All-optical probes of quantum vacuum nonlinearity

Felix Karbstein

Helmholtz-Institut Jena & Friedrich-Schiller-Universität Jena
Probing quantum vacuum nonlinearity with high-intensity lasers

Felix Karbstein

Helmholtz-Institut Jena & Friedrich-Schiller-Universität Jena
Outline

(i) Introduction

(ii) Our approach

(iii) Vacuum birefringence

(iv) Conclusions & Outlook
(i) Introduction
The quantum vacuum is not empty and boring, but rather a highly nontrivial interacting medium.
The quantum vacuum is not empty and boring, but rather a highly nontrivial interacting medium.

- knows about particle content and interactions of the theory,
  in QED: $e^-$, $e^+$, $\gamma$ interacting via $e$: electron charge

- particle-antiparticle fluctuations, virtual (= off-shell) particles

- happens everywhere/all the time
The quantum vacuum is not empty and boring, but rather a highly nontrivial interacting medium.

At 1-loop level:
The **quantum** vacuum is not empty and boring, but rather a highly nontrivial interacting medium.

At 1-loop level:

\[ \lambda_c \sim \tau_c \sim \frac{1}{m_e} \]

\[ \lambda_c = 3.9 \cdot 10^{-13} \text{m} \]

\[ \tau_c = 1.3 \cdot 10^{-21} \text{s} \]
The **quantum** vacuum is not empty and boring, but rather a highly nontrivial interacting medium.

At 1-loop level:

- in particular affects **photon propagation**
The quantum vacuum is not empty and boring, but rather a highly nontrivial interacting medium.

At 1-loop level:

- in particular affects photon propagation; no measurable consequences
The **quantum** vacuum is not empty and boring, but rather a highly nontrivial interacting medium.

At 1-loop level:

- in particular affects **photon propagation**; *no measurable* consequences

- vacuum has to be distorted, e.g., by external **electromagnetic field**
The **quantum** vacuum is not empty and boring, but rather a highly nontrivial interacting medium.

At 1-loop level:

\[ e^- \rightarrow \ldots \rightarrow \text{Nonlinear couplings between electromagnetic fields.} \]

- in particular affects **photon propagation**; **no measurable** consequences

- vacuum has to be distorted, e.g., by external **electromagnetic field**
The quantum vacuum is not empty and boring, but rather a highly nontrivial interacting medium.

At 1-loop level:

- in particular affects photon propagation; \textbf{no measurable consequences}

- vacuum has to be distorted, e.g., by external electromagnetic field
(i) Introduction

Quantum vacuum nonlinearity manifests itself in various effects, e.g.,

- direct light-by-light scattering

[Euler, Kockel: Naturwiss. 1935]
Quantum vacuum nonlinearity manifests itself in various effects, e.g.,

- direct light-by-light scattering

\[ \text{[Euler, Kockel: Naturwiss. 1935]} \]
\[ \text{[Karplus, Neuman: Phys. Rev. 1950]} \]

- vacuum birefringence

\[ \text{[Toll: PhD thesis 1952]} \]
Quantum vacuum nonlinearity manifests itself in various effects, e.g.,

- direct light-by-light scattering

- vacuum birefringence

- quantum reflection
Quantum vacuum nonlinearity manifests itself in various effects, e.g.,

- direct light-by-light scattering

- vacuum birefringence

- quantum reflection

- photon splitting
Quantum vacuum nonlinearity manifests itself in various effects, e.g.,

- direct light-by-light scattering

- vacuum birefringence

- quantum reflection

- photon splitting

- photon merging
(ii) Our approach
(ii) Our approach

**Problem**: Most analytical calculations have been performed either for uniform, constant or planewave backgrounds (null-fields).

- Photon polarization tensor

  [Batalin, Shabad: JETP 1971]
  [Baier, Milshtein, Strakhovenko: JETP 1975]

↔ the electromagnetic fields delivered by focused high-intensity lasers are highly inhomogeneous
(ii) Our approach

**Problem:** Most analytical calculations have been performed either for uniform, constant or planewave backgrounds (null-fields).

- Photon polarization tensor

\[ \text{[Batalin, Shabad: JETP 1971]} \]
\[ \text{[Baier, Milshtein, Strakhovenko: JETP 1975]} \]
\[ \text{[Becker, Mitter: J. Phys. A 1975]} \]

↔ the electromagnetic fields delivered by focused high-intensity lasers are highly inhomogeneous

- Pulsed, focused Gaussian beams
(ii) Our approach

Our approach: The locally constant field approximation constitutes a good approximation, for the special case where no real electrons and positrons are present and the field changes only slightly over distances of Compton wavelength. 

$$A(x)$$

$$w \gg \lambda_c$$

[Heisenberg, Euler: Z. Phys. 1936]
Our approach: The locally constant field approximation constitutes a good approximation, for

\[ A(x) \]

\[ w \gg \lambda_c \]

- analytical insights possible without having to solve the problem for the exact, inhomogeneous background field configuration.
Our approach: The locally constant field approximation constitutes a good approximation, for

- analytical insights possible without having to solve the problem for the exact, inhomogeneous background field configuration.

→ Polarization tensor in pulsed, focused Gaussian beams

\[
\Pi^{\rho\sigma}(k, k'|A) = (g^{\rho\beta}k'^{\alpha} - g^{\rho\alpha}k'^{\beta}) \left[ \int_x e^{i(k+k')x} \frac{\partial^2 L[A]}{\partial F^{\alpha\beta} \partial F^{\mu\nu}}(x) \right] (k'^{\mu} g^{\nu\sigma} - k'^{\nu} g^{\mu\sigma})
\]

[FK, Shaisultanov: Phys. Rev. D 91 085027 (2015)]
(iii) Vacuum birefringence
(iii) Vacuum birefringence

Conventional scenario:

- vacuum birefringence → ellipticity: photons in polarization mode induced ↔ probe photons

\[ \vec{B} \sim \text{const.} \]

[BMV (Biréfringence Magnétique du Vide) experiment, Toulouse]
[PVLAS (Polarizzazione del Vuoto con Laser) experiment, Padova/Ferrara]

Laser

probe photons

Detector

length \( l \)
Conventional scenario:

\[ \vec{B} \sim \text{const.} \]

- Vacuum birefringence → ellipticity:
  - photons in polarization mode induced:

\[ \leftrightarrow \]

microscopic:

- length \( l \)

- \( \sim \lambda_c \)

[BMV (Biréfringence Magnétique du Vide) experiment, Toulouse]

[PVLAS (Polarizzazione del Vuoto con Laser) experiment, Padova/Ferrara]
(iii) Vacuum birefringence

Conventional scenario:

\[ \vec{B} \sim \text{const.} \]

[BMV (Biréfringence Magnétique du Vide) experiment, Toulouse]

[PVLAS (Polarizzazione del Vuoto con Laser) experiment, Padova/Ferrara]
(iii) Vacuum birefringence

Conventional scenario:

- vacuum birefringence $\rightarrow$ ellipticity: $\Delta \phi \sim \alpha \frac{l}{\lambda} \left(\frac{eB}{m_e^2}\right)^2$

$\vec{B} \sim \text{const.}$

$\downarrow$ relative phase shift between $\parallel$ and $\perp$ modes

Laser

Detector

length $l$

probe photons

[BMV (Biréfringence Magnétique du Vide) experiment, Toulouse]

[PVLAS (Polarizzazione del Vuoto con Laser) experiment, Padova/Ferrara]
### (iii) Vacuum birefringence

**Conventional scenario:**

- Vacuum birefringence → ellipticity: \( \Delta \phi \sim \alpha \frac{l}{\lambda} \left( \frac{eB}{m_e^2} \right)^2 \) → relative phase shift between \( || \) and \( \perp \) modes

\[ N_{\perp} \sim \left( \frac{\Delta \phi}{2} \right)^2 N_{\text{in}} \]

**[BMV (Biréfringence Magnétique du Vide) experiment, Toulouse]**

**[PVLAS (Polarizzazione del Vuoto con Laser) experiment, Padova/Ferrara]**
(iii) Vacuum birefringence

Analogous scenario with pump = high-intensity laser:

(iii) Vacuum birefringence

Analogous scenario with pump = high-intensity laser:

\[ \Delta \phi \sim \alpha \frac{l}{\lambda} \left( \frac{e \mathcal{E}}{m_e^2} \right)^2 \]

(iii) Vacuum birefringence

Analogous scenario with $\text{pump} = \text{high-intensity laser}$:

- in a recent study we account for the full inhomogeneous field profile of a linearly polarized, pulsed Gaussian laser beam

- $\text{pump}$: 1PW class laser ($W = 30J, \tau = 30fs, \lambda = 800nm, w_0 = 1\mu m$)

- $\text{probe}$: x-ray beam from FEL ($\omega = 12914eV, N_{in} \simeq 10^{12}$)

(iii) Vacuum birefringence

An analogous scenario with pump = high-intensity laser:

→ demand for high-purity x-ray polarimetry

(iii) Vacuum birefringence

Analogous scenario with pump = high-intensity laser:

→ demand for high-purity x-ray polarimetry

- experimental confirmation of vacuum birefringence requires $\frac{N_\perp}{N_{\text{in}}} > \mathcal{P}$.

Polarization purity record $\Theta \omega = 12914\text{eV}$:

$$\mathcal{P} = 5.7 \cdot 10^{-10}$$
(iii) Vacuum birefringence

Our theoretical approach:

Idea: Interpret vacuum birefringence as *vacuum emission process*:

- laser fields correspond to macroscopic electromagnetic fields
- taking this literally means not to resolve the individual photons constituting the beams

[FK, Shaisultanov: Phys. Rev. D 91 113002 (2015)]
(iii) Vacuum birefringence

Our theoretical approach:

**Idea:** Interpret vacuum birefringence as **vacuum emission process**:

[FK, Shaisultanov: Phys. Rev. D 91 113002 (2015)]

- laser fields correspond to macroscopic electromagnetic fields
- taking this literally means not to resolve the individual photons constituting the beams

↔ vacuum in the presence of pump and probe beams = |0⟩

- the signal of quantum vacuum nonlinearity is encoded in (single) photons = |γ(p)(k)⟩ emitted from the strong field region

→ amplitude: \( S_p(k) = \langle \gamma_p(k) | \int_x a_\mu(x) j^\mu(x) |0⟩ \).
(iii) Vacuum birefringence

Our theoretical approach:

**Idea:** Interpret vacuum birefringence as **vacuum emission process:**

\[ S_{(p)}(\vec{k}) = \langle \gamma_p(\vec{k}) | \int_x a_\mu(x) j^\mu(x) | 0 \rangle. \]

[FK, Shaisultanov: Phys. Rev. D 91 113002 (2015)]
(iii) Vacuum birefringence

Our theoretical approach:

**Idea:** Interpret vacuum birefringence as **vacuum emission process**:

\[ S(p)(\vec{k}) = \langle \gamma_p(\vec{k}) | \int_x a_\mu(x) j^\mu(x) | 0 \rangle. \]

[FK, Shaisultanov: Phys. Rev. D 91 113002 (2015)]

\[ \rightarrow \text{amplitude:} \quad S(p)(\vec{k}) = \langle \gamma_p(\vec{k}) | \int_x a_\mu(x) j^\mu(x) | 0 \rangle. \]
(iii) Vacuum birefringence

Our theoretical approach:

**Idea:** Interpret vacuum birefringence as *vacuum emission process*:

\[ S_{(p)}(\vec{k}) = \langle \gamma_p(\vec{k}) | \int_x a_\mu(x) j^\mu(x) | 0 \rangle. \]

\[ j^\mu(x) = \int_{x'} \Pi^{\mu\nu}(x, x' | \mathcal{A}) A_\nu(x') \]

[FK, Shaisultanov: Phys. Rev. D 91 113002 (2015)]
(iii) Vacuum birefringence

Our theoretical approach:

**Idea**: Interpret vacuum birefringence as vacuum emission process:

$$\rightarrow \text{amplitude: } S_p(k) = \langle \gamma_p(k) | \int_x a_\mu(x) j^\mu(x) | 0 \rangle.$$ 

$$j^\mu(x) = \int_{x'} \Pi^{\mu\nu}(x, x' | A) A_\nu(x')$$

[FK, Shaisultanov: Phys. Rev. D 91 113002 (2015)]
(iii) Vacuum birefringence

Our theoretical approach:

**Idea:** Interpret vacuum birefringence as **vacuum emission process**:

\[ S_{(p)}(\vec{k}) = \langle \gamma_p(\vec{k}) | \int_x a_{\mu}(x) j^\mu(x) | 0 \rangle. \]

\[ \rightarrow N_\perp = \int \frac{d^3 k}{(2\pi)^3} | S_{(\perp)}(\vec{k}) |^2 \]

\[ j^\mu(x) = \int_{x'} \Pi^{\mu\nu}(x, x' | A) A_\nu(x') \]
(iii) Vacuum birefringence


- we consider three different cases
(iii) Vacuum birefringence

Our results:

- we consider three different cases

→ case (a): 

\[ \text{[FK, et al.: in preparation 2015]} \]
(iii) Vacuum birefringence


- we consider three different cases

→ case (a):  

\[ \gamma_p(k) \]  

\[ w(z) \]  

probe

pump

\[ \theta \]  

\[ w_0 \]  

\[ \sqrt{2}w_0 \]  

\[ Z_R \]  

\[ \lambda \]
(iii) Vacuum birefringence


- we consider three different cases

→ case (a):

\[ \gamma_p(\vec{k}) \]

[Graph showing a plot with time constants for different temperatures: T → ∞, T = 500fs, T = 30fs, for \( \omega = 12914 \text{eV} \)]
(iii) Vacuum birefringence


- we consider three different cases

→ case (a):

\[ \gamma_p(\vec{k}) \]

\[ \frac{T[\text{s}]}{N} \frac{dN(\perp)}{dk_z'} \]

\[ \omega = 12914\text{eV} \]

\[ T \to \infty \]

\[ T = 500\text{fs} \]

\[ T = 30\text{fs} \]

\[ \lambda \]

pump

Photon 2015, Budker Institute of Nuclear Physics, Novosibirsk, June 17th 2015
(iii) Vacuum birefringence

Our results:

- we consider three different cases

→ case (a):

\[ \frac{N_{\perp}}{N_{\text{in}}}|_{T=30\text{fs}} = 1.39 \cdot 10^{-12} \approx \frac{\mathcal{P}}{410} \]
(iii) Vacuum birefringence

Our results:

- we consider three different cases

(iii) Vacuum birefringence


- we consider three different cases

→ case (b):
(iii) Vacuum birefringence


- we consider three different cases

→ case (b):  and case (c):  

\( \gamma_p(k) \)

\( r \)

\( w(z) \)

probe

pump

\( \theta \)

\( w_0 \)

\( \sqrt{2}w_0 \)

\( Z_R \)
(iii) Vacuum birefringence

Our results:

- we consider three different cases

→ case (c):

\[ \gamma_p(\vec{k}) \]

\[ \text{pump} \]

\[ \theta(3w_0) \]

\[ \omega = 12914\text{eV}, T = 30\text{fs} \]

\[ \frac{dN^{(\perp)}}{d\cos \vartheta} \]

\[ \frac{dN^{(\perp)}}{d\vartheta} \]
(iii) Vacuum birefringence

Our results:

- we consider three different cases

→ case (c):

\[ \gamma_p(\vec{k}) \]

\[ \text{pump} \]

\[ \lambda \]

\[ \theta(3w_0) \]

\[ \frac{N_{\perp}}{N_{\text{in}}} \mid T=30\text{fs} \]

\[ \omega = 12914\text{eV}, \; T = 30\text{fs} \]

\[ (b) \frac{dN(\perp)}{d\cos \varphi} \]

\[ (c) \frac{dN(\perp)}{d\varphi} \]

\[ \mathcal{P} > 0 \]
(iii) Vacuum birefringence


- we consider three different cases

→ case (c):

→ repetition rate 1Hz: \( N_\perp \approx 265/\text{hour} \)
(iv) Conclusions and Outlook
(iv) Conclusions

- I focused on **all-optical probes** of quantum vacuum nonlinearity.

- I presented and advocated a different perspective to analyze optical signatures of **quantum vacuum nonlinearities**.

- I exemplarily discussed **vacuum birefringence**.
(iv) Conclusions & Outlook

- I focused on **all-optical probes** of quantum vacuum nonlinearity.

- I presented and advocated a different perspective to analyze optical signatures of **quantum vacuum nonlinearities**.

- I exemplarily discussed **vacuum birefringence**.

- Our approach can be straightforwardly generalized to the study of other (inhomogeneous) electromagnetic field profiles.

- It can be easily adopted to various other optical probes.
(iv) Conclusions & Outlook

- I focused on **all-optical probes** of quantum vacuum nonlinearity.

- I presented and advocated a different perspective to analyze optical signatures of **quantum vacuum nonlinearities**.

- I exemplarily discussed **vacuum birefringence**.

- Our approach can be straightforwardly generalized to the study of other (inhomogeneous) electromagnetic field profiles.

- It can be easily adopted to various other optical probes.

Thank you for your attention!