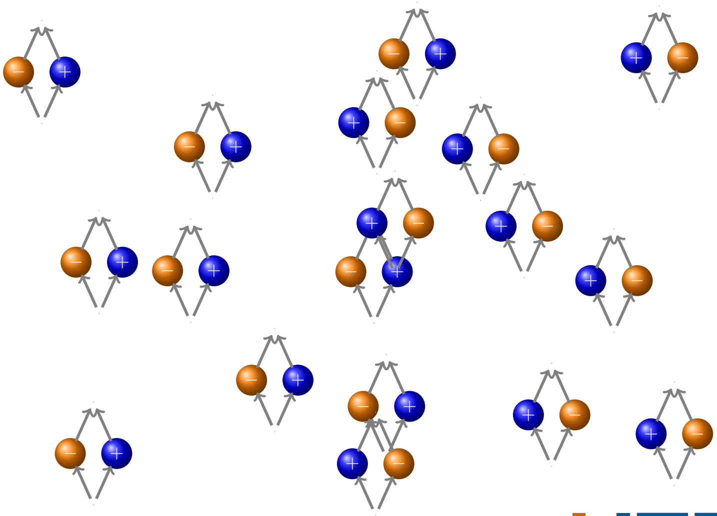
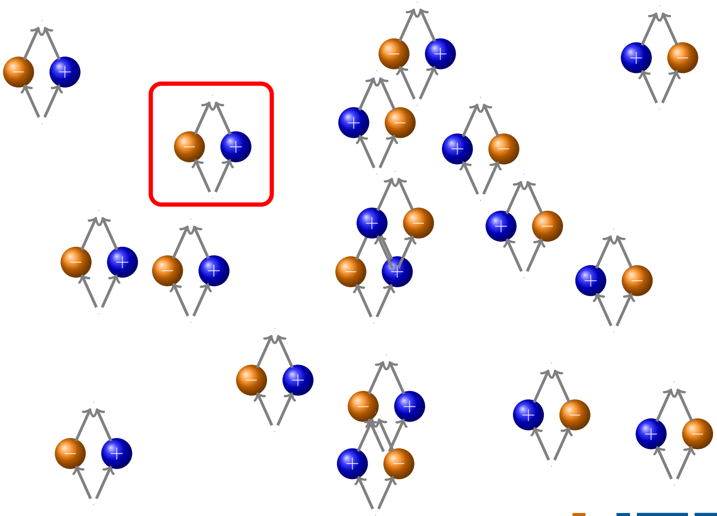
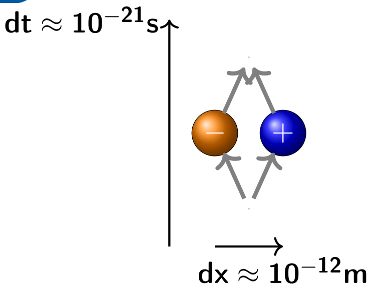
Vacuum in Quantum Field Theory



Vacuum in Quantum Field Theory



Virtual Electron-Positron Pair

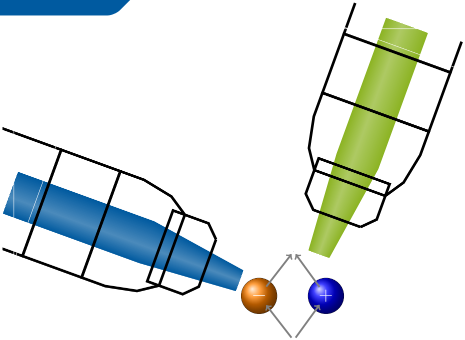


- Vacuum fluctuations
- QED scale: $\varepsilon_{crit} = m_e^2/e = 1.3 \times 10^{18}$V/m

F. Sauter: Z. Phys. 69(742), 1931

J. S. Schwinger: Phys. Rev. 82(664), 1951

High-Intensity Light-by-Light Scattering



- Laser light as source
- Probing quantum vacuum

Outline

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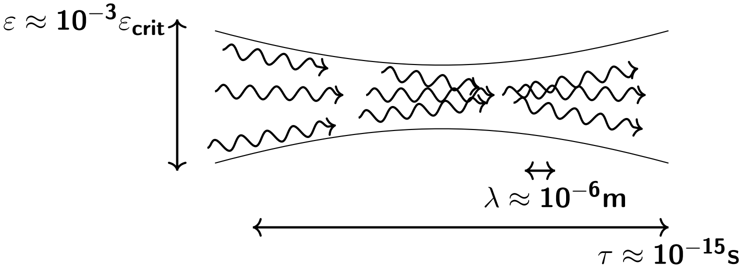
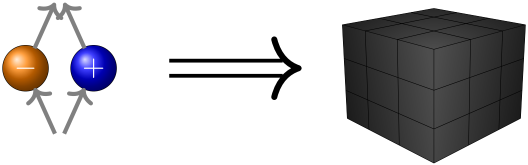
Low Energy Photons



- All-optical laser system
- Slowly varying background field
- Photons γ_ω with energy $\omega \approx 1\text{eV}$

Vacuum Fluctuations



- Optical photons cannot resolve quantum fluctuations (different scales)
- Vacuum fluctuations $\rightarrow$ effective background field
- Virtual pair $\rightarrow$ "black box"

QED Lagrangian

$$\mathcal{L}_{\text{QED}} = \mathcal{L}_{\text{int}} + \mathcal{L}_{\text{kin}} = \bar{\psi}(\mathrm{i}\gamma^{\mu} D_{\mu} - m)\psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \tag{3}$$

- Dirac matrices
- Bispinor fields for spin-1/2 particles
- Covariant derivative $D_{\mu} \equiv \partial_{\mu} + \mathrm{i}eA_{\mu}$
- Interaction term
- Kinetic term
- Coupling constant e, Mass m

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Effective Interactions

$$\mathcal{L}_{\text{int}}\left(\psi, \bar{\psi}, A_\mu\right) = \bar{\psi}(\mathrm{i}\gamma^\mu\left(\partial_\mu + \mathrm{i}eA_\mu\right) - m)\psi \tag{4}$$

- "Integrating out" electrons and positrons $\psi, \ \bar{\psi}$
- Effective Lagrangian $\mathcal{L}_{\text{int}}\left(\psi, \bar{\psi}, A_\mu\right) \to \mathcal{L}_{\text{eff}}\left(A_\mu\right)$
- Gauge invariance demands $\mathcal{L}_{\text{eff}}\left(A_\mu\right) = \mathcal{L}_{\text{eff}}\left(F_{\mu\nu}\right)$
- Lowest order non-linear contributions $\left(F_{\mu\nu}F^{\mu\nu}\right)^2, \ \left(F_{\mu\nu}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}\right)^2$

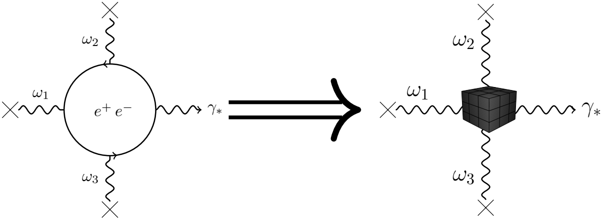
Euler-Heisenberg Lagrangian

$$\mathcal{L}_{\mathrm{EH}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\alpha^2}{90 m^4} \left(\left(F_{\mu\nu} F^{\mu\nu} \right)^2 + \frac{7}{4} \left(F_{\mu\nu} \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta} \right)^2 \right) \tag{5}$$

- Optical background field $\omega_\gamma \ll m$
- Photon-photon scattering mediated by virtual particles
- Nonlinear dynamics of electromagnetic fields in vacuum
- One-loop $\rightarrow$ fine-structure constant $\alpha \sim e^2$

W. Heisenberg et al.: Z. Phys. 98(714), 1936

Vacuum Emission



- Leading contribution: one loop, four lines
- Effective nonlinearities
- Three couplings to external field ω
- Single signal emission $\rightarrow$ photon γ_* with new properties

Field Strength Tensor

$$\overline{F^{\mu\nu}} \to F^{\mu\nu}(x) + f^{\mu\nu}(x) \tag{6}$$

- Local constant field approximation:
  Replace constant field $\overline{F^{\mu\nu}}$ $\to$ slowly varying fields
- Background fields $F^{\mu\nu}(x)$ in weak field limit $eF^{\mu\nu} \ll m^2$
- Field strength tensor of signal photons $f^{\mu\nu}(x)$

Z. Bialynicka-Birula al.: Phys. Rev. D 2 (1970) 2341

Effective Interaction

$$\Gamma = \Gamma^{(1)} + \Gamma^{(2)} + \Gamma^{(3)} + \ldots = \int_x f^{\mu\nu}(x) \left. \frac{\partial \mathcal{L}_{\mathrm{HE}}}{\partial \overline{F}^{\mu\nu}} \right|_{\overline{F} \to F(x)} + \mathcal{O}(m > 1) \quad (7)$$

- Expansion in terms of probe photons m
- $\Gamma^{(1)}$: stimulated vacuum emission
- Expand probe photon field $f^{\mu\nu} \to$ polarizations states:

$$\hat{f}^{\mu\nu}_{(p)}(k) = k^{\mu} \epsilon^{*\nu}_{(p)}(k) - k^{\nu} \epsilon^{*\mu}_{(p)}(k) \quad (8)$$

F. Karbstein et al.: Phys. Rev. D **91** (2015) no.11, 113002

Zero-to-Single Signal Photon Transition Amplitude

$$S_{(p)}(\vec{k}) \sim \epsilon^{*\nu}_{(p)}(\vec{k})\, k^{\mu} \int \mathrm{d}^4\mathrm{x}\ \mathrm{e}^{\mathrm{i\,kx}} \frac{\partial \mathcal{L}_{\mathrm{HE}}}{\partial \overline{F}^{\mu\nu}} \bigg|_{\overline{F} \to F(x)} \tag{9}$$

- Euler-Heisenberg Lagrangian $\mathcal{L}_{\mathrm{HE}}$
- Electric and magnetic background fields $F^{\mu\nu}(x)$
- Signal photon, polarization p
- Global information
- Momentum spectrum

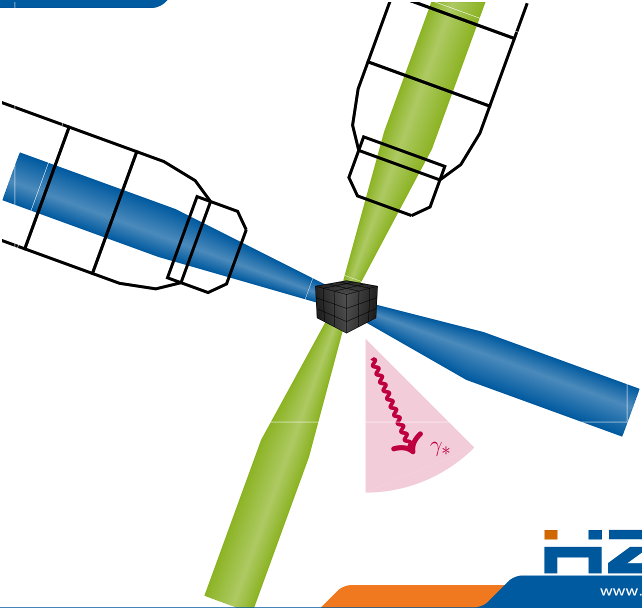
F. Karbstein et al.: Phys. Rev. D **91** (2015) no.11, 113002

Photon Emission

$$d^3 N_{(p)}(\vec{k}) = dk\, d\phi\, d\cos\theta\, \frac{1}{(2\pi)^3} \left| k S_{(p)}(\vec{k}) \right|^2 \qquad (10)$$

- Directional emission characteristics
- Signal photon polarization p
- Spherical coordinates
- Signal photon energies k
- Far-field detection

F. Karbstein et al.: Phys. Rev. D **91** (2015) no.11, 113002


γ_*

Résumé: Vacuum Emission Formalism

Positive Aspects

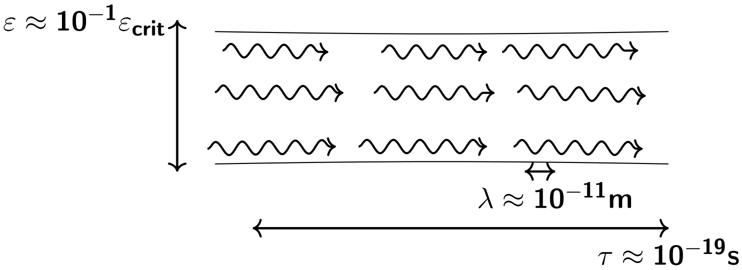
- Electric and magnetic fields as input
- Signal photons as output

Challenges

- Signal to noise ratio
- Signal optimization
- Numerics - Fields varying on different scales

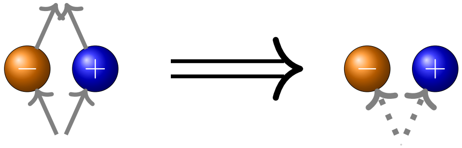
Outline

High Energy Photons



- Rapidly varying background field
- Photon energy $\omega_x \approx 10$keV

Multiphoton Pair Production



- Hard X-rays can probe quantum fluctuations
- Described by QED Lagrangian
- Transfer of energy, linear & angular momentum
- Virtual particles become real

E. Brezin et al.: Phys. Rev. D 2 (1970), 1191

Multiphoton Pair Production

- Hard X-rays can probe quantum fluctuations
- Described by QED Lagrangian
- Scattering $\rightarrow$ transfer of energy, linear & angular momentum
- Virtual particles can become real

E. Brezin et al.: Phys. Rev. D 2 (1970), 1191

QED Lagrangian

$$\mathcal{L}_{\mathrm{QED}}\left(\hat{F}_{\mu\nu}\right) = \bar{\psi}(\mathrm{i}\gamma^{\mu} D_{\mu} - m)\psi - \frac{1}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} \tag{11}$$

- Field strength tensor $\hat{F}_{\mu\nu}$
- Dirac matrices
- Bispinor fields for spin-1/2 particles
- Covariant derivative $D_{\mu} \equiv \partial_{\mu} + \mathrm{i}e\hat{A}_{\mu}$
- Coupling constant e, Mass m

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Mean-Field QED Lagrangian

$$\mathcal{L}_{\text{QED}}\left(\hat{F}_{\mu\nu}\right) \to \mathcal{L}_{\text{QED}}\left(F_{\mu\nu}\right) \tag{12}$$

- Hard X-rays $\omega_x \sim \mathcal{O}(m)$
- Mean-field approximation
  $F_{\mu\nu} \approx \langle \hat{F}_{\mu\nu} \rangle \to$ classical background field
- Quantum nature of electrons & positrons
- Dynamics of charged particles in electromagnetic background field

D. Vasak et al.: Annals Phys. **173** (1987), 462

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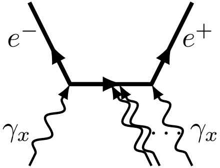
Production Process



- Similar to Breit-Wheeler process: $n\gamma_x \to e^- e^+$
- Emission of electrons and positrons

G. Breit et al.: Phys. Rev. **46** (1934) 1087

D. L. Burke et al.: Phys. Rev. Lett., 79:1626–1629, 1997

Wigner-Weyl Approach

$$\mathbb{W}(\mathrm{x},\mathrm{p}) = \frac{1}{2} \int \mathrm{d}^4\mathrm{y}\ \mathrm{e}^{\mathrm{i}\,\mathrm{p}\mathrm{y}}\ U(A_\mu,\mathrm{x},\mathrm{y})\ \left[\bar{\psi}\left(\mathrm{x} - \frac{\mathrm{y}}{2}\right), \psi\left(\mathrm{x} + \frac{\mathrm{y}}{2}\right)\right] \qquad (13)$$

- Wigner operator
- Phase-space formalism
- Gauge transporter $U(A_\mu, \mathrm{x}, \mathrm{y})$
- $\mathbb{W}(\mathrm{x},\mathrm{p})$ is gauge invariant
- Quasi-probabilities

D. Vasak et al.: Annals of Physics 173(462-492), 1987

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Equal-Time Formalism

$$W(\mathbf{x},\mathbf{p},t) = \int \frac{\mathrm{d}p_0}{2\pi} \mathbb{W}(\mathrm{x},\mathrm{p}) = \frac{1}{4}\left(\mathbb{s} + \mathrm{i}\gamma_5 \mathbb{p} + \gamma^\mu \mathbb{v}_\mu + \gamma^\mu \gamma_5 \mathbb{a}_\mu + \sigma^{\mu\nu} \mathbb{t}_{\mu\nu}\right) \tag{14}$$

- Projection on equal-time
- Initial-value problem
- Expansion in Dirac bilinears
- Wigner components: mass density $\mathbb{s}$, charge density $\mathbb{v}_0$,...

D. Vasak et al.: Annals of Physics 173(462-492), 1987

I. Bialynicki-Birula et al.: Phys. Rev. D 44(6), 1991

Equation of Motion

$$\left(D_t + D + \Pi\right)\ \vec{\mathbb{w}} = \overline{M}\ \vec{\mathbb{w}} \tag{15}$$

- Matrix $\overline{M}$
- Wigner components $\vec{\mathbb{w}}$
- Pseudo-differential operators $\mathbf{D_t}\left(F_{\mu\nu}\right)$, $\mathbf{D}\left(F_{\mu\nu}\right)$, $\mathbf{\Pi}\left(F_{\mu\nu}\right)$
- Well-defined observables
- Initial-value problem

D. Vasak et al.: Annals of Physics 173(462-492), 1987

I. Bialynicki-Birula et al.: Phys. Rev. D 44(6), 1991

Observables: Particle Density

$$N(t \to \infty) = \int \mathrm{d}^3 p \, f(\mathbf{p}, t \to \infty) \tag{16}$$

$$f(\mathbf{p}, t) = \int \mathrm{d}^3 x \, \frac{\mathbb{s}(\mathbf{x}, \mathbf{p}, t) + \mathbf{p} \cdot \mathbb{v}(\mathbf{x}, \mathbf{p}, t)}{\omega(\mathbf{p})} \tag{17}$$

- Total production yield $N(t \to \infty)$
- Particle momentum spectrum $f(\mathbf{p}, t)$
- One-particle energy $\omega(\mathbf{p}) = \sqrt{1 + \mathbf{p}^2}$

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Quantum Kinetic Theory

$$\begin{pmatrix} \dot{F} \\ \dot{G} \\ \dot{H} \end{pmatrix} = \begin{pmatrix} 0 & W & 0 \\ -W & 0 & -2\omega \\ 0 & 2\omega & 0 \end{pmatrix} \begin{pmatrix} F \\ G \\ H \end{pmatrix} + \begin{pmatrix} 0 \\ W \\ 0 \end{pmatrix} \tag{18}$$

- Spatially homogeneous electric background field $\mathbf{E}(t) = E(t)\,\mathbf{e}_z$
- No magnetic field
- Particle density $F(t)$
- Source term W

S. A. Smolyansky et al. hep-ph/9712377 GSI-97-72, 1997

S. Schmidt et al.: Int.J.Mod.Phys. E7 709-722, 1998

J. C. R. Bloch et al.: Phys. Rev. D 60(116011), 1999

Classical Limit

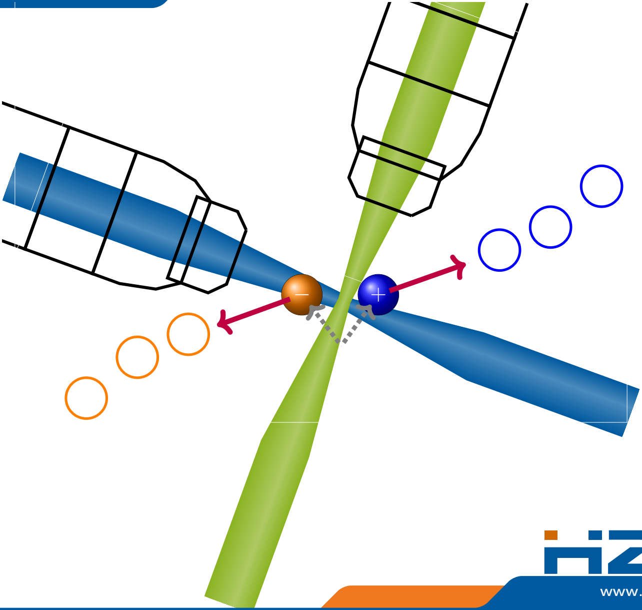
$$\partial_t f^+ + \mathbf{v} \cdot \left(\nabla_x f^+ \right) + e \left(\mathbf{E} + \mathbf{v} \times \mathbf{B} \right) \cdot \nabla_p f^+ = 0 \qquad (19)$$

$$\partial_t f^- + \mathbf{v} \cdot \left(\nabla_x f^- \right) - e \left(\mathbf{E} + \mathbf{v} \times \mathbf{B} \right) \cdot \nabla_p f^- = 0 \qquad (20)$$

- Vlasov equation
- Positron distribution function f^+
- Electron distribution function f^-
- Particle number conservation

G. R. Shin et al. Phys. Rev. A 48:1869–1874, (1993)

High-intensity Light-by-Light Scattering



Résumé: Wigner Formalism

Positive Aspects

- Arbitrary vector potentials as input
- Time evolution
- Particle spectrum

Challenges

- Beyond mean-field approximation
- Back-reaction and particle collisions
- Partial differential equations

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Background Fields

Generic input

- No constraints on background fields
- Full-scale simulation
- Polarization sensitive results

Paraxial beams

- Good approximation of laser beams
  for total number of signal photons
- Highly flexible computational scheme

Generic Background Fields

$$\mathbf{A}(t,\mathbf{x}) = \int \mathrm{d}^3k \sum_i a_{0i}(\mathbf{k})\mathbf{e}_i(\mathbf{k})\mathrm{e}^{\mathrm{i}\mathbf{k}\cdot\mathbf{x}}\mathrm{e}^{-\mathrm{i}\omega t} \tag{21}$$

- Vector potential $\mathbf{A}(t,\mathbf{x})$ given in terms of amplitudes a_{0i}
- Two transverse polarization modes $\mathbf{e}_i(\mathbf{k})$
- Spatial Fourier transform
- Time evolution as phase factor $\mathrm{e}^{-\mathrm{i}\omega t}$
- Solution to Maxwell equations

A. Blinne et al. Phys. Rev. D (99), (2019) no.1, 016006

Paraxial Approximation

Wave vectors

$$\kappa_\perp^2 \ll \kappa^2 \tag{22}$$

Photons in background field propagate in same direction κ

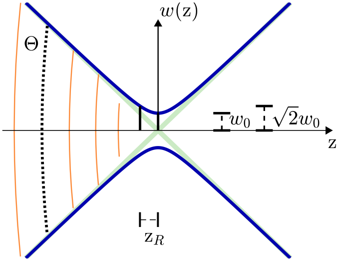
Field components

$$\mathbf{E} = \mathcal{E}\hat{\mathbf{e}}_E, \qquad \mathbf{B} = \mathcal{E}\hat{\mathbf{e}}_B \tag{23}$$

$$\hat{\mathbf{e}}_E \cdot \hat{\mathbf{e}}_B = \hat{\mathbf{e}}_E \cdot \hat{\mathbf{e}}_\kappa = \hat{\mathbf{e}}_B \cdot \hat{\mathbf{e}}_\kappa = 0, \quad \hat{\mathbf{e}}_E \times \hat{\mathbf{e}}_B = \hat{\mathbf{e}}_\kappa \tag{24}$$

Fields are characterized by an overall field amplitude $\mathcal{E}$

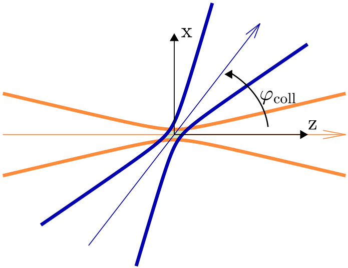
Paraxial Approximation: Gaussian Beam



Transverse widening $w(z) = w_0 \sqrt{1 + (z/z_R)^2}$ Rayleigh range $z_R = \pi w_0^2 / \lambda$ Beam divergence Θ

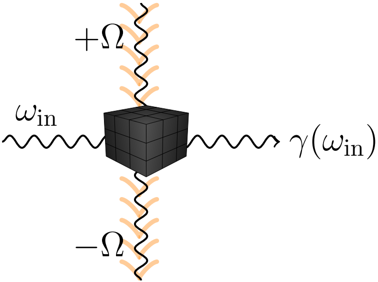
- $\mathcal{E}(x) = \mathcal{E}_0 \, e^{-\frac{(z \pm t)^2}{(\tau/2)^2}} \frac{w_0}{w(z)} e^{-\frac{r^2}{w^2(z)}} \cos\big(\omega(z \pm t) + \Phi(x)\big)$
- Frequency $\omega = \frac{2\pi}{\lambda}$ Field strength $\mathcal{E}_0$ Duration τ

Colliding Beams



- Collision angle φ_{coll}
- Different angle $\rightarrow$ change kinematics of scattered photons

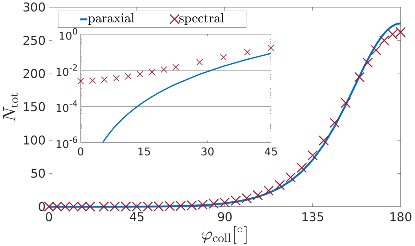
Stimulated Photon Emission

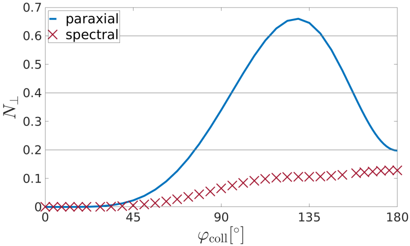


- Photons with energy $\Omega \rightarrow$ stimulated emission
- Characteristics of signal photon γ similar to ingoing photon ω_{in}

F. Karbstein et al.: Phys. Rev. D **91** (2015) no.11, 113002

Signal Photon Rate



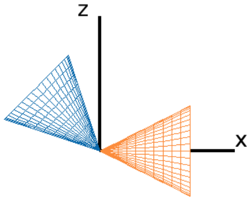


Parameters: $W = 25$J, $\tau = 25$fs, $\lambda = 800$nm

- Collision of two optimally focused laser pulses
- Single-pulse photon emission
- Paraxial approximation cannot resolve signal photon polarization

A. Blinne et al.: Phys. Rev. D **99** (2019) no.1, 016006

Two-Beam Setup

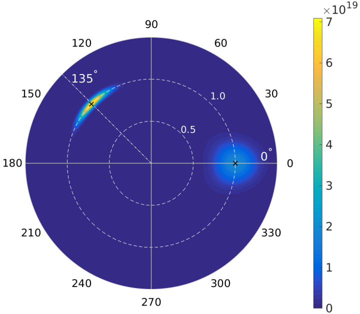


Beam 1: $W = 50\text{J}$, $\tau = 5\text{fs}$, $\lambda = 800\text{nm}$

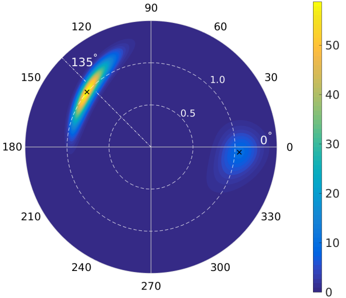
Beam 2: $W = 135\text{J}$, $\tau = 30\text{fs}$, $\lambda = 800\text{nm}$, $\varphi_{\mathrm{coll}} = 135^{\circ}$

Combine short-pulsed beam with long-pulsed beam

Signal Photon Characteristics



Beam 1: $W = 50\text{J}$, $\tau = 5\text{fs}$, $\lambda = 800\text{nm}$

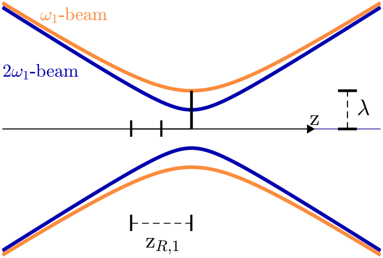


Beam 2: $W = 135\text{J}$, $\tau = 30\text{fs}$, $\lambda = 800\text{nm}$, $\varphi_{\text{coll}} = 135^\circ$

- Differential numbers of laser and signal photons
- Maxima in signal photons shifted from laser frequency ω
- Signal photons with wider angular distribution

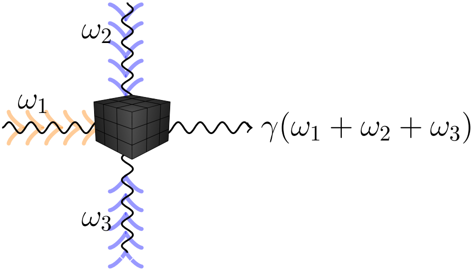
A. Blinne et al.: Phys. Rev. D 99 (2019) no.1, 016006

Frequency Doubling



- Second beam with doubled frequency
- 50 % energy loss
- All beams are "optimally" focused

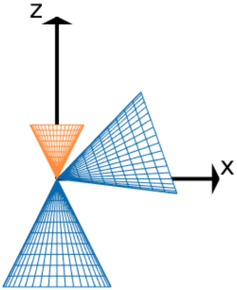
Four-Wave Mixing



- Photon scattering gives rise to fourth energy
- Kinematics of signal photon $\gamma \to$ deviate from incoming beams

E. Lundstrom et al.: Phys. Rev. Lett. **96** (2006), 083602

Three-Beam Setup



Parameters: $W = 25\text{J}$, $\tau = 25\text{fs}$, $\lambda = 800\text{nm} \rightarrow \omega_{\mathbf{1}} = 1.55\text{eV}$

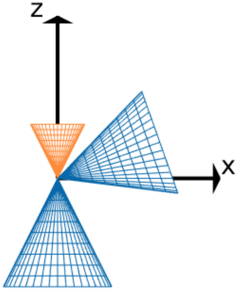
Parameters: $W = 6.25\text{J}$, $\tau = 25\text{fs}$, $\lambda = 400\text{nm} \rightarrow \omega_{\mathbf{2}} = 3.1\text{eV}$, $\varphi_{\mathbf{2}} = 70.5^{\circ}$, $\varphi_{\mathbf{3}} = 180^{\circ}$

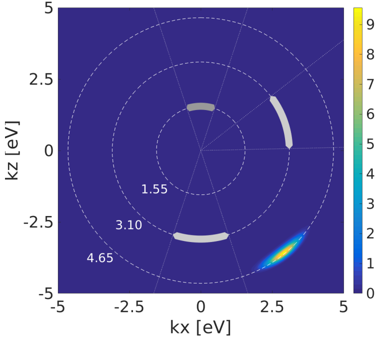
Combine high-intensity beam with two frequency-doubled beams

E. Lundstrom et al.: Phys. Rev. Lett. **96** (2006) 083602

N. Seegert: PhD Thesis, 2017

Directional Emission Characteristics





- Frequency-tripled signal
- Outside of background beam foci (grey areas)

H. Gies et al.: Phys. Rev. D **97** (2018) no.7, 076002

Takeaways: Light-by-light Scattering at Low Energies

Summary

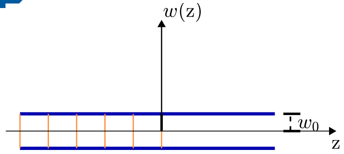
- Vacuum emission picture
  $\rightarrow$ photon-photon scattering beyond plane-wave approximation
- Multi-beam setups
- Directional emission characteristics
- Signatures in signal photon polarization

Outlook

- Multi-scale problems
- Higher modes

Outline

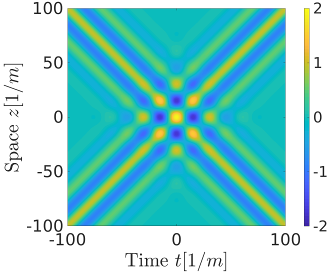
Paraxial Approximation: Unfocused Beam



transverse profile $w(z) = w_0$ no beam divergence

- High-energy photon beams → hard to focus
- $\mathcal{E}(t,z) = \varepsilon\, \varepsilon_{crit}\, \mathrm{e}^{-\frac{(z\pm \mathrm{t})^2}{(\tau/2)^2}} \cos\left(\omega(z \pm \mathrm{t}) + \varphi\right)$
- Frequency $\omega = \frac{2\pi}{\lambda}$ Field strength ε Duration τ
- Perpendicular, unidirectional, electric & magnetic fields

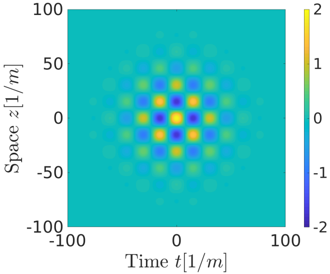
Colliding Beams



$\mathcal{E}_\pm(z,t) = \varepsilon\, \varepsilon_{crit}\, \mathrm{e}^{-\frac{(z\pm t)^2}{(\tau/2)^2}} \cos(\omega(z \pm t))$ **Frequency** $\omega = \frac{2\pi}{\lambda}$ **Field strength** ε **Duration** τ

- Two colliding beams
- Non-vanishing Lorentz invariants in vicinity of collision center
- Incoming and outgoing beams

Standing Wave Approximation

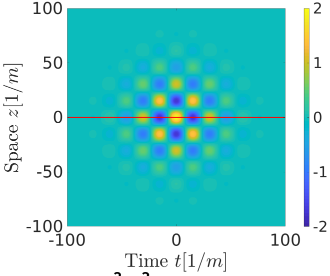


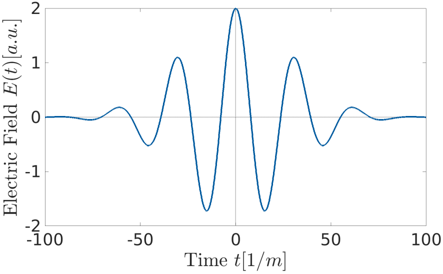
$\mathcal{E}_\pm(z,t) = \varepsilon\, \varepsilon_{crit}\, \mathrm{e}^{-\frac{z^2+t^2}{(\tau/2)^2}} \cos(\omega(z \pm t))$

Frequency $\omega = \frac{2\pi}{\lambda}$ Field strength ε Duration τ

- Local standing wave
- Background fields vanish at $t \to \pm\infty$

Dipole Approximation



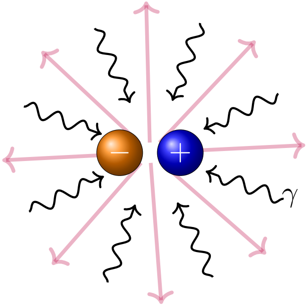


$$\mathcal{E}_{\pm}(z,t) = \varepsilon\, \varepsilon_{crit}\, \mathrm{e}^{-\frac{z^2+t^2}{(\tau/2)^2}} \cos(\omega(z \pm t))$$

Frequency $\omega = \frac{2\pi}{\lambda}$ Field strength ε Duration τ

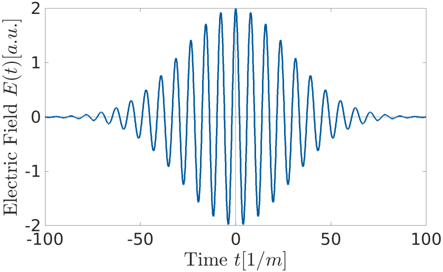
- Single point in space $z = z_0$
- Spatially homogeneous electric field
- Magnetic field vanishes automatically

Multiphoton Pair Production: Dipole Approximation



- Photons γ do not carry linear momentum
- Transfer of energy and angular momentum
- One photon can decay into particle pair

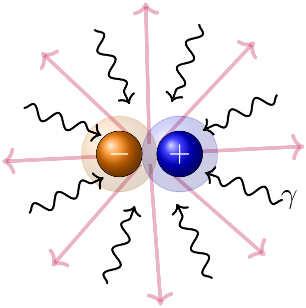
Ponderomotive Energy



Frequency $\omega = \frac{2\pi}{\lambda}$ **Field strength** ε

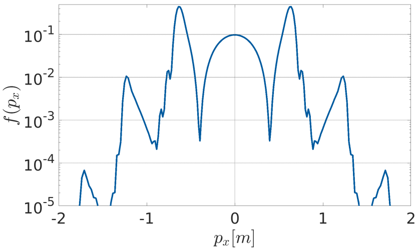
- Created particles quiver in oscillating field
- Time-averaged energy $U \propto \varepsilon^2/\omega^2$

Effective Multiphoton Pair Production



- e^-e^+ interact with electric background field
- Particles behave as if they had a higher mass
- Effective mass $m_* = m\sqrt{1 + \varepsilon^2/(2\omega^2)}$

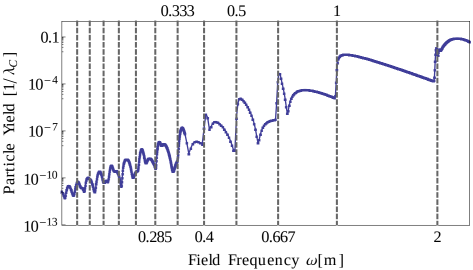
Particle Distribution



Parameters: $\tau = 40m^{-1}, \ \varepsilon = 0.2, \ \omega = 0.8m$

- Above-Threshold peaks
- Peak position predictable via effective mass concept
- Energy conservation: $\left(\frac{n\omega}{2}\right)^2 = m_*^2 + p_n^2$

Particle Yield

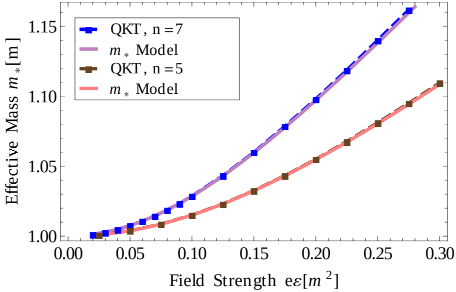


Parameters: $\tau = 100m^{-1}$, $\varepsilon = 0.1$

- Resonant at n-photon frequencies: $\omega_n = 2m_*/n$

C. Kohlfürst et al.: Phys. Rev. Lett. **112** (2014), 050402

Effective Mass



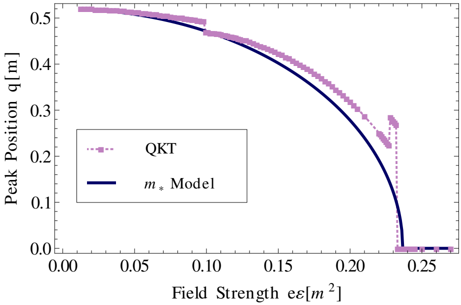
Parameters: $\tau = 100m^{-1}$, $n = 7$

Parameters: $\tau = 100m^{-1}$, $n = 5$

- Comparison: numerical simulation (QKT) - m_* model

C. Kohlfürst et al.: Phys. Rev. Lett. **112** (2014), 050402

Channel Closing

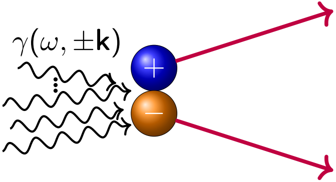


Parameters: $\tau = 300m^{-1}$, $\omega = 0.322m$

- Above-Threshold peak position varies with field strength ε
- Resonance: Peak at threshold ($q = 0$)

C. Kohlfürst et al.: Phys. Rev. Lett. 112 (2014), 050402

Multiphoton Pair Production: Standing-Wave Approximation



- Transfer of energy, linear and angular momentum
- Scattering channels distinguishable
- Unique momentum spectrum

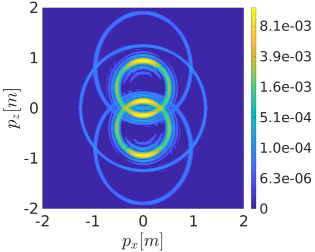
Energy-Momentum Conservation

$$\text{Energy}: \quad E_{e^+} + E_{e^-} = n_+\omega + n_-\omega \tag{25}$$

$$\text{Momentum}: \quad p_{z,e^+} + p_{z,e^-} = n_+\omega - n_-\omega \tag{26}$$

- Standing wave formed by two laser beams propagating in $\pm z$
- Number of contributing photons per laser beam n_+ and n_-
- Photons with energy ω and momentum $k = \pm\omega$

Momentum Spectrum

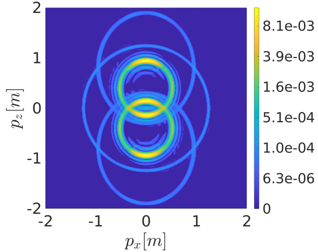


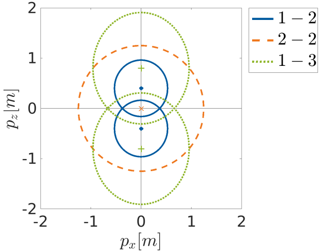
Parameters: $\tau = 60m^{-1}$, $\omega = 0.8m$, $\varepsilon = 0.2$

- Offset in p_z possible
- Above-Threshold pair production

I. Aleksandrov et al.: in preparation

Momentum Spectrum: Channels

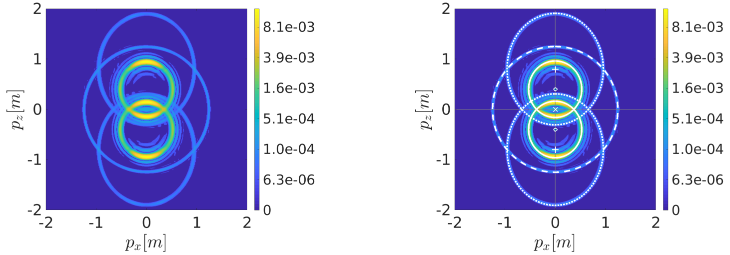




Parameters: $\tau = 60m^{-1}$, $\omega = 0.8m$, $\varepsilon = 0.2$

- Multiphoton channels: $n_+ - n_-$ and $n_- - n_+$
- Circles: $n_+ = n_-$
- Ellipses: $n_+ \neq n_-$

Momentum Spectrum: Channels



Parameters: $\tau = 60 m^{-1}$, $\omega = 0.8m$, $\varepsilon = 0.2\, E_{\mathrm{cr}}$

- Overlay of analytical and numerical results
- Interference pattern: Angular momentum conservation

Takeaways: Light-by-light Scattering at High Energies

Summary

- Phase-space formalism $\rightarrow$ pair production processes in the non-perturbative threshold domain
- Background-field dependent threshold

Outlook

- Back-reaction
- Beyond mean-field
- $3D$-simulation

Thank you!

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Futher Reading I

- A. Blinne, H. Gies, F. Karbstein, C. Kohlfürst and M. Zepf, Phys. Rev. D **99** (2019) no.1, 016006 [arXiv:1811.08895 [physics.optics]].
- H. Gies, F. Karbstein and C. Kohlfürst, Phys. Rev. D **97** (2018) no.3, 036022 [arXiv:1712.03232 [hep-ph]].
- H. Gies, F. Karbstein, C. Kohlfürst and N. Seegert, Phys. Rev. D **97** (2018) no.7, 076002 [arXiv:1712.06450 [hep-ph]].
- C. Kohlfürst, H. Gies and R. Alkofer, Phys. Rev. Lett. **112** (2014) 050402 [arXiv:1310.7836 [hep-ph]].
- C. Kohlfürst, Phys. Rev. D **99** (2019) no.9, 096017 [arXiv:1812.03130 [hep-ph]].