Connecting electromagnetic vacuum structure with some QCD phenomena

Stefan Evans[1,2], Ralf Schützhold[1], and Johann Rafelski[2]

Margaret Island Symposium

Particles and Plasmas

June 7, 2023

(1) HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

(2) A Physics

1823 - Caspar David Friedrich

2023 - Saguaro National Park

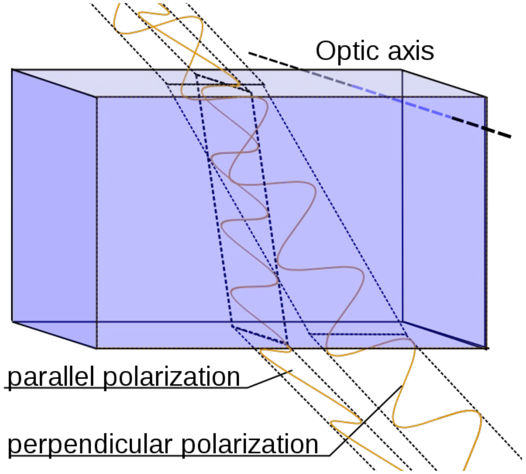
Overview: probing the QED + QCD vacuum

1 - Established wisdom: vacuum as a medium

- QED effective action in constant EM fields (known since 1935)
- Light-light scattering, nonperturbative effects
- QED and QCD are inseparable – role of axions
- Today’s widespread interest in strong field experimental environments

2 - Probing vacuum birefringence in laboratory

- PVLAS: high finesse (Fabry-Perot)
- Current status at HIBEF: high intensity lasers
- Role of axions in light-light scattering



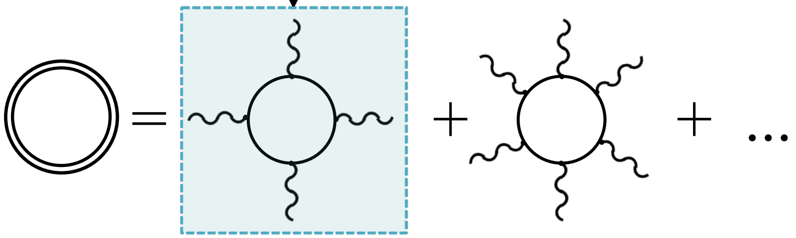
3 - Advancing QED and QCD theory for extreme field environments

- Higher order QED loops
- Opportunities for studying QED with large coupling and QCD

QED effective action in constant EM fields

The vacuum response of virtual spin 1/2 particles in presence of (infrared) long wavelength external fields:

Light-light scattering: Euler and Kockel. Naturwiss 23 no.15, 246 (1935).



$$\mathcal{L}^{1/2}_{\mathrm{EHS}} = \frac{1}{8\pi^2}\int_0^\infty \frac{du}{u^3}\, e^{-i(m^2-i\epsilon)u}\left(e^2u^2ab\,\frac{\cosh(eau)\cos(ebu)}{\sinh(eau)\sin(ebu)} - 1\right),$$

Euler-Heisenberg-Schwinger (EHS) action contains an imaginary part

$$a^2 - b^2 = \mathcal{E}^2 - \mathcal{B}^2 = 2S\,,$$
$$a^2b^2 = (\mathcal{E}\cdot\mathcal{B})^2 = P^2\,.$$

Heisenberg and Euler. Zeitschrift für Physik 98, 714 (**1936**).

Weisskopf. Kong. Dan. Vid. Sel. Mat. Fys. Med. 14, N6, 1 (**1936**).

Schwinger. Phys. Rev. 82, 664 (**1951**).

$$\lambda_C\frac{|\nabla\cdot\mathcal{E}|}{|\mathcal{E}|} \ll 1\,,\quad \lambda_C\frac{|\nabla\cdot\mathcal{B}|}{|\mathcal{B}|} \ll 1$$
$$\lambda_C = \hbar/mc = 386\ \mathrm{fm}$$

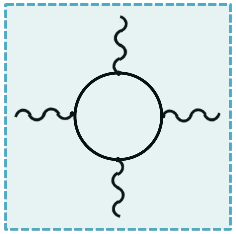
Light-light scattering

With the leading light-light scattering contribution, Maxwell equations in vacuum acquire properties of a nonlinear dielectric.

Total EM Lagrangian: $\mathcal{L}_{\rm EM} = \dfrac{\mathcal{E}^2 + \mathcal{B}^2}{2} + \mathcal{L}^{1/2}_{\rm EHS}$

$$\boxed{\begin{aligned} a^2 - b^2 &= \mathcal{E}^2 - \mathcal{B}^2 = 2S\,, \\ a^2 b^2 &= (\mathcal{E}\cdot\mathcal{B})^2 = P^2\,. \end{aligned}}$$

Light-light scattering:



$$\mathcal{L}^{1/2}_{\rm EHS} = \frac{2\alpha^2}{45 m^4}(4S^2 + 7P^2)$$

Distinguishing EM fields $\mathcal{E}, \mathcal{B}$ from source fields $D, \mathcal{H}$:

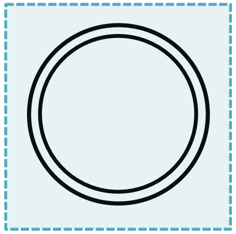
$$\mathcal{D} = \frac{\partial \mathcal{L}_{\rm EM}}{\partial \mathcal{E}} = \mathcal{E} + \underset{\uparrow}{\frac{\partial \mathcal{L}^{1/2}_{\rm EHS}}{\partial \mathcal{E}}}, \quad \mathcal{H} = -\frac{\partial \mathcal{L}_{\rm EM}}{\partial \mathcal{B}} = \mathcal{B} - \underset{\uparrow}{\frac{\partial \mathcal{L}^{1/2}_{\rm EHS}}{\partial \mathcal{B}}}$$

Driving vacuum birefringence

Nonperturbative effects

At fields near the EHS critical field $\boxed{\mathcal{E}_{\mathrm{EHS}} = \frac{m^2c^2}{e\hbar} = 1.32 \cdot 10^{18}\,\frac{\mathrm{V}}{\mathrm{m}} = 4.41 \cdot 10^{9} c\mathrm{T}\,.}$

Nonperturbative in external photons: vacuum non-persistence (e$^+$e$^-$ decay)



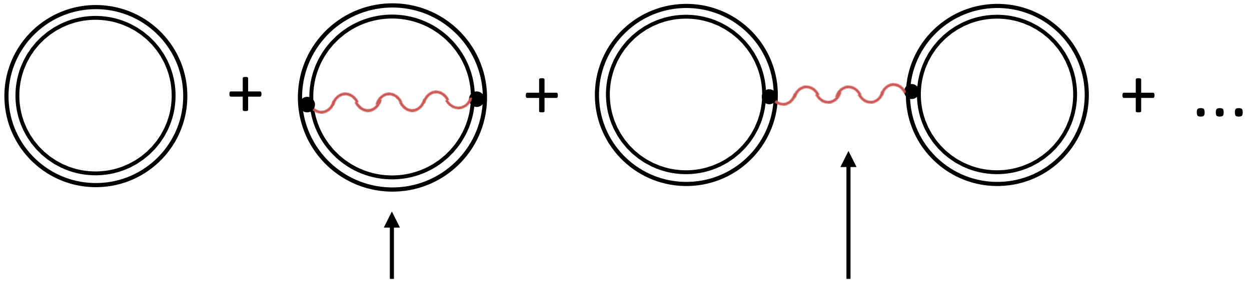
$$| \langle 0_{t=-\infty} | 0_{t=+\infty} \rangle |^2 = e^{-2L^3 T \mathrm{Im}[\mathcal{L}^{1/2}_{\mathrm{EHS}}]}\,,$$

$$\mathrm{Im}[\mathcal{L}^{1/2}_{\mathrm{EHS}}] = \frac{e^2ab}{8\pi^3} \sum_{n=1}^{\infty} \frac{\coth(n\pi b/a)}{n} e^{-n\pi m^2/ea}$$

$$\boxed{\begin{aligned} a^2 - b^2 &= \mathcal{E}^2 - \mathcal{B}^2 \\ a^2b^2 &= (\mathcal{E} \cdot \mathcal{B})^2 \end{aligned}}$$

In extreme fields ($\mathcal{B} \gg \mathcal{E}_{EHS}/c$), higher order QED effects become important.

Nonperturbative in external photons + perturbative in virtual photon terms:



Ritus, Sov. Phys. JETP 42, 774 (1975)

Gies and Karbstein, JHEP 1703, 108 (2017)

QED and QCD are inseparable – role of axions

As vacuum birefringence sensitivity nears the QED regime, experiments will also capture effects of QCD axions. Originally proposed as a solution to the strong CP problem in QCD, possible axions (and axion-like-particles) would have broad implications for laboratory and astrophysical environments.

Peccei and Quinn, Phys. Rev. Lett. 38 (1977), 1440-1443

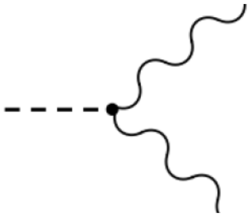
Weinberg, Phys. Rev. Lett. 40 (1978), 223-226

Pseudoscalar axion-photon coupling

$$\mathcal{L}_{\rm int} = G_{\rm A}\phi\mathcal{E}\cdot\mathcal{B}$$

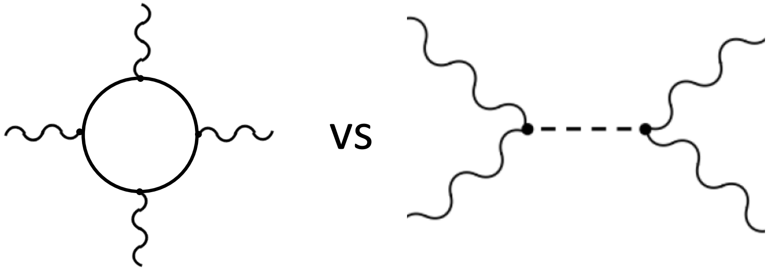
gives rise to:

Axion decay (and production)



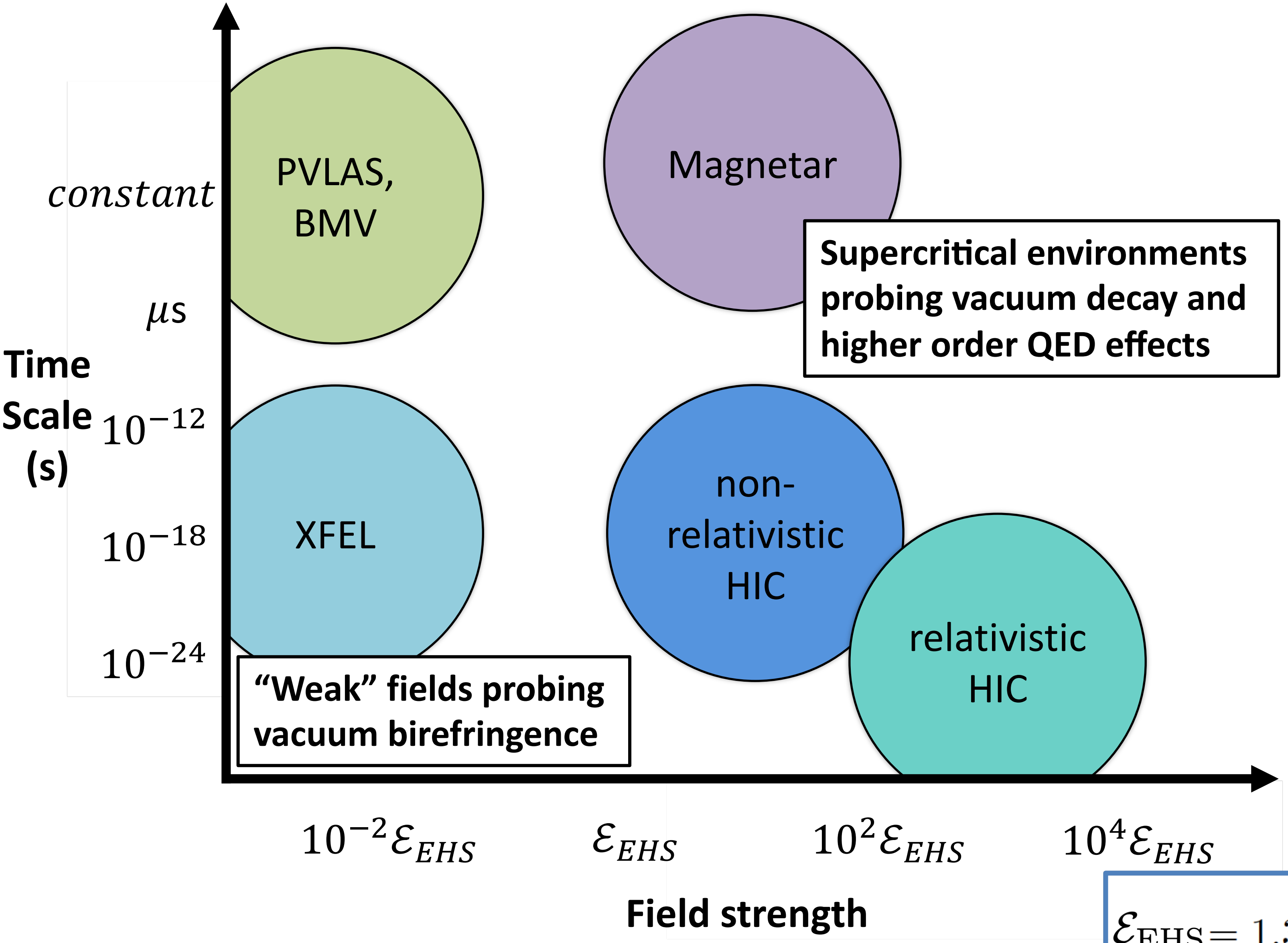
Relevant to astrophysical processes

Virtual excitations competing with QED



In laboratory probes of vacuum structure

Today's experimental environments

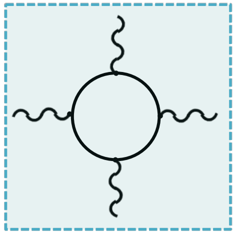


Supercritical environments probing vacuum decay and higher order QED effects

"Weak" fields probing vacuum birefringence

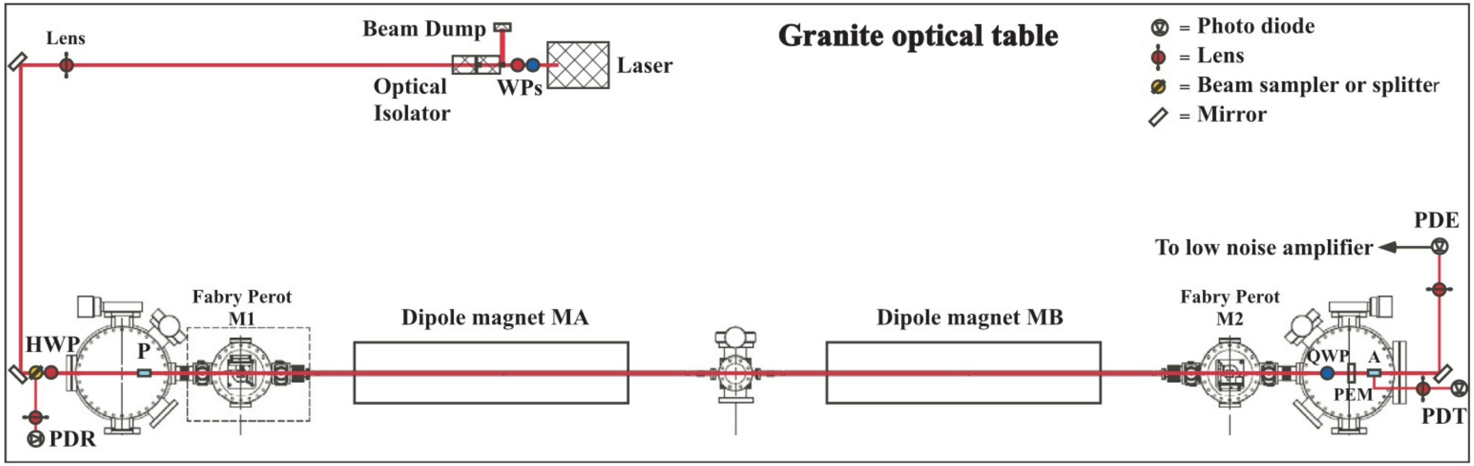
$$\mathcal{E}_{\mathrm{EHS}} = 1.32 \cdot 10^{18}\,\frac{\mathrm{V}}{\mathrm{m}}$$

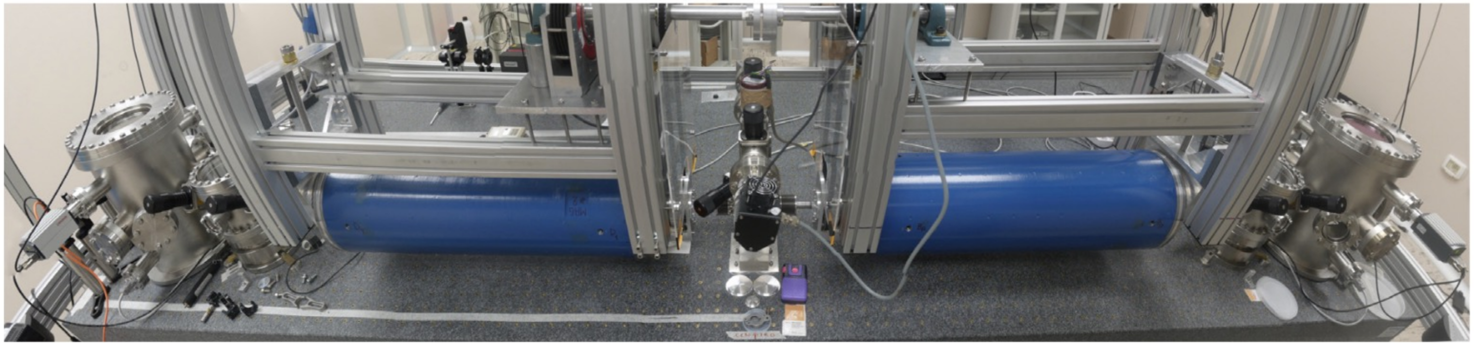
PVLAS: high finesse (Fabry-Perot)



The current sensitivity frontier (7 × QED signal) set by PVLAS ($\mathcal{B}\sim 2.5$ T $\ll \frac{\mathcal{E}_{EHS}}{c}$, but with finesse, $\mathcal{B} \to 10^6$ T).

Seeking a polarization flip in 1064 nm laser probe:





Ejlli, Della Valle et al. Phys. Rept. 871 (2020), 1-74

PVLAS: high finesse (Fabry-Perot)

In 2006 PVLAS observed a birefringence signal far greater the expected QED effect, attributing it to an axion-like-particle.

Zavattini et al. Phys. Phys. Rev. Lett. 96, (2006) 110406

A subsequent PVLAS upgrade and new measurement did not confirm this signal and so it was assumed to be an intrumental error.

Zavattini et al. Phys.Rev.D 77 (2008) 032006

This generated substatial interest in laboratory-based probes sensitive to virtual axion excitations, which due to e.g. confinement or running coupling may escape astronomical searches for real, free-streaming axions.

Ahlers, Gies, Jaeckel and Ringwald, Phys. Rev. D 75 (2007), 035011

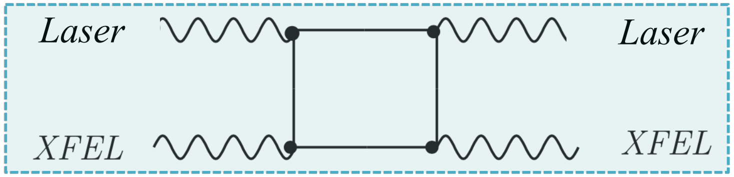
Masso and Redondo, Phys. Rev. Lett. 97 (2006), 151802

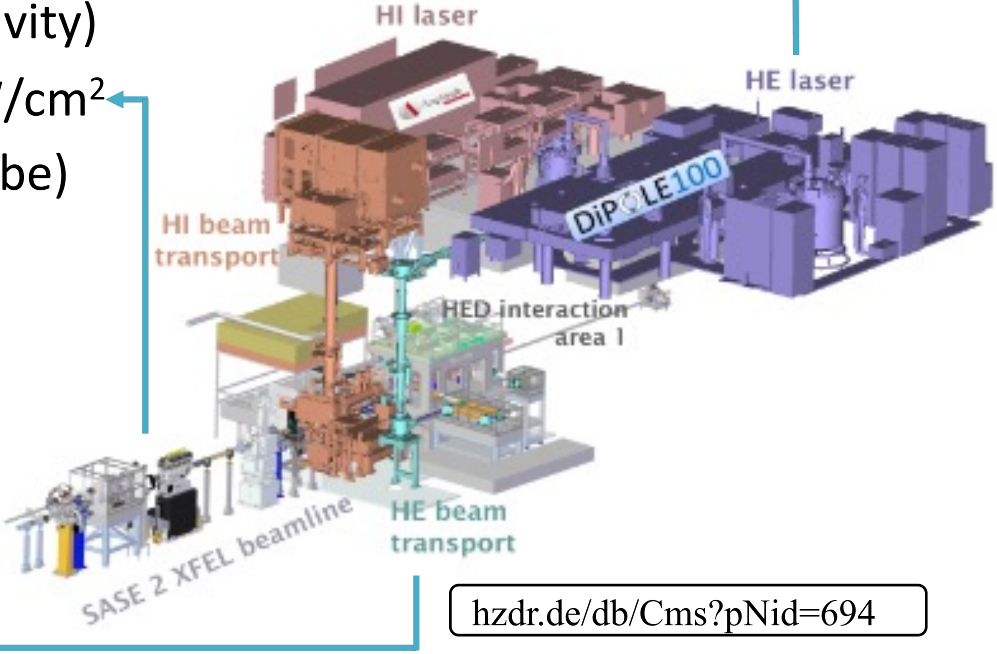
Current status at HIBEF: high intensity lasers

Strong field probes at Helmholtz International Beamline for Extreme Fields:

- Optical lasers: $10^{21} – 10^{22}$ W/cm^2
  ($\mathcal{B}\sim 10^{6}$ T reaches PVLAS sensitivity)
- European XFEL: 5-25 keV, 10^{18} W/cm^2
  (compare to PVLAS 1064nm probe)

Zastrau et al. J. Synchrotron Rad. (2021). 28, 1393–1416





hzdr.de/db/Cms?pNid=694

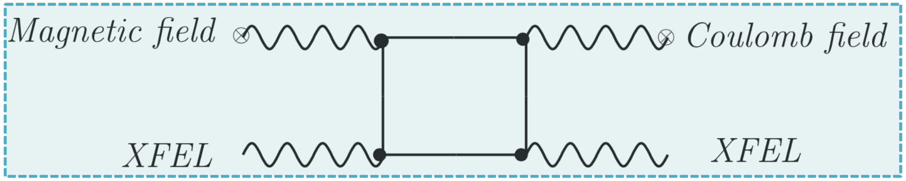
Laser-laser collisions:
Vacuum birefringence and diffraction beyond PVLAS sensitivity

Ahmadiniaz, Cowan, Sauerbrey, Schramm, Schlenvoigt and Schützhold, Phys. Rev. D 101, 116019 (2020)

Ahmadiniaz, Cowan, Grenzer, Viñas, Garcia, Šmíd, Toncian, Trejo, Schützhold, arXiv:2208.14215

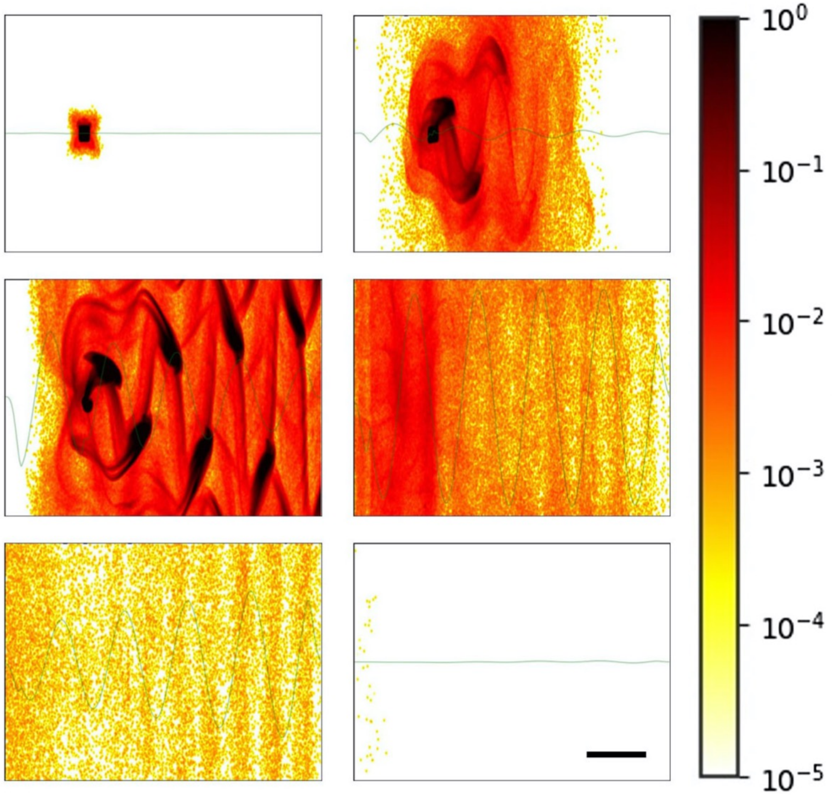
Current status at HIBEF: high intensity lasers

Coherent laser-plasma interactions enhancing the birefringence effect:



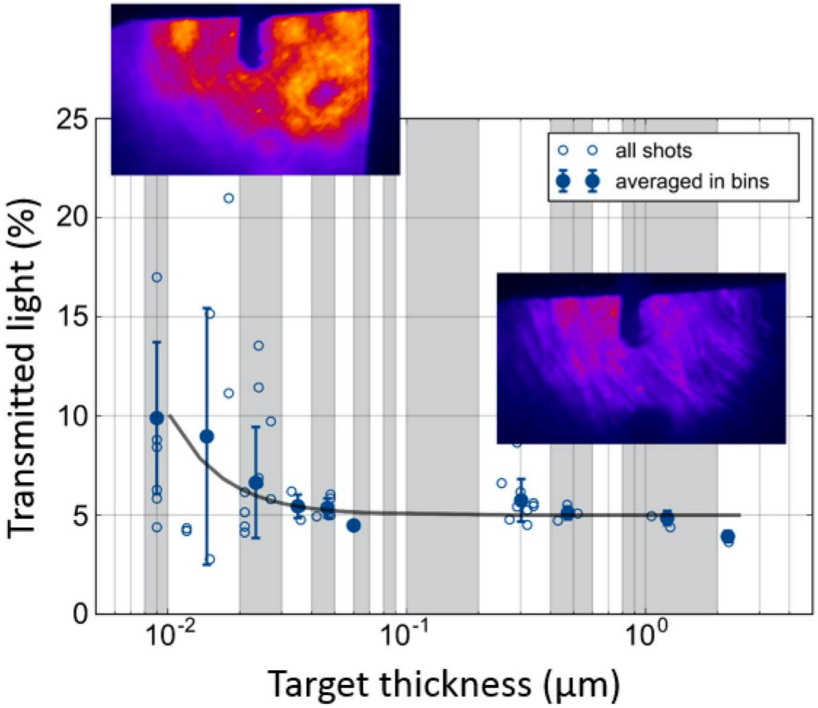
Possible coherent interactions with 10^8 Carbon nuclei, and further prospects with Hydrogen:

Simulation:



Ahmadiniaz, Bussmann, Cowan, Debus, Kluge, Schützhold, Phys. Rev. D. 104, L011902 (2021)

Experiment:



Poole et al. New J. Phys. (2018) 20, 013019

Role of axions in light-light scattering

Total (Maxwell+EHS+axion) action (**heavy axion limit – omitting kinetic term**)

$$\mathcal{L}^{(1)} = S - \frac{m_{\mathrm{A}}^2}{2}\varphi^2 + G_{\mathrm{A}}\varphi P + \frac{e^4}{(4\pi)^2}\frac{2}{45m_e^4}\left(4S^2 + 7P^2\right)$$

$$\boxed{\begin{aligned}\mathcal{E}^2 - \mathcal{B}^2 &= 2S\\ (\mathcal{E}\cdot\mathcal{B})^2 &= P^2\end{aligned}}$$

The ALP contribution is configuration-mixed with EM part

$$\tilde{\varphi} = \varphi - G_{\mathrm{A}}\frac{P}{m_{\mathrm{A}}^2}$$

Giving supplement to the EHS pseudoscalar-dependent (P^2) coefficient:

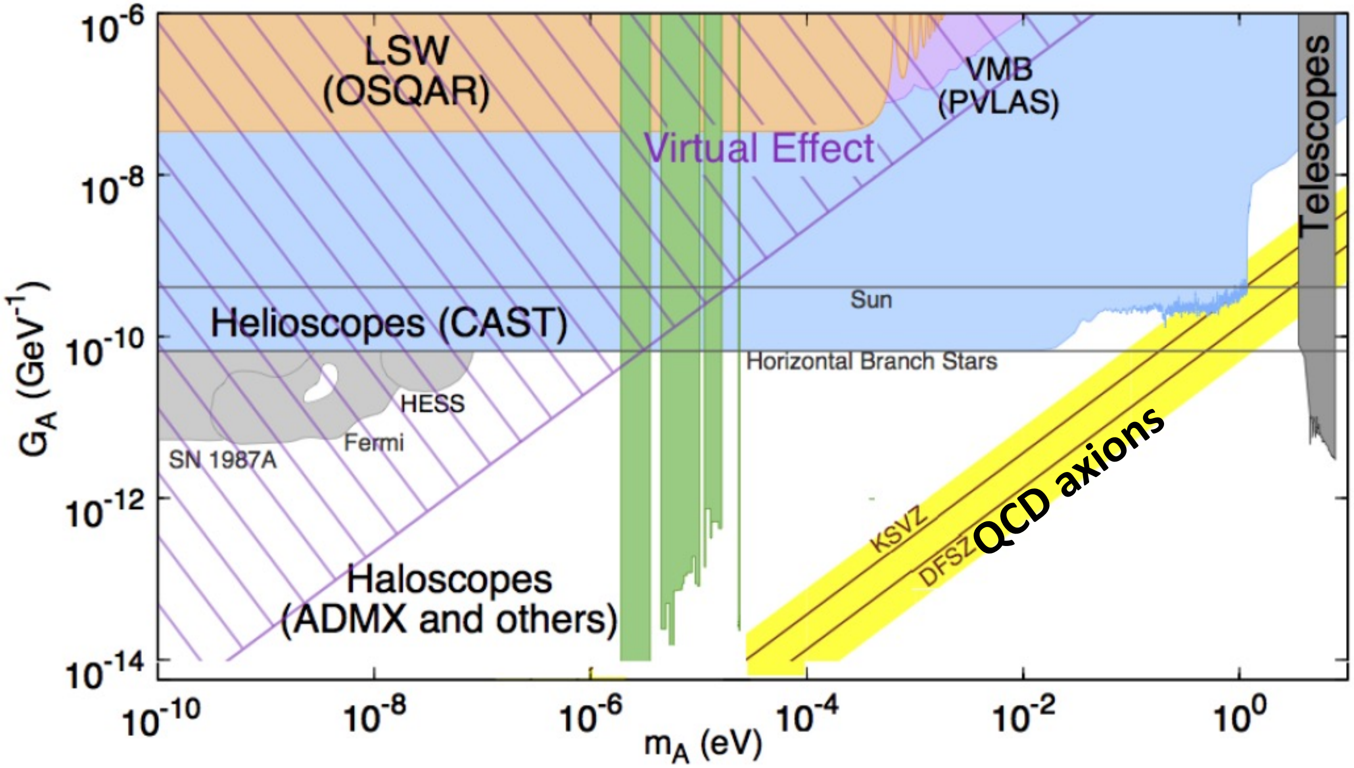
$$\boxed{\begin{aligned}-\frac{m_{\mathrm{A}}^2}{2}\varphi^2 + G_{\mathrm{A}}\varphi P &= -\frac{m_{\mathrm{A}}^2}{2}\left(\varphi - G_{\mathrm{A}}\frac{P}{m_{\mathrm{A}}^2}\right)^2 + \frac{G_{\mathrm{A}}^2}{2m_{\mathrm{A}}^2}P^2\\ &= -\frac{m_{\mathrm{A}}^2}{2}\tilde{\varphi}^2 + \frac{G_{\mathrm{A}}^2}{2m_{\mathrm{A}}^2}P^2\,,\end{aligned}}$$

$$P^2 \rightarrow P^2\left(1 + \frac{45m_e^4}{28\alpha^2}\frac{G_{\mathrm{A}}^2}{m_{\mathrm{A}}^2}\right)$$

Evans and Rafelski, Phys. Lett. B. 791 (2019) 331-334

Role of axions in light-light scattering

Considering the case where external fields are quasi-constant over **both** the axion and electron Compton wavelengths, we compare virtual axion action to the EHS. We see where the axion (labelled "Virtual Effect") and QED effect are dominant.



Adapted Fig. 111.1 in: Ringwald, Rosenberg and Rybka, Ch 111 in: Tanabashi et al. [Particle Data Group], PRD 98 (2018) 030001

Evans and Rafelski, Phys. Lett. B. 791 (2019) 331-334

Axion modification of EHS coefficient:

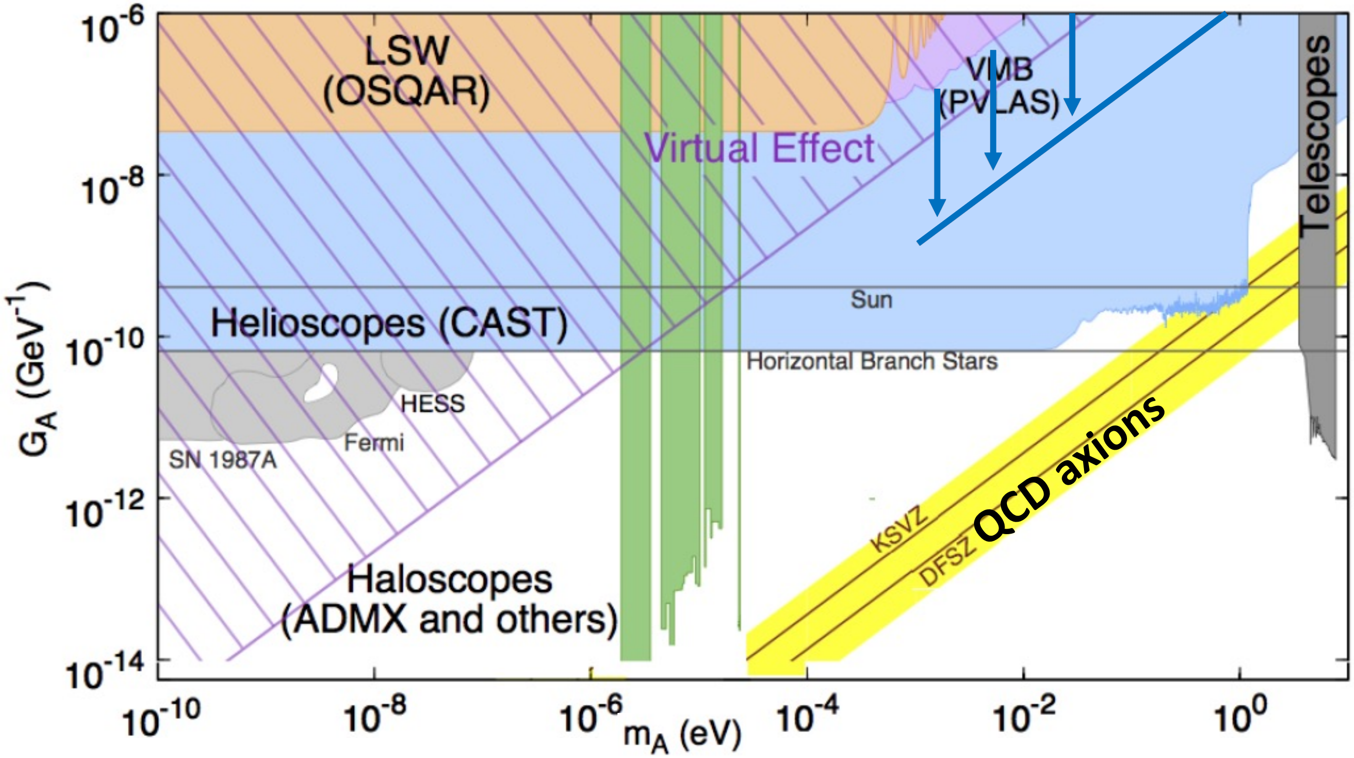
$$P^2\left(1+\underbrace{\frac{45m_e^4}{28\alpha^2}\frac{G_A^2}{m_A^2}}\right)$$

When >1, axion effect surpasses QED response

Role of axions in light-light scattering

Quasi-constant fields are only appropriate for PVLAS:

For order keV energy XFEL beams, we must consider spatial variation and time dependence of the fields on the axion Compton wavelength scale. Here **only** the QED effects operate under the quasi-constant approximation:



Nonlocal contributions to the effective action enhance the axion signal.

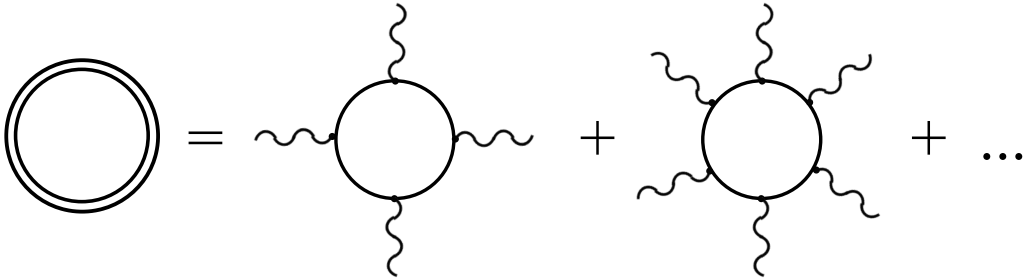
Adapted Fig. 111.1 in: Ringwald, Rosenberg and Rybka, Ch 111 in: Tanabashi et al. [Particle Data Group], PRD 98 (2018) 030001

Evans and Schützhold, In preparation.

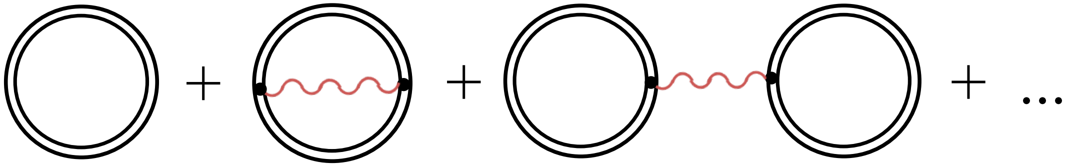
Extreme fields: higher order QED effects

Magnetized neutron stars suggested to contain EM fields on order 10^2-10^4 times the EHS critical field, and even greater in heavy ion collisions. Vacuum is **nonperturbative in external photons and (perturbative?) in virtual photons:**

EHS:



Higher order:

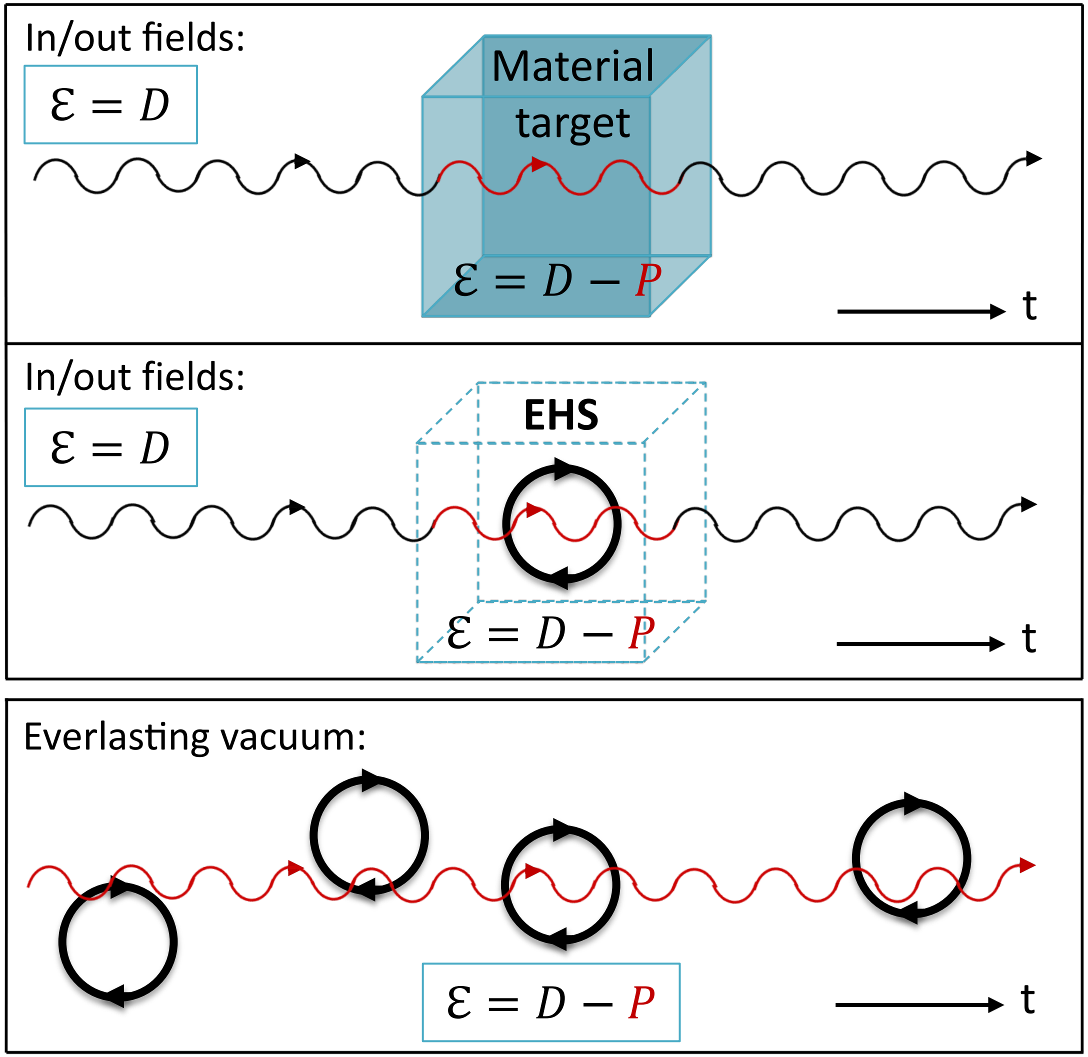


QED is a nonlinear theory: are external fields described correctly?

- Switch on/off QED: asymptotic fields are defined by a structure-less linear EM vacuum and "scatter" off of the structured vacuum.
- In a structured vacuum, the EM fields are affected by the nonlinear EM response at all times.
- Weisskopf's suggestion (1936), introduced quantitatively by Gies and Karbstein (2016), is to include polarization corrections to asymptotic fields

Nonperturbative approach to higher order QED loops

Defining in/out fields:



Material scattering problem: in a finite spacetime domain, polarization fields $P, \mathcal{M}$ distinguish screened fields $\mathcal{E}, \mathcal{B}$ from source fields $D, \mathcal{H}$.

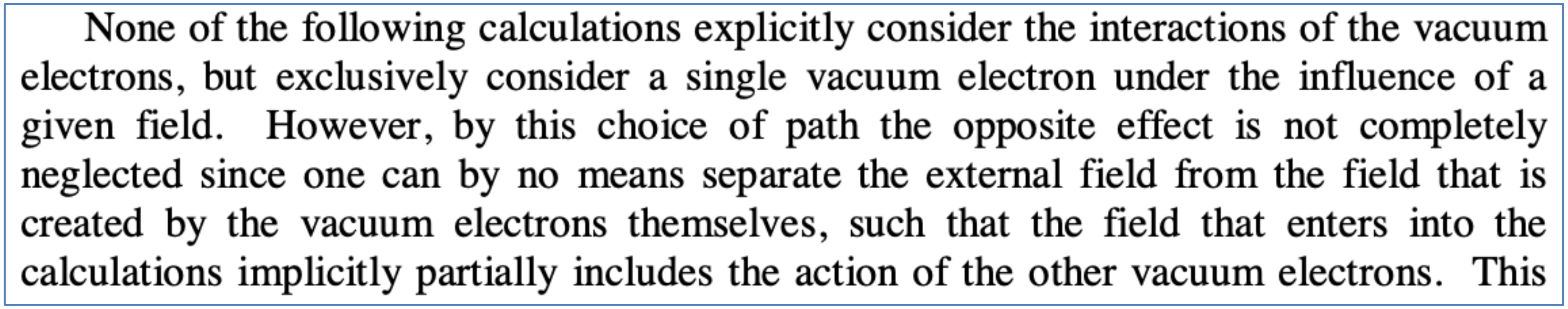
EHS action in the image of a scattering problem: the vacuum structure only occupies a finite spacetime domain.

Everlasting (**fortwährend**) vacuum: polarization effects exist at all times.

Weisskopf Suggestion

Why does an everlasting vacuum matter?

It requires us to include screening effects in the in/out fields used to derive the QED effective action. Weisskopf's insight from **1936**:



None of the following calculations explicitly consider the interactions of the vacuum electrons, but exclusively consider a single vacuum electron under the influence of a given field. However, by this choice of path the opposite effect is not completely neglected since one can by no means separate the external field from the field that is created by the vacuum electrons themselves, such that the field that enters into the calculations implicitly partially includes the action of the other vacuum electrons. This

At first, EHS action includes implicitly the action of other electrons in its derivation, but when we add Maxwell action using $\mathcal{E}$, $\mathcal{B}$, we lose the everlasting vacuum effects:

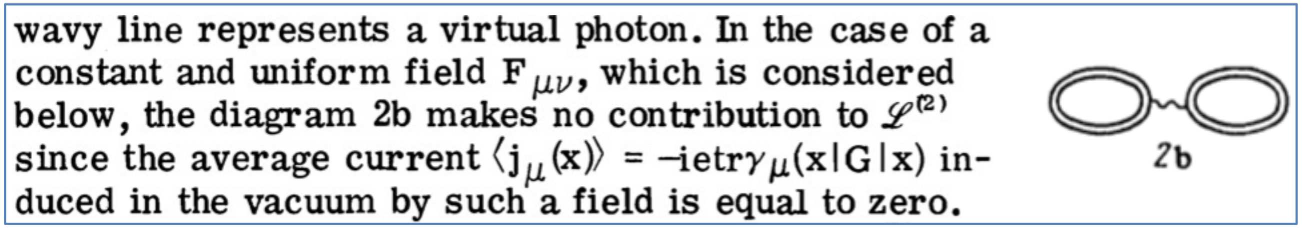
$$\mathcal{L}_{\rm EM}(\mathcal{E},\mathcal{B}) = \frac{\mathcal{E}^2+\mathcal{B}^2}{2} + \mathcal{L}^{1/2}_{\rm EHS}(\mathcal{E},\mathcal{B})$$

Weisskopf, Kong. Dan. Vid. Sel. Mat. Fys. Med. 14, N6, 1 (1936).

Recent work by Gies and Karbstein

Weisskopf’s 1936 suggestion was left unnoticed for 80 years:

In contradiction with Weisskopf’s insight, in 1975 Ritus claimed that higher order reducible diagrams vanish in the constant field limit: as photon momentum $k \to 0$, the action vanishes with (squared) current $\propto k^2$:



wavy line represents a virtual photon. In the case of a constant and uniform field $F_{\mu\nu}$, which is considered below, the diagram 2b makes no contribution to $\mathscr{L}^{(2)}$ since the average current $\langle j_\mu(x)\rangle = -ie\,\mathrm{tr}\,\gamma_\mu(x|G|x)$ induced in the vacuum by such a field is equal to zero.

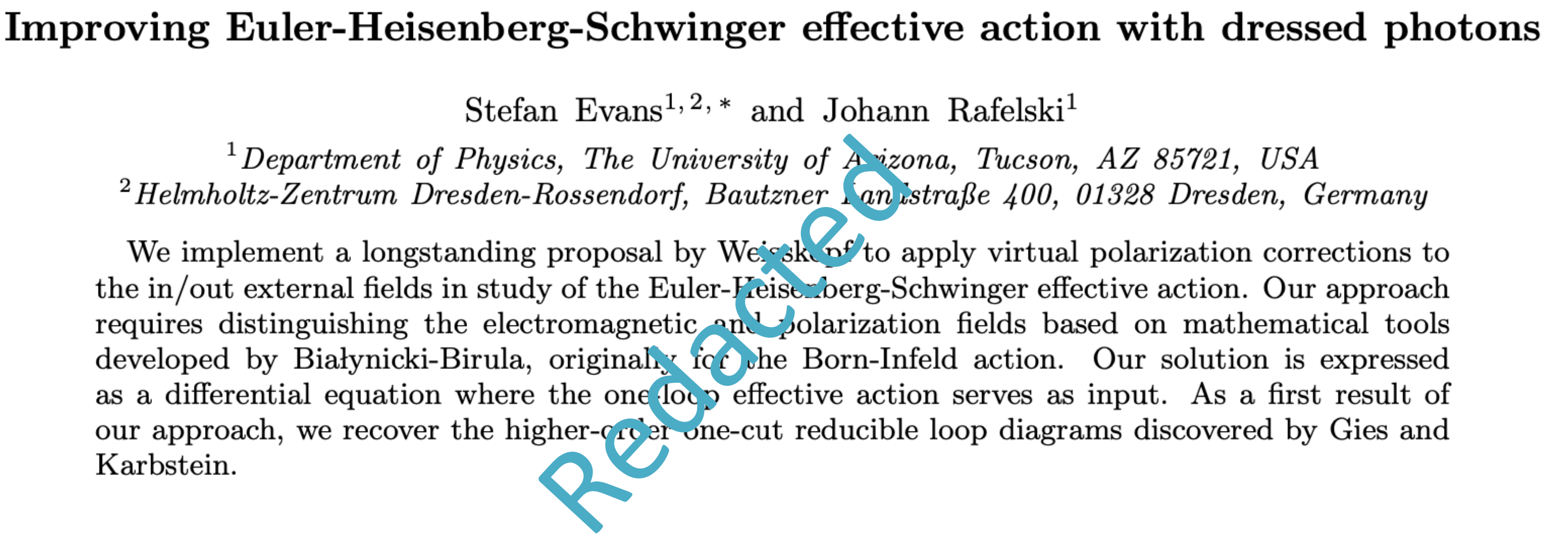
V. I. Ritus, The Lagrange Function of an Intensive Electromagnetic Field and Quantum Electrodynamics at Small Distances. Sov. Phys. JETP 42, 774 (1975)

Gies and Karbstein in 2017 discovered that the pole of the virtual photon propagator connecting the two loops ($\propto 1/k^2$) perfectly cancels the vanishing current in the quasi-constant EM field limit: the first proof of nonvanishing reducible diagram corrections to EHS effective action.

H. Gies and F. Karbstein, An Addendum to the Heisenberg-Euler effective action beyond one loop, JHEP 1703, 108 (2017)

N. Ahmadiniaz, F. Bastianelli, O. Corradini, J. P. Edwards and C. Schubert, One-particle reducible contribution to the one-loop spinor propagator in a constant field, Nucl. Phys. B 924 377-386 (2017)

Nonperturbative approach to higher order QED loops



Improving Euler-Heisenberg-Schwinger effective action with dressed photons

Stefan Evans[1,2,*] and Johann Rafelski[1]

[1] *Department of Physics, The University of Arizona, Tucson, AZ 85721, USA*
[2] *Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany*

We implement a longstanding proposal by Weisskopf to apply virtual polarization corrections to the in/out external fields in study of the Euler-Heisenberg-Schwinger effective action. Our approach requires distinguishing the electromagnetic and polarization fields based on mathematical tools developed by Białynicki-Birula, originally for the Born-Infeld action. Our solution is expressed as a differential equation where the one-loop effective action serves as input. As a first result of our approach, we recover the higher-order one-cut reducible loop diagrams discovered by Gies and Karbstein.

Applying an iterative expansion of our nonperturbative in one-cut reducible loop diagram summation, we obtain the perturbative loop corrections to the EHS action. Our first attempt (presented at the Balaton Workshop, 2019) was different from Gies and Karbstein's result (factor -1/2 difference between our perturbative two-loop actions).

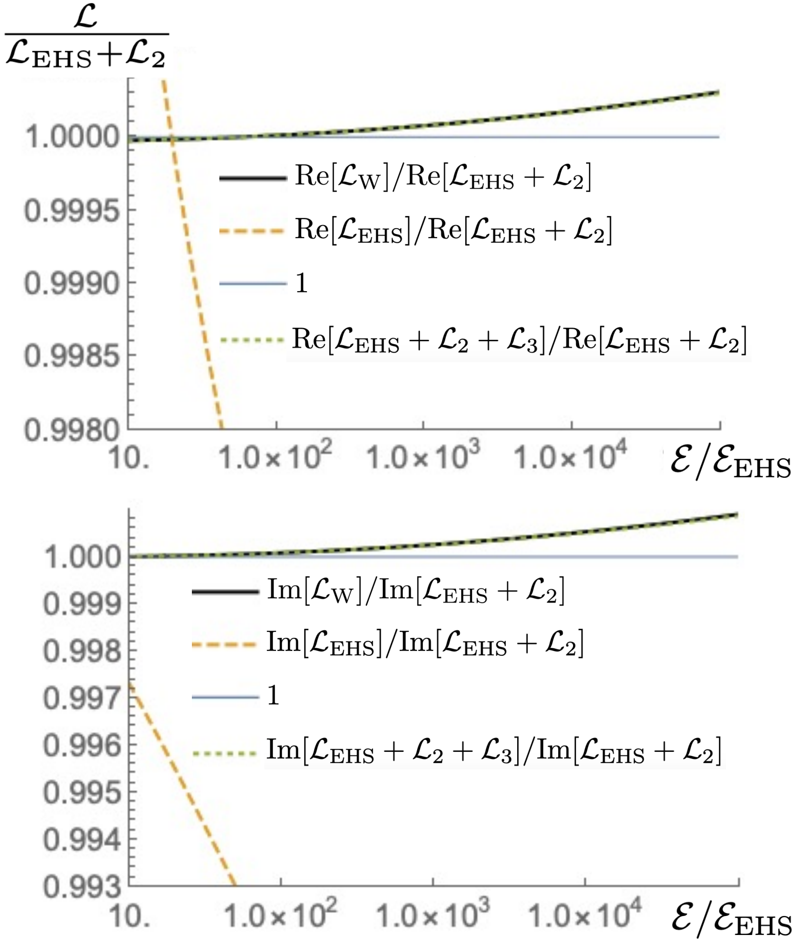
We are grateful for discussion with Gies (2019) to resolve the 1/2-factor difference.

Gies, Karbstein, 2019, Private communication

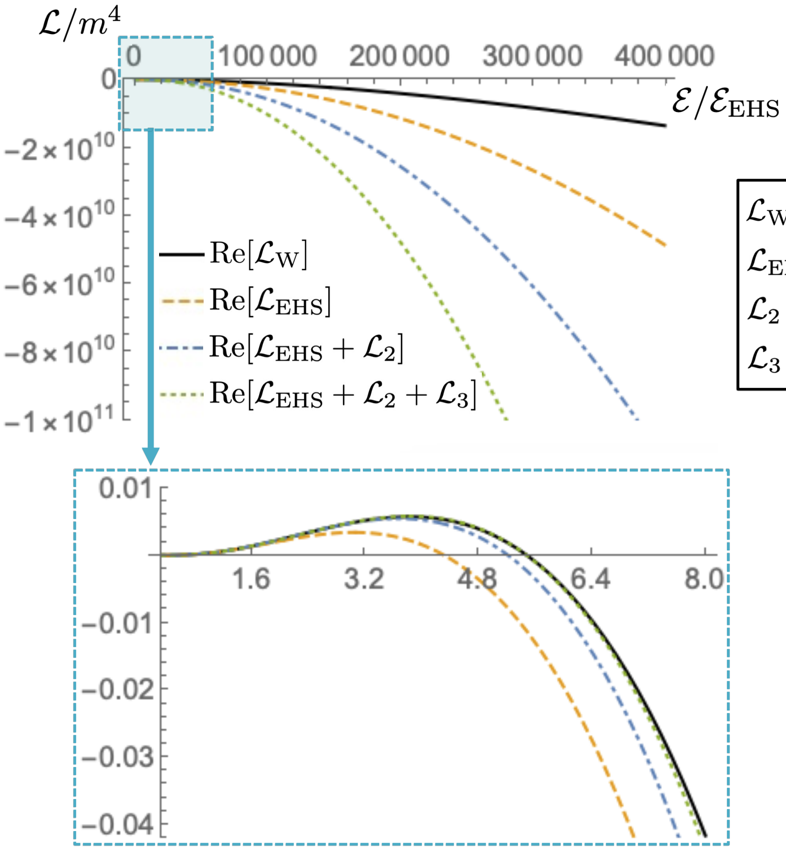
Later (2022), we resolved the remaining minus sign discrepancy.

Opportunities for studying QED with large coupling and QCD

Agreement with Gies and Karbstein's perturbative result for $\alpha = 1/137$:

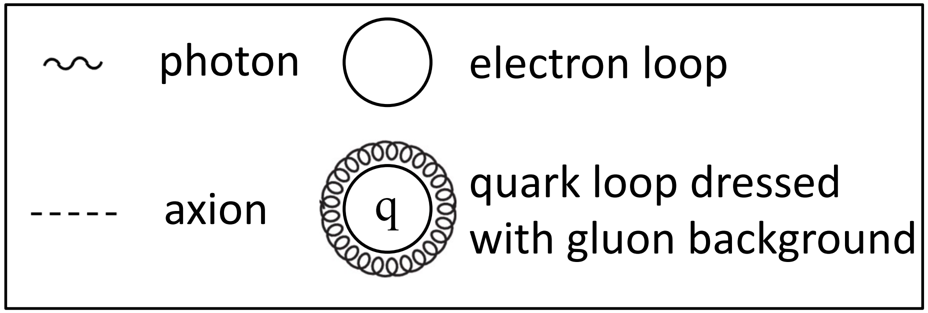


A convergent action for strong coupling $\alpha = 1/2$



$\mathcal{L}_{\rm W}$ = infinite-loop
$\mathcal{L}_{\rm EHS}$ = one-loop
$\mathcal{L}_2$ = two-loop
$\mathcal{L}_3$ = three-loop

On the horizon: path toward QED+QCD



Study of QED + virtual axions in highly magntized neutron stars

QED and Yang-Mills effective action mix: quark loops coupling to chromo-EM + EM fields

Savvidy, Phys. Lett. B 71 (1977), 133-134

Ozaki, Arai, Hattori and Itakura, Phys. Rev. D 92 (2015) no.1, 016002

Application toward study of fractals:

Deppman, Margaret Island Symposium (2023)