FOR 2783
Proj. T1/T2

Optical Signatures of Quantum Vacuum Nonlinearities in the Strong Field Regime (Poster No. 10)

Leonhard Klar, Felix Karbstein, Holger Gies

Theoretisch-Physikalisches-Institut, Friedrich-Schiller-Universität Jena
Helmholtz Institute Jena

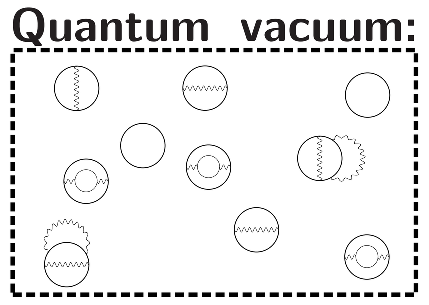
FRIEDRICH-SCHILLER-UNIVERSITÄT JENA
HELMHOLTZ Helmholtz-Institut Jena

Motivation: What is vacuum?

Classical vacuum:

- No matter
- No radiation
- No temperature
- No gravity

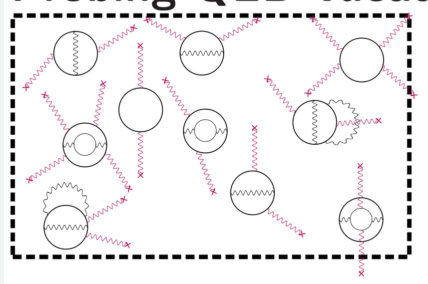
Quantum vacuum:



- Virtual pair fluctuations
- QFT: loop diagrams without external lines

- Quantum electrodynamics: fluctuations of positron and electron "fill" the vaccum
- W. Heisenberg and H. Euler predicted nonlinear behavior of light *(Heisenberg, Euler, Zeits. Phys.* **98** *(1936))*

Probing QED vacuum:



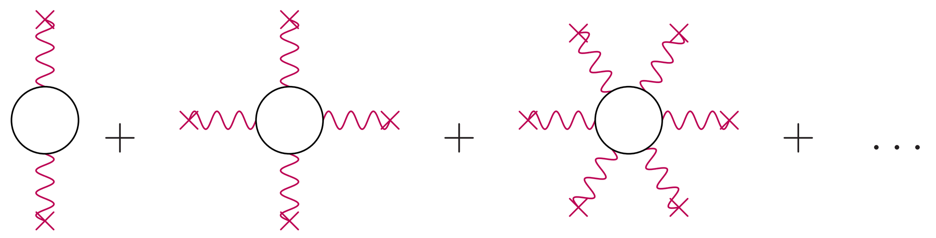
- Basic idea: polarization of virtual particles mediate nonlinear interaction of strong electromagnetic fields
- Analogous effect known from nonlinear media in solid state physics

- Nowadays: laser facilities *(ELI, XFEL, JETI, ATLAS)* provide necessary intensities
- Challenge: measure small signal beyond background of driving fields

Heisenberg-Euler Lagrangian

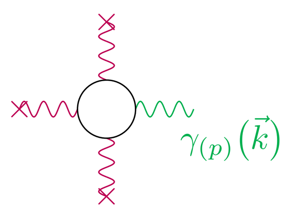
- Heisenberg-Euler Lagrangian describes dynamics
- Effektive Lagrangian: focus on "weak" fields $|F^{\mu\nu}| \ll \mathcal{E}_{\mathrm{crit}} = \frac{m^2}{e} \approx 1.3 \times 10^{18}\frac{\mathrm{V}}{\mathrm{m}}$ and higher-loops are suppressed by powers of $\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}$
- Use (pseudo) scalars $\mathcal{F} \equiv \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$ and $\mathcal{G} \equiv \frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}$, where $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$

$$\mathcal{L}_{\mathrm{eff}}^{\text{1-loop}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{2}{45}\frac{\alpha^2}{m^4}\left(4\mathcal{F}^2 + 7\,\mathcal{G}^2\right) + m^4\,\mathcal{O}\left(\left(\frac{\alpha F^2}{m^4}\right)^3\right)$$



- Contribution of interest: $\mathcal{L}_{\mathrm{int}} = \frac{2}{45}\frac{\alpha^2}{m^4}\left(4\mathcal{F}^2 + 7\,\mathcal{G}^2\right)$; the four leg diagram

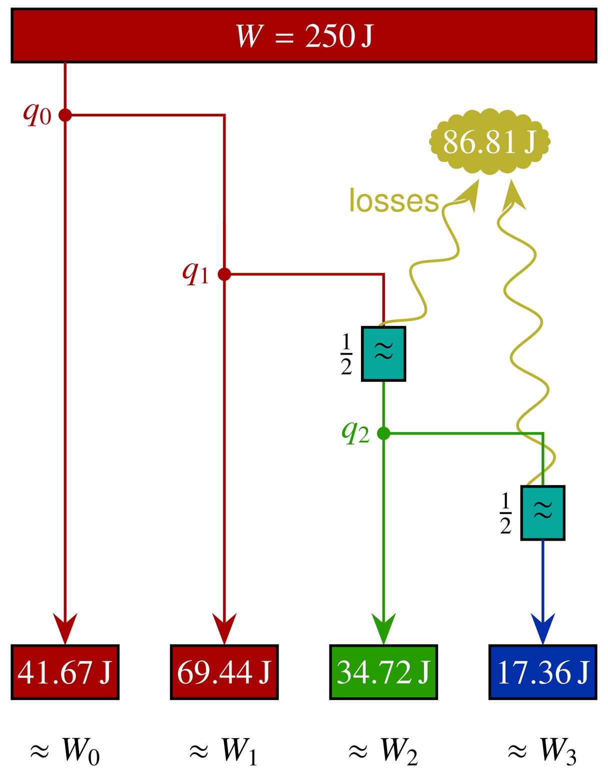
Vacuum Emission Picture



- Count signal photons $\gamma_{(p)}(\vec{k})$ with polarization p and wave vector $\vec{k}$ encoding the optical signatures of QED vacuum nonlinearities
- Feynman diagramm: three background legs and one signal leg

- Signal photon amplitude $S_{(p)}(\vec{k}) = \langle\gamma_{(p)}(\vec{k})|\int \mathrm{d}^4x\mathcal{L}_{\mathrm{int}}|0\rangle$
- Differential number of signal photons $\mathrm{d}^3N_{(p)}(\vec{k}) = \mathrm{d}k\,\mathrm{d}\cos\vartheta\,\mathrm{d}\varphi\frac{k^2}{(2\pi)^3}\left|S_{(p)}(\vec{k})\right|^2$
- Signal photon density $\rho_{(p)}^{k_i,k_f}(\vartheta,\varphi) = \frac{1}{(2\pi)^3}\int_{k_i}^{k_f}\mathrm{d}k\left|kS_{(p)}(\vec{k})\right|^2$
- Result allows deep analysis of signal properties *(Karbstein, Shaisultanov, Phys. Rev. D* **92** *(2015))*

Example Scenario

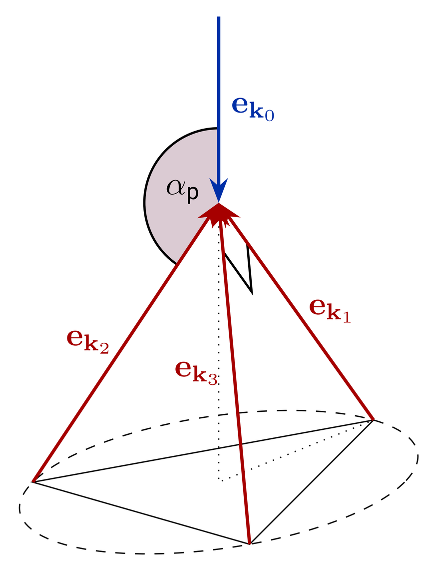


- Four laser pulses originating from a single high-intensity laser pulse
- Assume 10 petawatt class [ELI-NP]: $W = 250$ J, $\omega_0 = 1.55\,\mathrm{eV}$, $\tau = 25\,\mathrm{fs}$
- Split beam and use second harmonic generation techniques (loss $\sim 50\%$) for generation four different pulses
- First: choose arbitrary pulse energies distributions here $W_0 = \frac{1}{6}W$ and $W_1 : W_2 : W_3 = 4 : 2 : 1$
- (semi) analytical approach allows estimating results for rearranged distributions

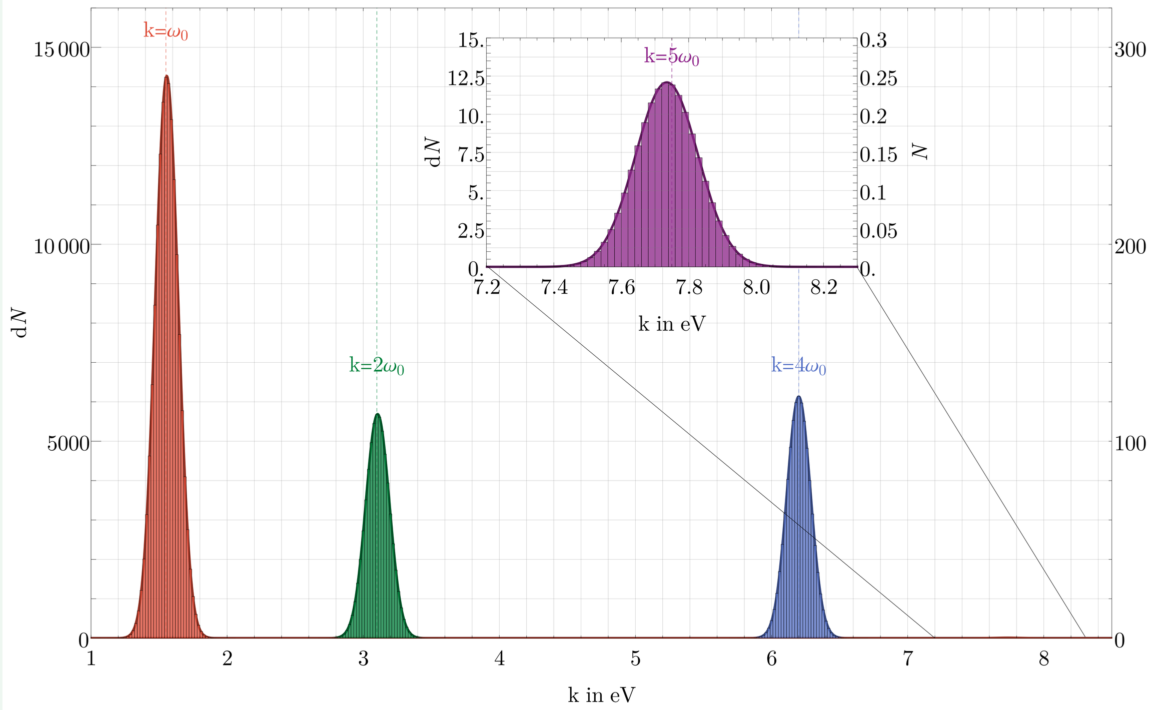
- Focus all laser pulses on the same spot with focus size $w_0 = 800\,\mathrm{nm}$
- Collide beams 1 to 3 with $\theta = 90°$
- Collision angle between beam 0 and each other: $\alpha_{\mathrm{P}} \approx 125.26°$
- Effective 4 beam collision with probe pulse $\vec{\mathcal{E}}_0$ and three pump pulses $\vec{\mathcal{E}}_1$, $\vec{\mathcal{E}}_2$, $\vec{\mathcal{E}}_3$
- Gaussian pulse profiles with infinite Rayleigh range:

$$\mathcal{E}_i(x) = \sqrt{\frac{W_i}{W}}\mathcal{E}_\star\,\mathrm{e}^{-\frac{(\tilde{\mathrm{k}}_\mathrm{i}\cdot\tilde{\mathrm{r}}-\omega\mathrm{t})^2}{\mathrm{k}_\mathrm{i}^2\tau^2}}\,\mathrm{e}^{-\frac{|\tilde{\mathrm{k}}_\mathrm{i}\times\tilde{\mathrm{r}}|^2}{\mathrm{k}_\mathrm{i}^2\mathrm{w}_0^2}}\cos\left(\tilde{\mathrm{k}}_\mathrm{i}\cdot\tilde{\mathrm{r}} - \omega\mathrm{t}\right)$$

- Limit is well-justified for considered collision angles



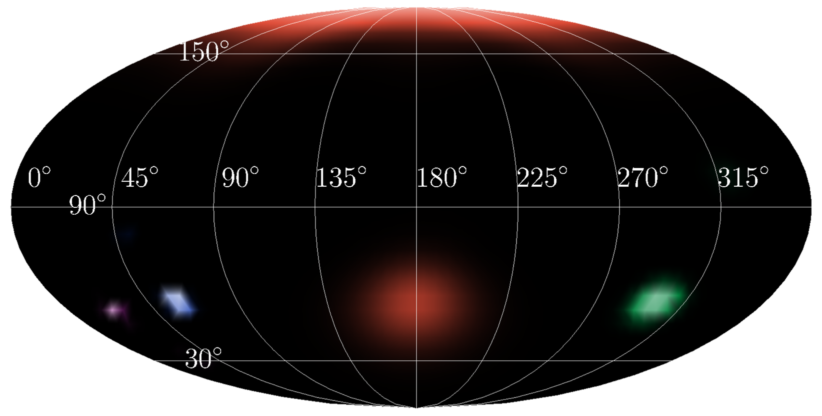
Result: Spectrum & Distributions

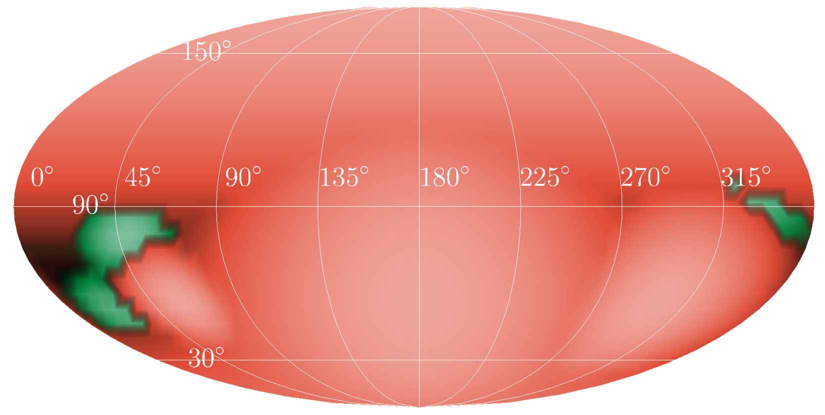


Estimate photon number per shot for the different frequency regions as visible in the spectrum:

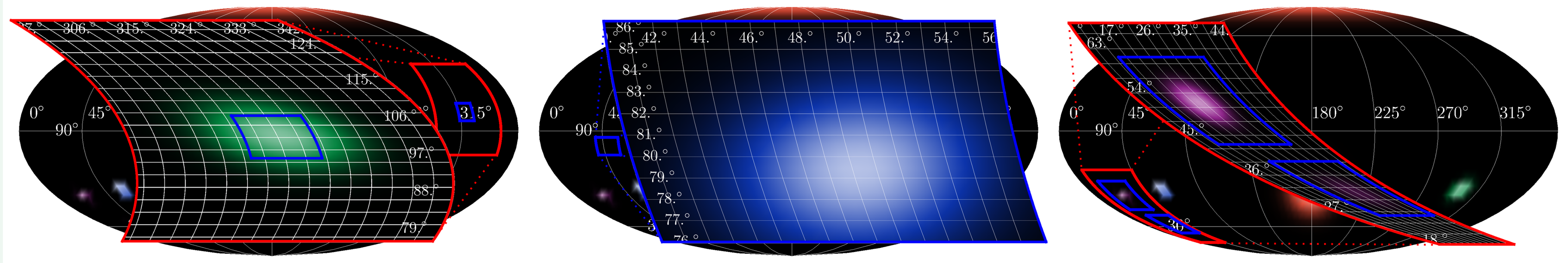
total N	signal	background
ω_0	3019	4.4×10^{20}
$2\,\omega_0$	1241	7×10^{19}
$4\,\omega_0$	1338	1.7×10^{19}
$5\,\omega_0$	2.81	0
total	5600	$\sim 10^{21}$

Signal photons, linear scale, ω separation Background (■), higher signal (■), log scale





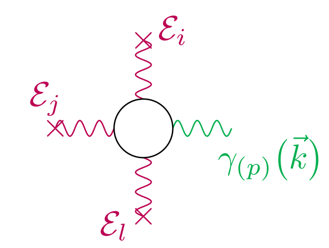
Result: Discernible Signal



k	$2\omega_0$	$4\omega_0$	$5\omega_0$, A	$5\omega_0$, B
φ^{Sig}	317.65°	49.43°	23.26°	31.32°
ϑ^{Sig}	101.77°	79.44°	50.85°	31.01°
N^{Sig}	62.02	129.40	2.31	0.46
N^{Backg}	10×10^{-3}	6×10^{-3}	0	0

- Signal emitted in regions beyond driving laser direction
- In blue framed regions: signal higher then background

Channel analysis



- Analysing the scattered signal by tracing back the origin: channel analysis *(Gies, et al., Phys. Rev. D* **103** *(2021))*
- Signal amplitude contains all triplets of the Gaussian beam profiles with $\vec{\mathcal{E}}_i(x) = \vec{e}_{\mathcal{E}_i}\mathcal{E}_i(x)$ and $\vec{B}_i(x) = \vec{e}_{B_i}\mathcal{E}_i(x)$: decomposing to $S_{(p)}(\vec{k}) = \sum_{i,j,l=0}^{3} S_{(p),ijl}(\vec{k})$, where

$$S_{(p),ijl}(\vec{k}) = \frac{1}{\mathrm{i}}\frac{e^2}{4\pi}\frac{m_e^2}{45}\sqrt{\frac{k^0}{2}}\left(\frac{e}{m_e^2}\right)^3\mathcal{I}_{ijl}(\vec{k})\,g_{(p);ijl}(\vec{k})$$

- Fourier integral $\mathcal{I}_{ijl}(\vec{k}) = \int \mathrm{d}^4x\,\mathrm{e}^{\mathrm{i}k_\mu x^\mu}\mathcal{E}_i(x)\,\mathcal{E}_j(x)\,\mathcal{E}_l(x)$
- Geometry factor $g_{(p),ijl}(\vec{k})$ depending on laser polarization $\vec{e}_{\mathcal{E}_i}$, $\vec{e}_{B_i}$ and polarization (p) of signal photons
- Subsets of combinations of (i,j,l) allow to analyze details of the signature of quantum vacuum nonlinearities depending on the field configurations
- Symmetry of $S_{(p),ijl}(\vec{k})$ leads to 12 *elastic* contributions $S_{(p),iji}$ with $i \neq j$ and 12 *inelastic* contributions $S_{(p),ijl}$ with $i \neq j \neq l \neq i$
- Neglecting pulse duration effects $\tau \to \infty$: $\Rightarrow k \to |\pm\omega_i \pm \omega_j \pm \omega_l|$
- Assume subleading focusing effects $\Rightarrow \vec{k} \to \vec{k}_{\mathrm{pw}} = \pm\omega_i\vec{e}_{k_i} \pm \omega_j\vec{e}_{k_j} \pm \omega_l\vec{e}_{k_l}$
- Here $\tau\omega_0 \simeq 59 \gg 1$: selection rule for contribution of channel: $|k - |\vec{k}_{\mathrm{pw}}|| < \Delta\omega$ with $\Delta\omega \simeq 0.513\omega_0$
- Sign represents microscopic absorption or emission

Example: channel $(ijl) = (013)$ with $(+-+)$

- $k = |\omega_0 - \omega_0 + 4\omega_0| = 4\omega_0$
- $\vec{k}_{\mathrm{pw}} = \omega_0\vec{e}_{k_0} - \omega_0\vec{e}_{k_1} + 4\omega_0\vec{e}_{k_3}$ with $|\vec{k}_{\mathrm{pw}}| \simeq 3.8\omega_0$
- Selection condition is fulfilled $\Rightarrow$ contribution to signal at spot $(49.4°, 79.4°)$
- Using only all permutations of (013) in $S_{(p)}(\vec{k})$ leads to $N_{(013)}^{\mathrm{Sig}} = 129$

Conclusion

- Signatures of quantum vacuum nonlinearities like photon-photon scattering are observable
- Channel analysis as useful theoretical tool to enhance the measurable result by adjusting beam splitting

E-mail: leonhard.klar@uni-jena.de