All optical signatures from the quantum vacuum

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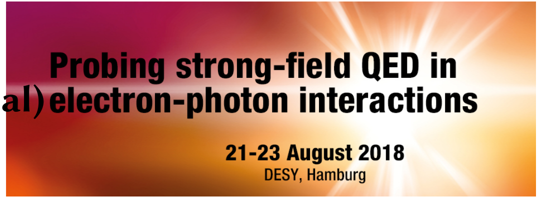
Probing Strong-Field QED, DESY, Hamburg 21-23 August, 2018

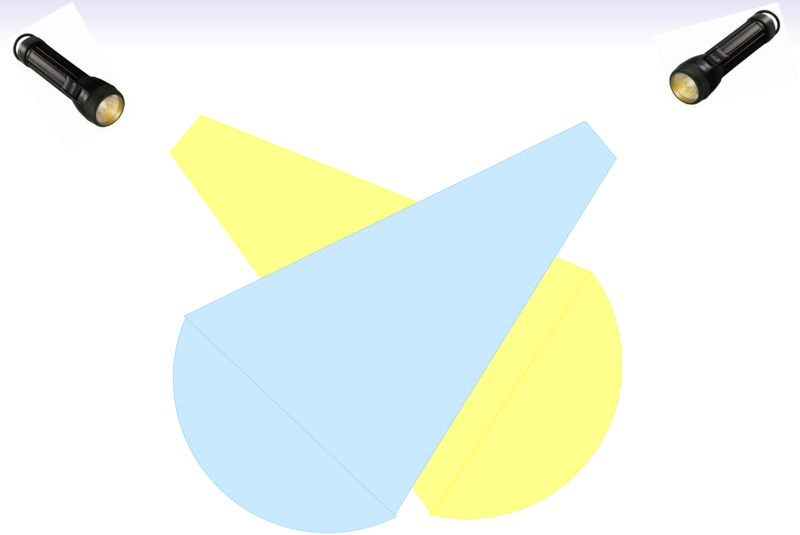
All-optical ...?

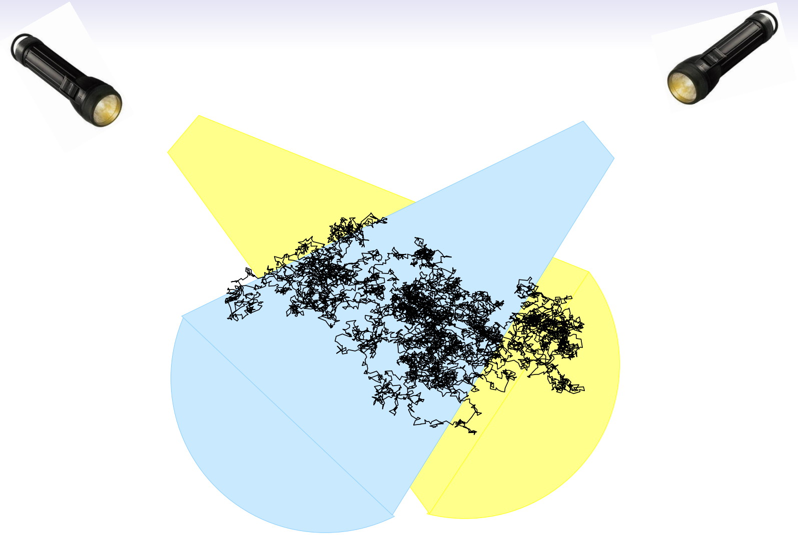

Probing strong-field QED in electron-photon interactions
21-23 August 2018
DESY, Hamburg

All-optical . . . ?

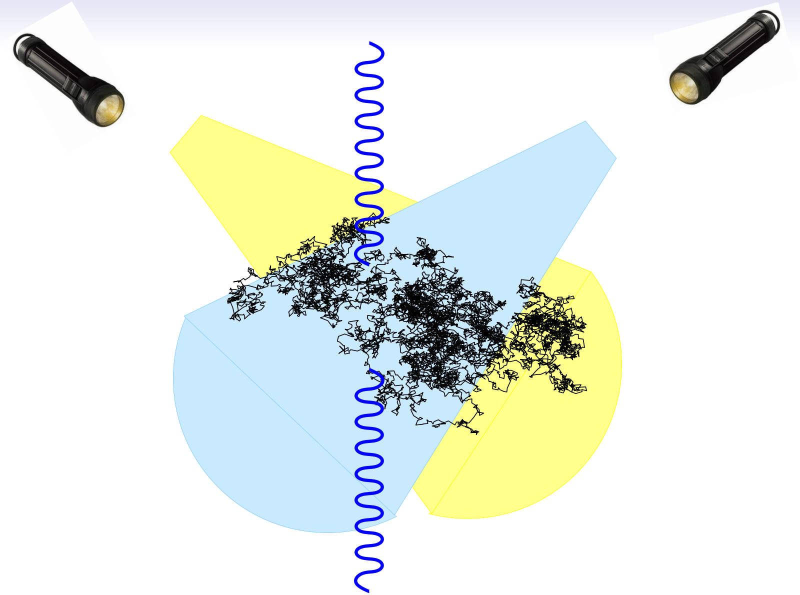
(virtual)

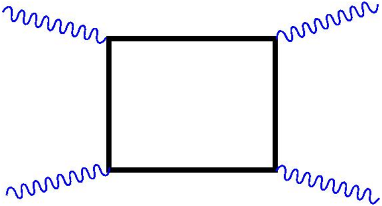






virtual electron-positron fluctuations





QED: nonlinear γ self-interactions

Low-energy frontier

▷ typical energies: $E = \omega \simeq \mathcal{O}(1)$ eV

$\ll m_{\mathrm{e}}$ electron mass scale

$\Longrightarrow$ Heisenberg-Euler regime: (Heisenberg,Euler 1936)

Folgerungen aus der Diracschen Theorie des Positrons.

Von **W. Heisenberg** und **H. Euler** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 22. Dezember 1935.)

"[. . .] für den speziellen Fall berechnet, [. . .] in dem sich das Feld auf Strecken der Compton-Wellenlänge wenig ändert."

Γ_{HE}

$$\Longrightarrow \left\{ \begin{array}{l} \text{low-energy} \\ \text{strong-field/high-intensity} \end{array} \right. \quad \text{regime}$$

$\neq$ e.g. $\gamma\gamma$ @ LHC

(Aaboud et al.[ATLAS]'17)

Wish list

- strong fields / high intensities
- high rep'rate / many photons
- efficient detectors / precision metrology

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- (sufficient funding / many students)
- accurate theoretical predictions

A theory challenge

▷ Heisenberg-Euler effective theory (Heisenberg,Euler'36;Weisskopf'36)

$\Longrightarrow$ quantum Maxwell equation:

$$0 = \partial_\mu \left(F^{\mu\nu} - \frac{1}{2}\,\frac{8}{45}\,\frac{\alpha^2}{m^4} F^{\alpha\beta} F_{\alpha\beta} F^{\mu\nu} - \frac{1}{2}\,\frac{14}{45}\,\frac{\alpha^2}{m^4} F^{\alpha\beta} F_{\alpha\beta} \tilde{F}^{\mu\nu} \right) + \mathcal{O}(F^5/m^8)$$

num. solvers, e.g. (King,Keitel'12; King,Böhl,Ruhl,14; Caneiro,Grismayer,Fonseca,Silva'16; Pons-Domenech,Ruhl'16)

incoming fields: e.g., $\sim 10^{20}\gamma$'s $\longleftrightarrow$ signals $\sim \mathcal{O}(1)\gamma$'s

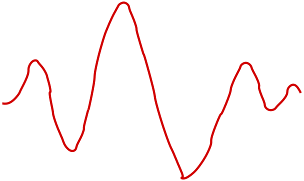
high-precision numerics

$\updownarrow$

real experiments:

non-ideal fields $\longrightarrow$ numerical description required

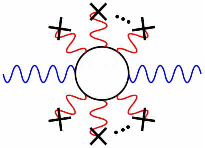
beyond plane wave ...



Commonly used strategies

▷ linearized EoM: $F \to F + f$

$$0 = \partial_\mu f^{\mu\nu} - \frac{8}{45}\frac{\alpha^2}{m^4} F_{\alpha\beta} F^{\mu\nu} \partial_\mu f^{\alpha\beta} - \frac{14}{45}\frac{\alpha^2}{m^4} \tilde{F}_{\alpha\beta} \tilde{F}^{\mu\nu} \partial_\mu f^{\alpha\beta} + \mathcal{O}((F^4/m^8)\partial f)$$



(Heinzl et al.'06)
(Di Piazza, Hatsagortsyan, Keitel'06)
(King, DiPiazza, Keitel'10)
(King, Keitel'12)
(HG, Karbstein, Seegert'13)

▷ general strategy: correlation functions

birefringence

γ merging, wave mixing, γ splitting, scattering

(Toll'54; Baier, Breitenlohner'67; Adler'71; … HG, Karbstein, Seegert'16)

In principle: known in HE limit

In practice: exp. growth of complexity

The classical-quantum divide

▷ high-intensity lasers, strong magnets, XFELs, pulsars, …

$\simeq$ classical fields F

▷ QED induced signals $\sim \alpha \left(\frac{eF}{m^2}\right)^2$

$$\left.\begin{array}{lcl} \text{ellipticity (birefringence)} & \rightarrow & \text{polarization flipped } \gamma\text{'s} \\ \text{enhanced off-axis components} & \rightarrow & \text{scattered } \gamma\text{'s} \\ \text{high-frequency components} & \rightarrow & \text{merged } \gamma\text{'s} \end{array}\right\} \simeq \text{quantum}$$

The classical-quantum divide

$\Longrightarrow$ vacuum emission picture (KARBSTEIN,SHAISULTANOV'15)

[IMAGE CREDIT: WWW.POLYTECHNIQUE.EDU]

The classical-quantum divide

$\Longrightarrow$ vacuum emission picture (Karbstein,Shaisultanov'15)

classical

[Image credit: www.polytechnique.edu]

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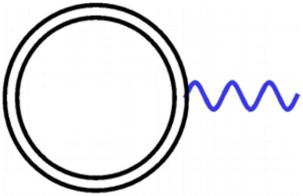


$\Longrightarrow$ induced current

$$j^{\mu}_{\mathrm{HE}}[A] = \frac{\delta \Gamma_{\mathrm{HE}}[A]}{\delta A_{\mu}}$$

Vacuum emission

▷ emission amplitude (Yakovlev'67;Karbstein,Shaisultanov'15)

$$S_{(p)}(\mathbf{k}) = \langle \gamma_{(p)}(\mathbf{k})| \int d^4x \, j^\mu_{\mathrm{HE}}[A](x) \, \hat{a}_\mu(x) \, |0\rangle$$

$\Longrightarrow$ differential photon number at detector

$$dN_{(p)}(\mathbf{k}) = \frac{d^3k}{(2\pi)^3} \, |S_{(p)}(\mathbf{k})|^2$$

Fermi's Golden Rule

Vacuum emission

▷ emission amplitude (Yakovlev'67;Karbstein,Shaisultanov'15)

$$S_{(p)}(\mathbf{k}) = \underbrace{\langle\gamma_{(p)}(\mathbf{k})|}_{\text{signal}} \int d^4x\ \underbrace{j^{\mu}_{\mathrm{HE}}[A](x)}_{\text{classical}}\ \underbrace{\hat{a}_{\mu}(x)}_{\text{quantum}}\ \underbrace{|0\rangle}_{\text{vacuum}}$$

$\Longrightarrow$ differential photon number at detector

$$dN_{(p)}(\mathbf{k}) = \frac{d^3k}{(2\pi)^3}\,|S_{(p)}(\mathbf{k})|^2$$

Fermi's Golden Rule

All-optical quantum vacuum signatures …

▷ …from a simple Fourier transform

$$S_{(p)}(\mathbf{k}) = \frac{\epsilon^*_{(p)\mu}(\mathbf{k})}{\sqrt{2k^0}} \int d^4x \; e^{ikx} \, j^\mu_{\mathrm{HE}}[A](x)$$

- analytically accessible for idealized fields

  const., plane-wave, paraxial beams, etc.

  (Karbstein,HG,Reuter,Zepf'15)

- fast algorithms available

  FFT

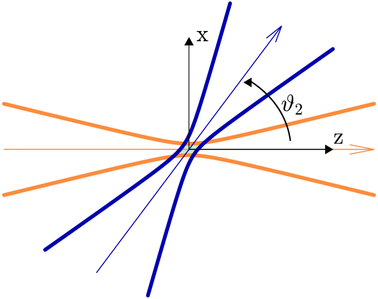
- straightforward discretization

  physical scales

All-optical quantum vacuum signatures: examples

- ▷ Collision of 2 optical pulses

(Tommasini,Michinel'10)
(King,Keitel'12)
(HG,Karbstein,Kohlfürst'17)



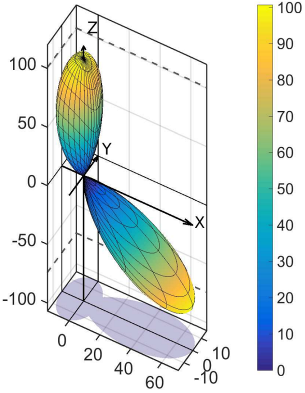
- ▷ Example: 2 identical PW-class lasers:

$W = 25\text{J}$	$f^{\#} = 1$ (diff. limit)
$\tau = 25\text{fs}$	$z_{\text{R}} = \pi\lambda$
$\lambda = 800\text{nm}$	paraxial Gaussian

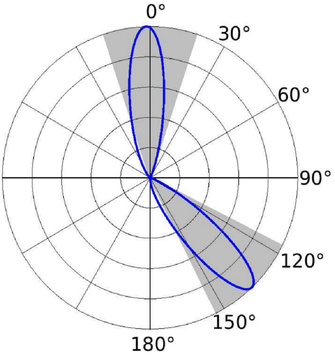
Example: colliding pulses

▷ collision under $\vartheta_2 = 135°$ (HG,Karbstein,Kohlfürst'17)

▷ number density of QED-induced photons



▷ emission characteristics



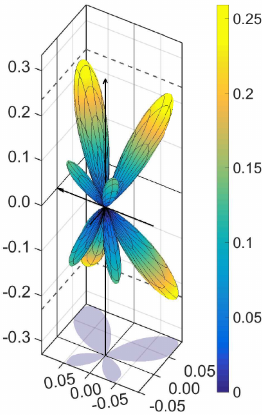
$\sim \mathcal{O}(100)$ γ's

signal γ's swamped by background

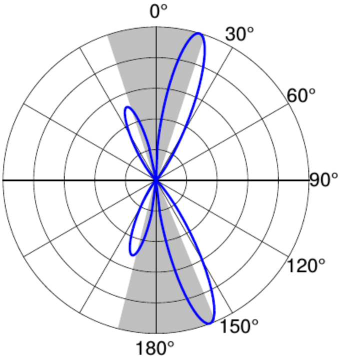
Example: colliding pulses

▷ collision under $\vartheta_2 = 175.8°$, $\perp$ polarization (HG,Karbstein,Kohlfürst'17)

▷ $\perp$ number density



▷ emission characteristics



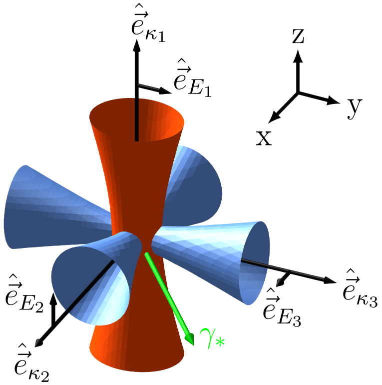
☹ $\sim \mathcal{O}(0.3)$ γ's

☺ signal outside pump beams

$\gamma\,\gamma$ scattering at the high-intensity frontier

▷ collision of 3 pulses

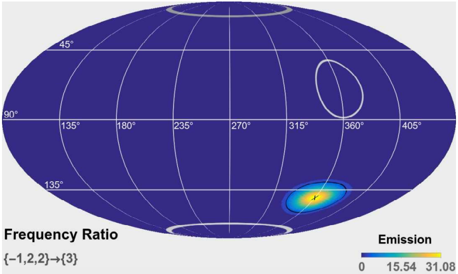
(Moulin,Bernard'02)
(Lundstrom et al.'05; Lundin et al.'06)
(HG,Karbstein,Kohlfürst,Seegert'17)
(King,Hu,Shen'18)



$W_1 = 25\text{J}$	$W_{2,3} = 6.25\text{J}$	$f^{\#} = 1$ (diff. limit)
$\lambda_1 = 800\text{nm}$	$\lambda_1 = 400\text{nm}$	$z_{\text{R}} = \pi\lambda$
$\tau = 25\text{fs}$	$\tau = 25\text{fs}$	paraxial Gaussian

$\gamma\,\gamma$ scattering at the high-intensity frontier

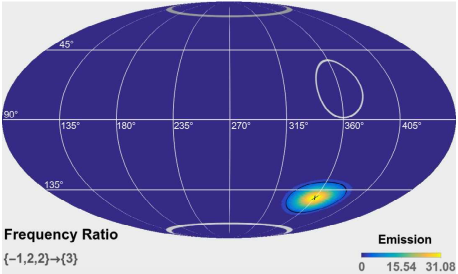
▷ collision of 3 pulses (planar config.) (HG,Karbstein,Kohlfürst,Seegert'17)



- $N = 3.03$ signal γ's
- $\omega_{\text{signal}} \simeq 3\omega$
- angular separation of signal
- prediction for signal divergence

$\gamma\,\gamma$ scattering at the high-intensity frontier

▷ collision of 3 pulses (planar config.) (HG,Karbstein,Kohlfürst,Seegert'17)



- $N = 3.03$ signal γ's
- $\omega_{\text{signal}} \simeq 3\omega$
- angular separation of signal
- prediction for signal divergence

▷ ELI-NP (10PW):

$$N \simeq 3030$$

Conclusions

- Strong-field QED in Heisenberg-Euler regime

  ...towards first discovery experiments

- All-optical signatures from the quantum vacuum

  ...experimental & theoretical control

- Vacuum emission picture

  ...conceptually, analytically, numerically simple