Gamma Factory Workshop
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FOR 2783
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FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

HI JENA
Helmholtz Institute Jena

Nonlinear QED effects:

Quantum Vacuum Nonlinearities @ Gamma Factory

Felix Karbstein
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Can the Gamma Factory be used to detect quantum vacuum nonlinearities, e.g., vacuum birefringence?

What are QED vacuum nonlinearities?

- classical ED is very successful in describing the physics of macroscopic e.m. fields

$$\mathcal{L}_{\mathrm{MW}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \qquad \text{(in vacuo)}$$

$$\Big\downarrow \ \mathrm{E.o.M.}$$

$$\partial_\mu F^{\mu\nu} = 0 \quad \rightarrow \quad \text{linear, superposition principle} \checkmark$$

$$\rightarrow \quad \text{there is no } \hbar$$

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- however, we believe in quantum (field) theory
  $\rightarrow$ "quantum vacuum"
  $\rightarrow$ classical theory should arise in formal limit of $\hbar \rightarrow 0$;
  quantum corrections are to be expected for $\hbar \neq 0$

- What is the "true" theory of ED accounting for quantum corrections?

What are QED vacuum nonlinearities? (2/2)

- "true" theory of ED of macroscopic fields

[Heisenberg, Euler: Z. Phys. **98** (1936)],
[Weisskopf: Mat. Fys. Medd. **14** (1936)],
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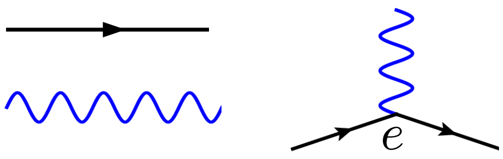
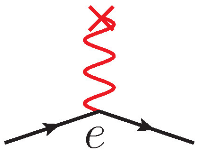
- QED:



+ macroscopic field



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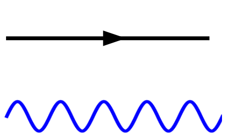
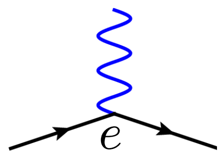
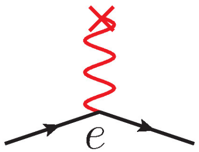
- QED:  

+ macroscopic field 

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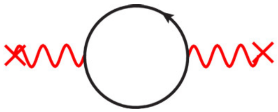
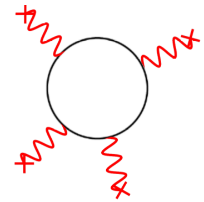
$\mathcal{L}_{\mathrm{HE}} = \mathcal{L}_{\mathrm{MW}} +$  $+$  $+ \cdots$

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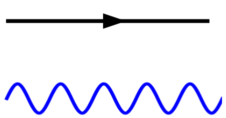

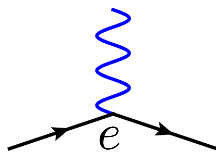

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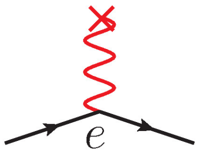
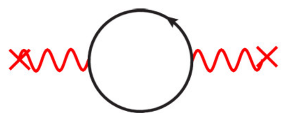


→ quantum corrections to classical Maxwell theory

$$\mathcal{L}_{\rm HE} = \mathcal{L}_{\rm MW} +$$



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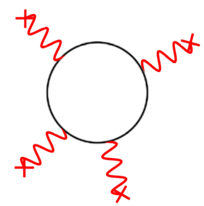

$$+ \cdots$$

$$\Big\downarrow \ \text{E.o.M.}$$

$$\partial_\mu \left(F^{\mu\nu} - \frac{\hbar e^4}{720\pi^2 (mc)^4 c} \left[4(F_{\alpha\beta}F^{\alpha\beta})\, F^{\mu\nu} + 7(F_{\alpha\beta}{}^{*}F^{\alpha\beta})\, {}^{*}F^{\mu\nu} \right] + \dots \right) = 0$$

→ nonlinear, ~~superposition principle~~

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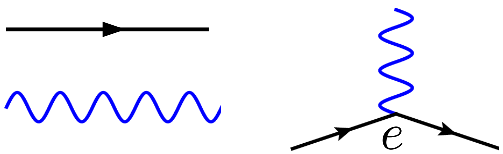
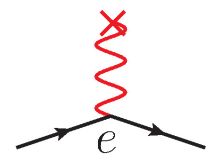
- QED:  + macroscopic field 

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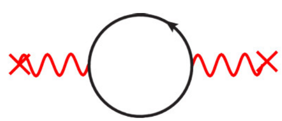
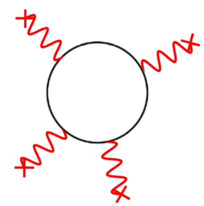
$\mathcal{L}_{\mathrm{HE}} = \mathcal{L}_{\mathrm{MW}} +$  $+$  $+ \cdots$

$\downarrow$ E.o.M.

$$\partial_\mu \left(F^{\mu\nu} - \frac{4\alpha}{45\pi}\frac{1}{2}\left(\frac{\vec{B}^2}{B_{\mathrm{cr}}^2} - \frac{\vec{E}^2}{E_{\mathrm{cr}}^2}\right) F^{\mu\nu} + \frac{7\alpha}{45\pi}\frac{\vec{E}\cdot\vec{B}}{E_{\mathrm{cr}}B_{\mathrm{cr}}}\, {}^*F^{\mu\nu} + \ldots \right) = 0$$

where $\alpha = \frac{e^2}{4\pi\hbar c\epsilon_0} \simeq \frac{1}{137}\,, \quad E_{\mathrm{cr}} = \frac{m^2c^3}{\hbar e} \simeq 1.3\times 10^{18}\,\frac{\mathrm{V}}{\mathrm{m}}\,, \quad B_{\mathrm{cr}} = \frac{E_{\mathrm{cr}}}{c} \simeq 4.4\times 10^{9}\,\mathrm{T}$

- decomposition of $F^{\mu\nu} \to \bar{F}^{\mu\nu} + f^{\mu\nu}$ and linearization of E.o.M. in probe light field

  pump probe

  $\to$ transverse eigenmodes with different speeds of light / refractive indices

  $\to$ vacuum birefringence

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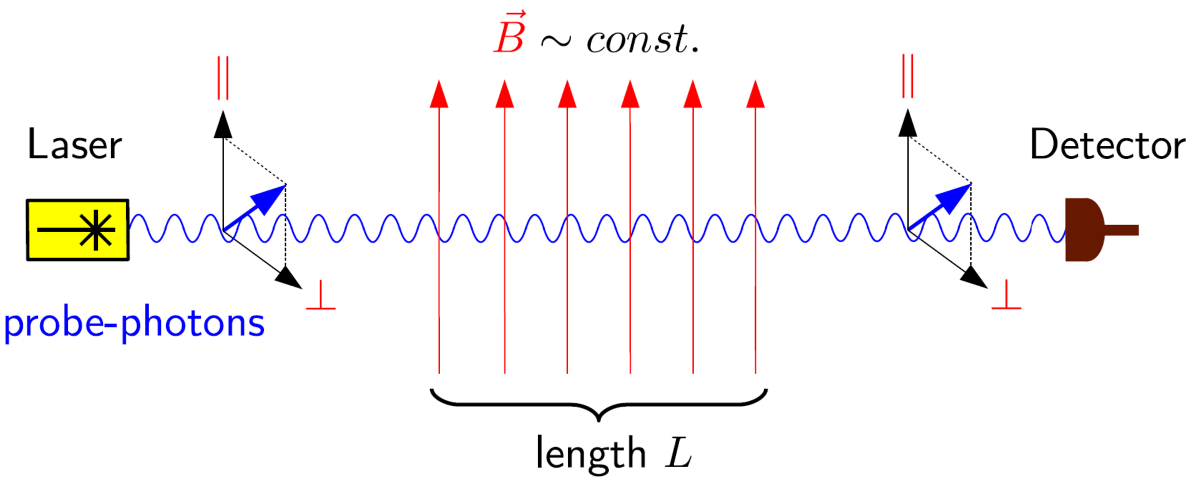

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$B = \mathcal{O}(1)\mathrm{T}$

$L_{\mathrm{LAB}} = \mathcal{O}(1)\mathrm{m}$

A promising signature: vacuum birefringence (1/2)

- decomposition of $F^{\mu\nu} \to \bar{F}^{\mu\nu} + f^{\mu\nu}$ and linearization of E.o.M. in probe light field

$$\underbrace{\bar{F}^{\mu\nu}}_{\text{pump}} + \underbrace{f^{\mu\nu}}_{\text{probe}}$$

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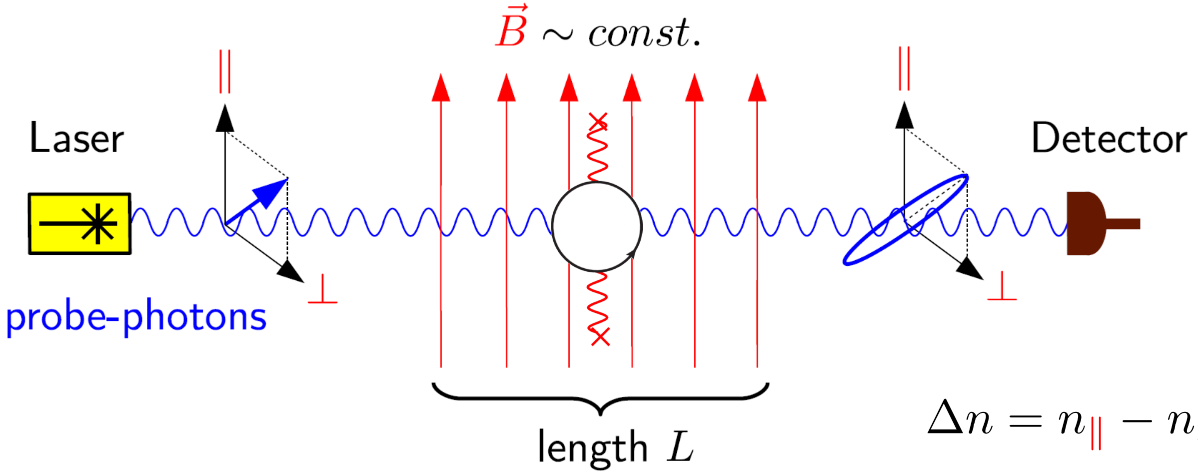

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$$B = \mathcal{O}(1)\mathrm{T}$$
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$$\Delta n = n_{\parallel} - n_{\perp} = \frac{1}{30}\frac{\alpha}{\pi}\left(\frac{B}{B_{\mathrm{cr}}}\right)^2$$

$\to$ ellipticity: $\Delta\phi = 2\pi\frac{L}{\lambda}\Delta n = \frac{\omega L}{\hbar c}\Delta n$

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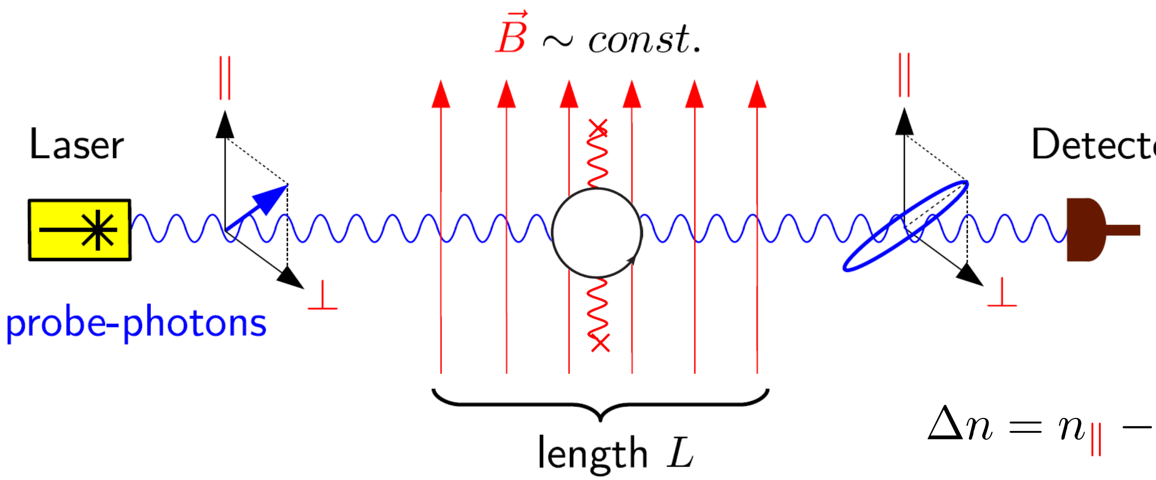

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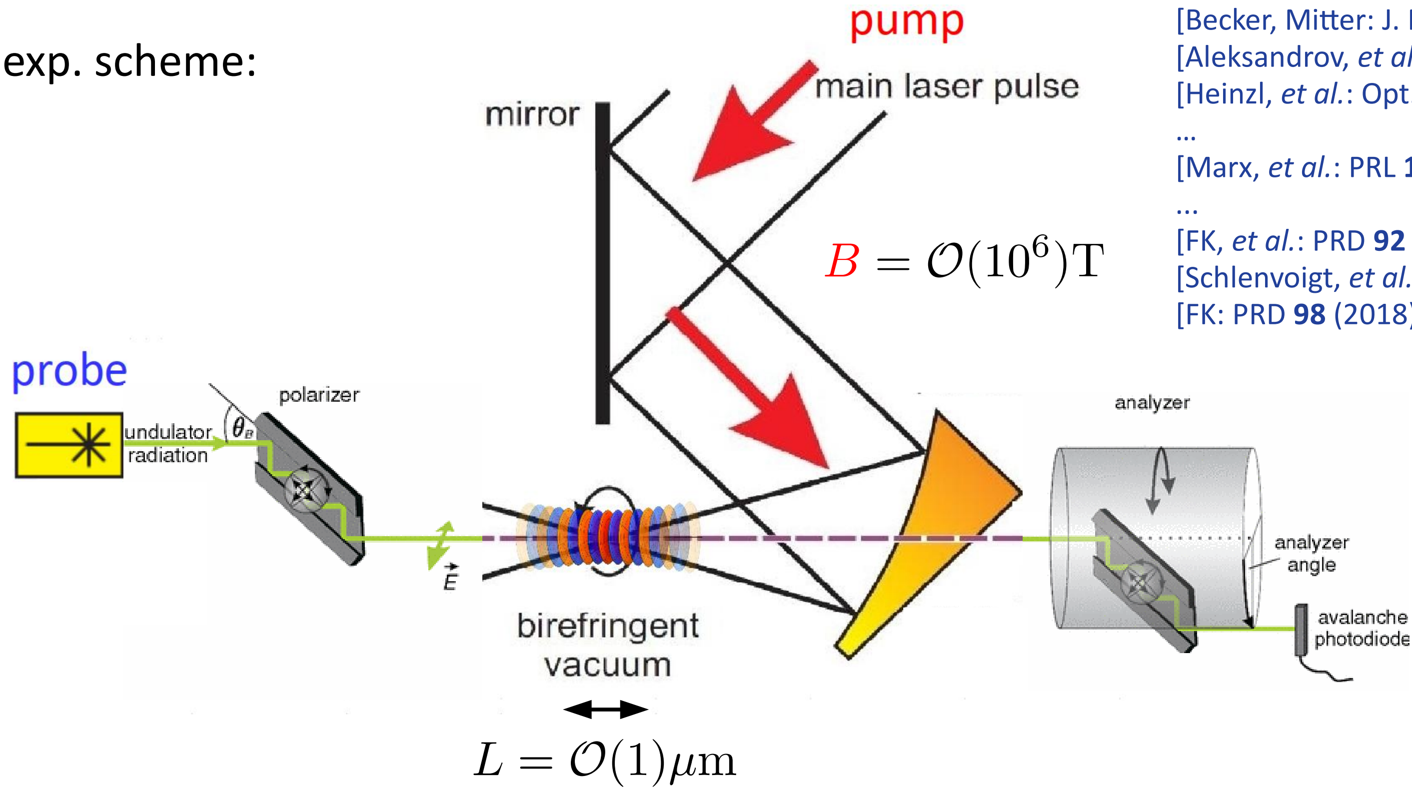
- planned experiments with pump = high-intensity laser at XFEL facilities [HiBEF, European XFEL]

- exp. scheme:



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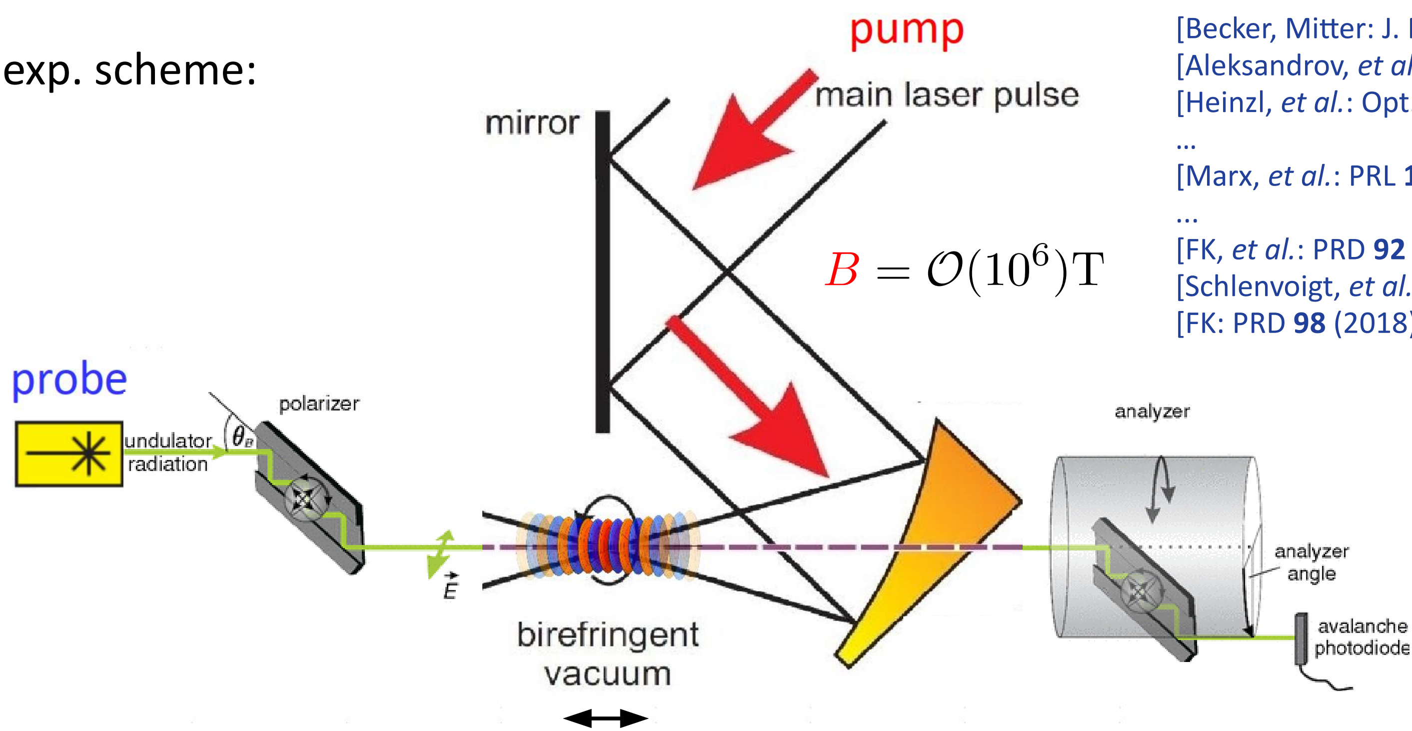

$B = \mathcal{O}(10^6)\mathrm{T}$

$L = \mathcal{O}(1)\mu\mathrm{m}$

$$\Delta\phi = \frac{\omega L}{\hbar c}\Delta n$$

$$\Delta\phi|_{\mathrm{HIBEF}} = \mathcal{O}(10^{-6}) \ @12914\,\mathrm{eV}$$

- Can something similar be done @ GF?

Vacuum birefringence @ Gamma Factory (1/5)

- typical starting point in studies of previously mentioned approaches: Heisenberg-Euler effective Lagrangian $\mathcal{L}_{\mathrm{HE}}(F^{\mu\nu})$ for small frequency fields

  $\rightarrow$ neglects derivative terms $\sim \partial_\alpha^n F^{\mu\nu}$ with $n \geq 1$, or powers of energies $\sim \omega^n F^{\mu\nu}$ in spectral domain, respectively

  $\rightarrow$ genuine reference scale is m, i.e., contributions $\sim (\frac{\omega}{mc^2})^n$ not accounted for

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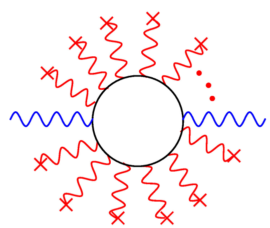
$\Pi^{\mu\nu}(\omega|F^{\mu\nu}) =$  known in: ① const. fields [Batalin, Shabad: JETP **60** (1971)]

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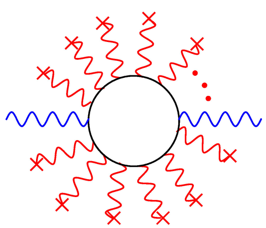
$\Pi^{\mu\nu}(\omega|F^{\mu\nu}) =$ 

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- ① $\rightarrow$ reliable study of the effect for $\vec{B} = const.$ envisioning the use of spare LHC magnet(s): $L \simeq 15\,\mathrm{m}$, $B \simeq 8.4\,\mathrm{T}$

Vacuum birefringence @ Gamma Factory (2/5)

- find the same formulas for $n_{\|,\perp}$ as from $\mathcal{L}_{\rm HE}$

$$\left\{\begin{matrix} n_{\|} \\ n_{\perp} \end{matrix}\right\} \simeq 1 + \frac{1}{90}\frac{\alpha}{\pi}\left(\frac{B}{B_{\rm cr}}\right)^2 \left\{\begin{matrix} 7 \\ 4 \end{matrix}\right\}, \qquad B_{\rm cr} \simeq 4.4 \cdot 10^9\ \mathrm{T}$$

given that $k^2 \simeq 0\,,\quad \frac{B}{B_{\rm cr}} \ll 1 \quad \text{and} \quad \left(\frac{B}{B_{\rm cr}}\right)^2 \left(\frac{\omega}{mc^2}\right)^2 \ll 1$ [FK: PRD **88** (2013)]

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$8.4\,{\rm T}\,,\ 400\,{\rm MeV}\qquad L \simeq 15\,{\rm m}$

$\rightarrow$ ellipticity: $\Delta\phi = \dfrac{\omega L}{\hbar c}(n_\| - n_\perp) \simeq \boxed{8.4\times 10^{-6}}$

(- there are also imaginary parts $\leftrightarrow$ polarization sensitive absorption coefficients due to the principle possibility of pair production, <u>but</u> exp. suppressed with $\frac{mc^2}{\omega}\frac{B_{\rm cr}}{B} \gg 1$)

[Baier, Katkov: PRD **75** (2007)]

- Alternatively ② $\rightarrow$ collision of γ beam with high-intensity laser field (= plane wave)

  "naive" estimate

- there are studies of vacuum birefringence with high-energy/γ probes

[Kotkin, Serbo: Phys. Lett. B **413** (1997)],
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2-steps: (a) Compton scatt. $e^- + \text{laser light} \rightarrow \gamma$

(b) vacuum birefringence

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  2-steps: (a) Compton scatt. $e^- + \text{laser light} \rightarrow \gamma$
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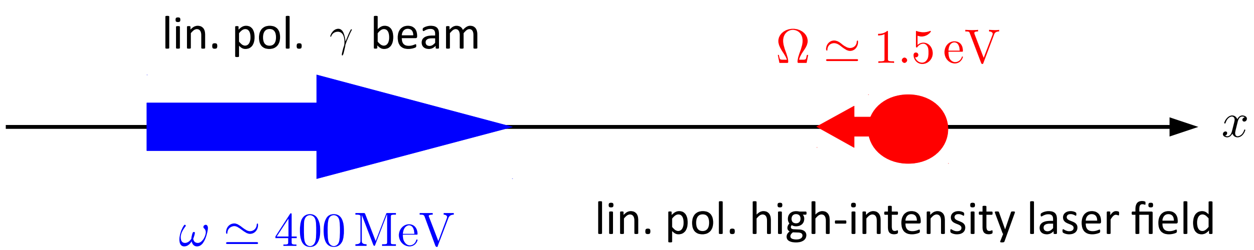
- here, the wave-vectors of the γ probe and high-intensity laser pump are

$$k^\mu \simeq \omega(1, \vec{e}_x) \quad \text{and} \quad \kappa^\mu \simeq \Omega(1, -\vec{e}_x)$$



Vacuum birefringence @ Gamma Factory (4/5)

- in the relevant limit we find again the same formulas for $n_{\|,\perp}$ as from $\mathcal{L}_{\mathrm{HE}}$

$$\left\{ \begin{array}{c} n_{\|} \\ n_{\perp} \end{array} \right\} \simeq 1 + \frac{1}{90}\frac{\alpha}{\pi}\frac{I}{I_{\mathrm{cr}}} \left\{ \begin{array}{c} 7 \\ 4 \end{array} \right\}, \qquad I_{\mathrm{cr}} = \epsilon_0 c \left(\frac{m^2 c^3}{e\hbar}\right)^2 \simeq 10^{29}\,\frac{\mathrm{W}}{\mathrm{cm}^2}$$

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$$\underset{0.005}{\uparrow} \quad 1.5\,{\rm eV}\,,\ 400\,{\rm MeV} \qquad \to \Big(\frac{\omega}{mc^2}\Big)^2 \simeq 6\times 10^5$$

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- $\frac{I}{I_{\mathrm{cr}}} \simeq \frac{P}{I_{\mathrm{cr}}w_0^2} \xrightarrow{w_0=1\mu\mathrm{m}} \frac{P}{10^6\,\mathrm{PW}} \qquad \to \; \frac{I}{I_{\mathrm{cr}}}\left(\frac{\omega}{mc^2}\right)^2 \simeq \frac{0.6\,P}{1\,\mathrm{PW}}$

$\to$ (principle) potential to go “beyond Heisenberg and Euler”

Vacuum birefringence @ Gamma Factory (5/5)

- $$P = 1\,\mathrm{PW}: \quad \Delta\phi = \frac{\omega L}{\hbar c}(n_{\parallel} - n_{\perp}) \simeq \Delta\phi\big|_{B=const.} \times \frac{10^{-6}}{15} \times \frac{10^{-6}}{(1.9\times 10^{-9})^2}$$
  $$\simeq \Delta\phi\big|_{B=const.} \times \mathcal{O}(10^5)$$

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- ⊖ but idealized assumptions: “perfect shots”, i.e., optimal synchronization, etc.
  high-intensity laser pulses have pulse durations of $\mathcal{O}(\mathrm{fs})$ rep. rate of $\mathcal{O}(\mathrm{Hz})$
  $\leftrightarrow$ magnetic field scenario where “every γ photon hits”

Vacuum birefringence @ Gamma Factory (5/5)

- $$P = 1\,\mathrm{PW}: \quad \Delta\phi = \frac{\omega L}{\hbar c}(n_{\parallel} - n_{\perp}) \simeq \Delta\phi\big|_{B=const.} \times \frac{10^{-6}}{15} \times \frac{10^{-6}}{(1.9\times10^{-9})^2}$$
$$\simeq \Delta\phi\big|_{B=const.} \times \mathcal{O}(10^5)$$

- ⊖ but idealized assumptions: “perfect shots”, i.e., optimal synchronization, etc.
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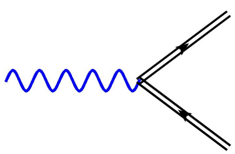
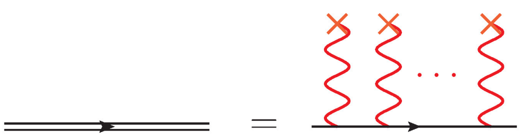
- ⊕ various other non-linear QED effects could potentially be investigated, if

$$\frac{I}{I_{\mathrm{cr}}}\left(\frac{\omega}{mc^2}\right)^2 \simeq \frac{0.6\,P}{1\,\mathrm{PW}} \rightarrow \mathcal{O}(1)$$, e.g., γ-photon induced pair production

in a strong laser field  with 

Conclusions and Outlook

- In this talk I have (briefly) discussed the possibility of studying (QED) vacuum nonlinearities in macroscopic electromagnetic fields at the Gamma Factory.

- The focus was on vacuum birefringence $\rightarrow$ ① LHC magnet
  ② high-intensity laser

- The Gamma Factory may complement and become a competitor to established and planned (high-intensity laser) experiments.

- Bounds on BSM signatures, e.g., minicharged particles that might so far have successfully evaded their detection.

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Thank you very much for your attention!