# Unruh effect & Schwinger mechanism in strong lasers?

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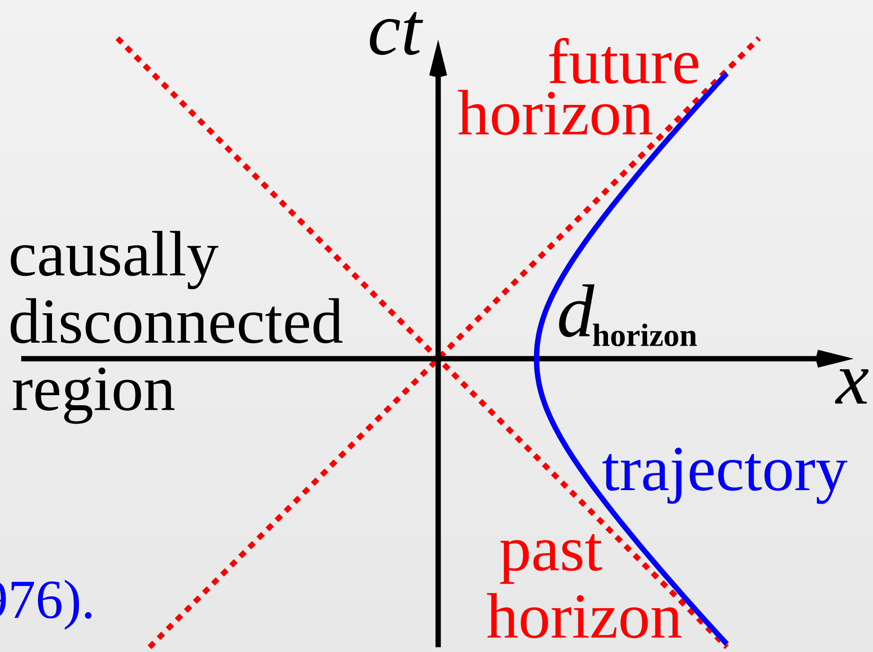
# Unruh Effect

Uniformly accelerated detector experiences inertial vacuum state as thermal bath with Unruh temperature

$$T_{\rm Unruh} = \frac{\hbar}{2\pi k_{\rm B} c}\, a = \frac{\hbar c}{2\pi k_{\rm B}} \frac{1}{d_{\rm horizon}}$$

Similarities to Hawking radiation (black hole evaporation)

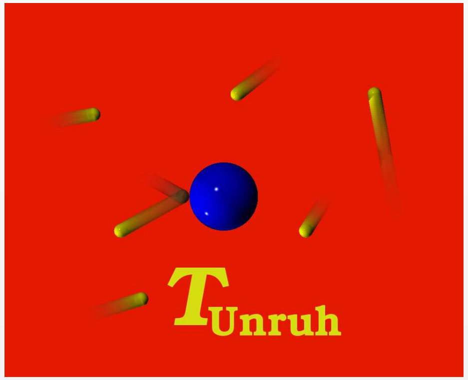
However: Time-reversal invariance

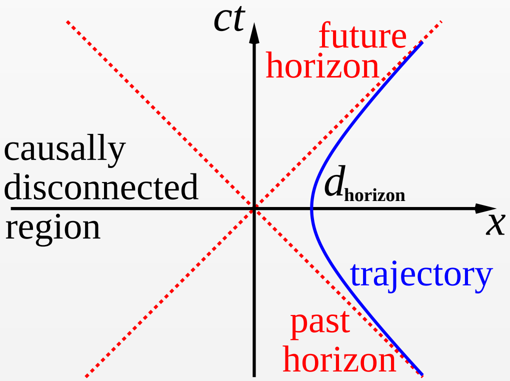


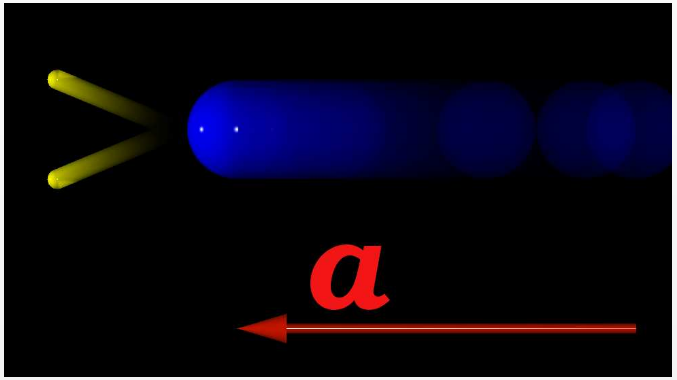

W. G. Unruh, Phys. Rev. D **14**, 870 (1976).

# Accelerated Scatterer

Scattering in accelerated frame (thermal bath)




Translation back into inertial frame

Conversion of (virtual) quantum vacuum fluctuations into (real) particle *pairs* by non-inertial scattering

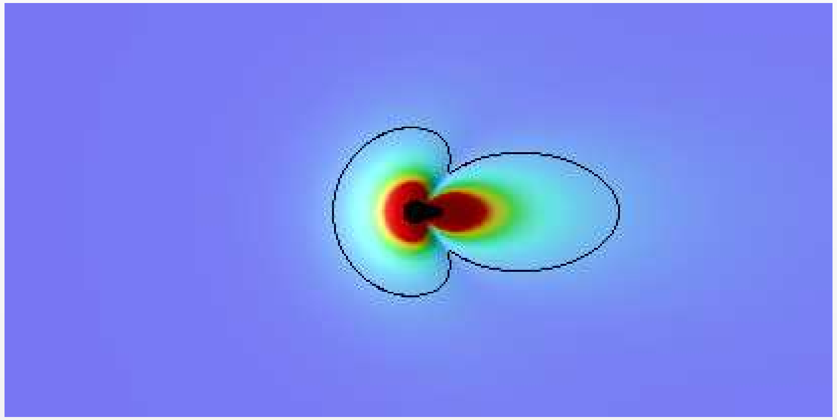
Vacuum entanglement → entangled pairs

Compare: P. Chen and T. Tajima, Phys. Rev. Lett. **83**, 256 (1999).

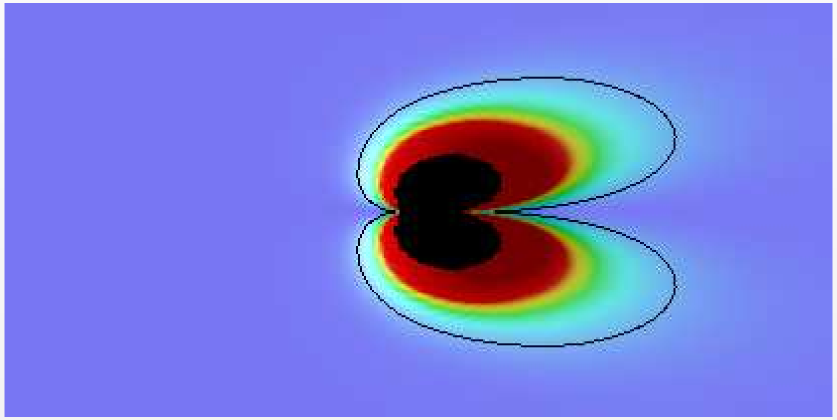
E.g., strongly accelerated electrons. . .

# Constant Electric Field ($\dot{a} = 0$)

R. S., G. Schaller, and D. Habs, Phys. Rev. Lett. **97**, 121302 (2006).



Unruh radiation



Larmor radiation

$\rightarrow$ blind spot: quantum (Unruh) radiation dominates within small forward cone with angle

$$\vartheta = \mathcal{O}\left(\frac{1}{\gamma}\sqrt{\frac{E}{E_S}}\right) \, , \; \mathfrak{P}_{\rm Unruh}(\vartheta) = \mathcal{O}\left(\frac{E^4}{E_S^4}\right) \ll 1$$

Schwinger limit $E_S = m_e^2/q_e = \mathcal{O}(10^{18}\,{\rm V/m})$

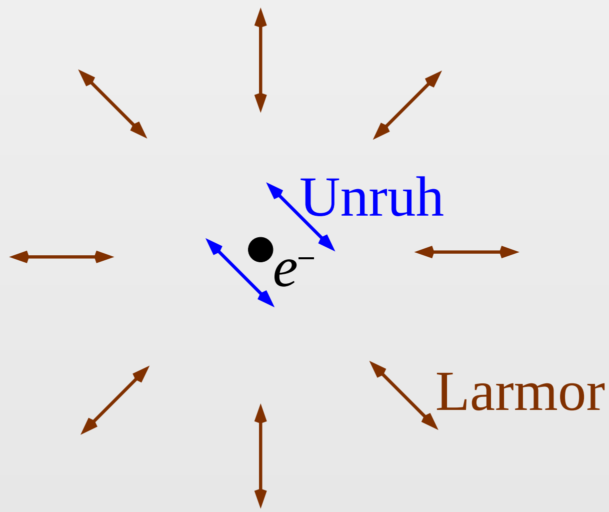
# Alternative Set-up ($\dot{a} \neq 0$)

Laser beam with linear polarization and $10^{18}\mathrm{W/cm}^2$
Counter-propagating electron pulse with $\gamma = 1000$
Laboratory frame: optical photons with energy 2.5 eV

Rest frame of electrons: strongly boosted field

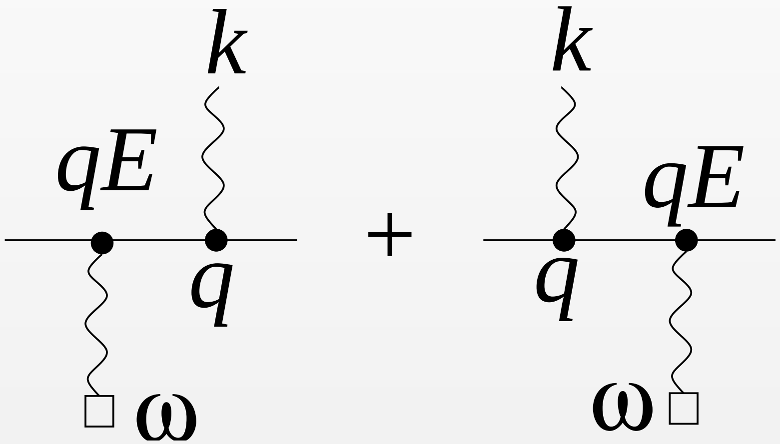
$$E \approx \frac{E_S}{300}, \quad \omega = 5\,\mathrm{keV} \approx \frac{m_e}{100}$$

Emission of entangled EPR-pairs of photons:
$k + k' = \omega$ (resonance)
perfectly correlated polarizations

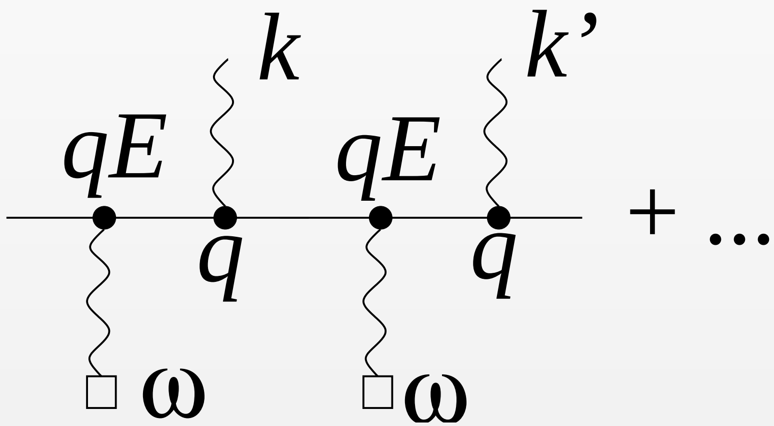


# Lowest-order Diagrams

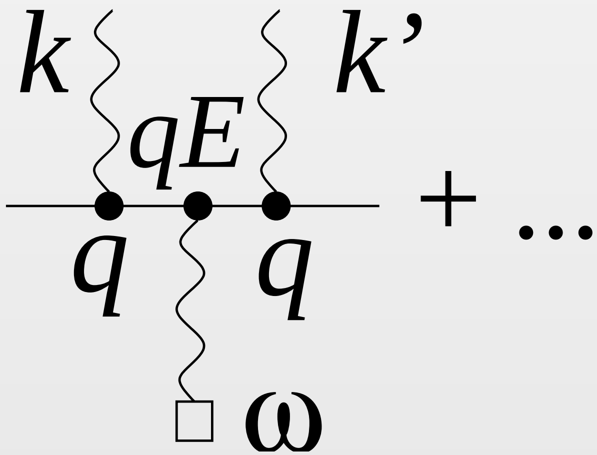
One-photon Larmor




Two-photon Larmor




Quantum radiation (Unruh):
$\omega = k + k'$
Thomson scattering
$\boldsymbol{p}_e^2/(2m_e) \ll \omega$
$\longrightarrow$ low-energy re-summation of
$q_e^2(q_e E_{\rm ext})^n$, cf. $\exp\{i(\boldsymbol{k}+\boldsymbol{k'})\cdot\boldsymbol{r}_e[qE_{\rm ext}]\}$



# Lowest-order Scaling

Quantum (Unruh) radiation (cf. $E^4/E_S^4$)

$$\mathfrak{P}_{\text{Unruh}} = \frac{\alpha_{\text{QED}}^2}{4\pi}\left[\frac{E}{E_S}\right]^2 \times \mathcal{O}\left(\frac{\omega T}{30}\right)$$

Classical counterpart (Larmor)

$$\mathfrak{P}_{\text{Larmor}}^{1\gamma} = \alpha_{\text{QED}}\left[\frac{qE}{m\omega}\right]^2 \times \mathcal{O}\left(\frac{\omega T}{2}\right)$$

One electron with $\gamma = 300$ after 100 cycles

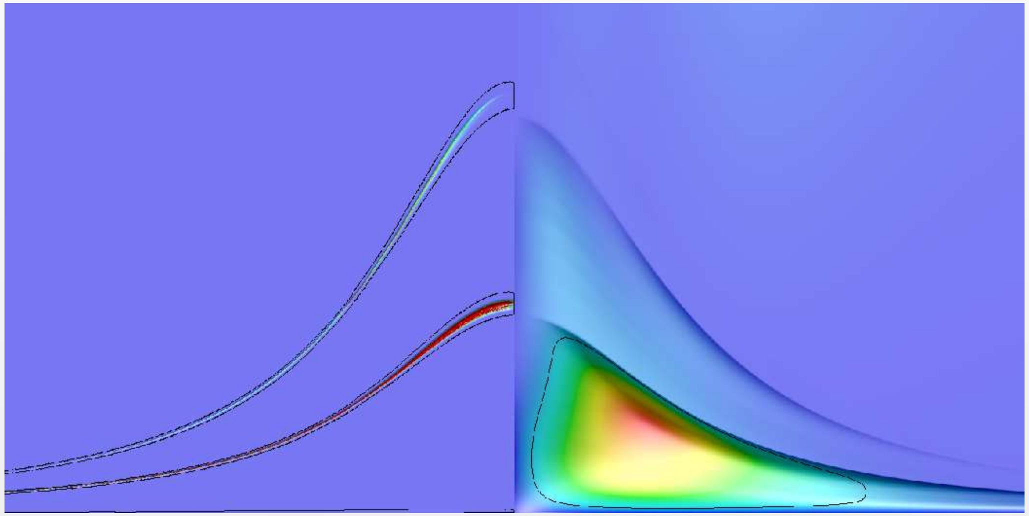
in Laser field with $10^{18}\text{W}/\text{cm}^2$ yields

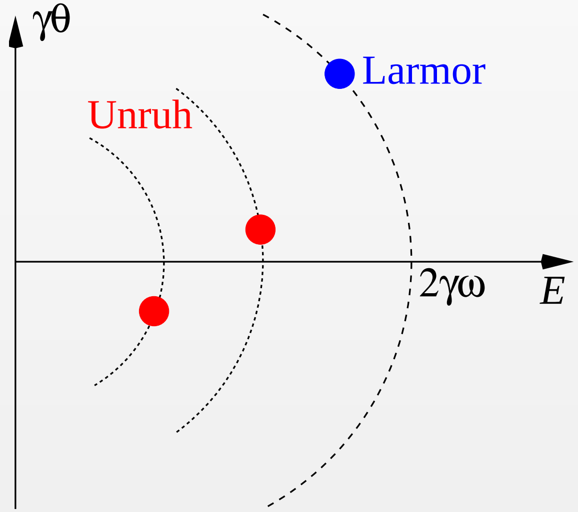
$\mathfrak{P}_{\text{Unruh}} = 4 \times 10^{-11}$ and $\mathfrak{P}_{\text{Larmor}}^{1\gamma} = \mathcal{O}(10^{-1})$

e.g., $N_e = 6 \times 10^9 \ldots$

# Distinguishability

Larmor monochromatic $k = \omega$, Unruh not $k + k' = \omega$ in rest frame of electron $\longrightarrow$ boost to lab frame






Larmor (left), Unruh (right)

$0 < E < 2\mathrm{MeV}$, $0 < \vartheta < 1/100$

$\longrightarrow$ monochromators

$\longrightarrow$ apertures (e.g., blind spot)

$\longrightarrow$ polarization filters

R. S., G. Schaller, and D. Habs, Phys. Rev. Lett. **100**, 091301 (2008).

# Schwinger Mechanism

Problem: non-perturbative imaginary part of

$\Gamma[A_\mu] = -i \ln \langle \text{in}|\text{out}\rangle = \ln[\det\{i(\partial\!\!\!/ - iqA\!\!\!/) - m\}] =?$

- very few analytic solutions ($\rightarrow$ Dirac operator)
  e.g., $\boldsymbol{E}(t) = E\boldsymbol{e}_z / \cosh^2(\Omega t)$
- 1D-scattering problem for $\boldsymbol{E}(t) = \boldsymbol{e}_z f(t)$
- approximations: WKB, instanton for
  $\boldsymbol{E}(t) = \boldsymbol{E}_0 f(t)$ or $\boldsymbol{E}(x) = \boldsymbol{E}_0 f(x)$ (i.e., 1D)
- numerical techniques (Monte Carlo worldline)

Keldysh parameter: non-perturbative vs multi-photon

$$\gamma = \frac{m\Omega}{qE} \rightarrow P_{e^+e^-} \propto \begin{cases} \exp\{-\pi E_S/E\} & : \ \gamma \ll 1 \\ (qE/[m\Omega])^{4m/\Omega} & : \ \gamma \gg 1 \end{cases}$$

# Assisted Schwinger Mechanism

Strong & slow + weak & fast pulse ($\rightarrow$ experiment)

$$\boldsymbol{E}(t) = \frac{E}{\cosh^2(\Omega t)}\,\boldsymbol{e}_z + \frac{\varepsilon}{\cosh^2(\omega t)}\,\boldsymbol{e}_z$$

Instanton action $\mathcal{A}_{\text{inst}} \rightarrow$ tunnelling exponent

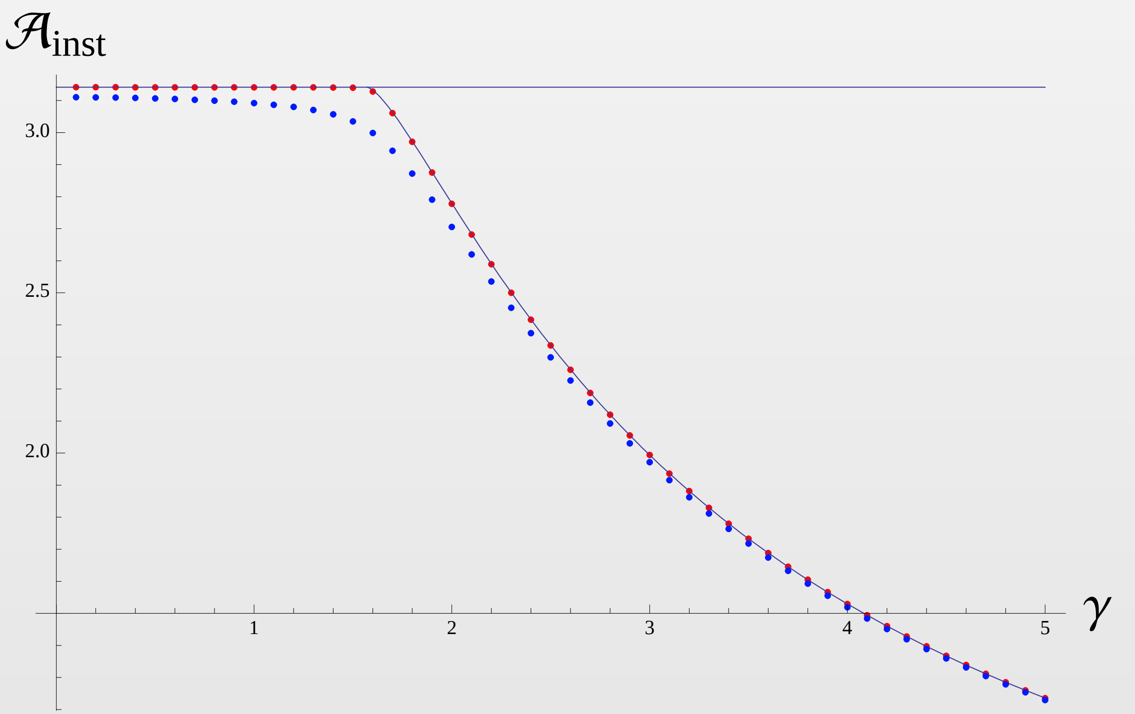
Combined Keldysh parameter

$$\gamma = \frac{m\omega}{qE}$$

Enhancement for $\gamma > \pi/2$

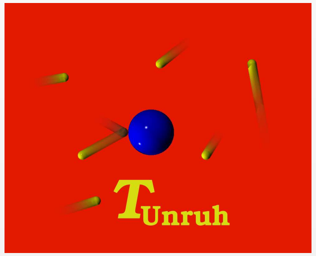
R. S., H. Gies, G. Dunne,

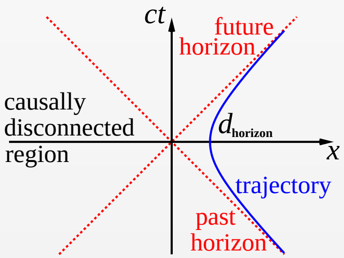
`arXiv:0807.0754`

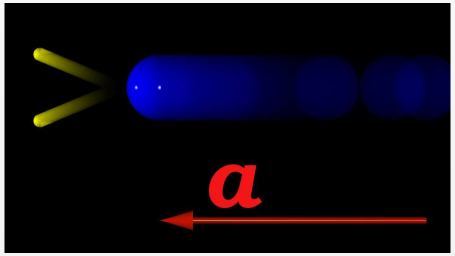


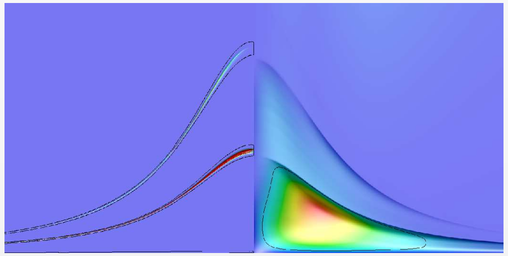
# Summary

- signatures of Unruh effect in near-future facilities
  $N_e = 6 \times 10^9$, $\gamma = 300$, $10^{18}\mathrm{W/cm^2}$, 100 cycles









- detectability?
  spatial interference of many electrons?
- Schwinger mechanism?
  $E \lll E_S = m_e^2/q_e = \mathcal{O}(10^{18}\,\mathrm{V/m})$


R. S., G. Schaller, and D. Habs, Phys. Rev. Lett. **97**, 121302 (2006).

R. S., G. Schaller, and D. Habs, Phys. Rev. Lett. **100**, 091301 (2008).

R. S., H. Gies, G. Dunne, `arXiv:0807.0754`

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# Low-Energy Effective Action

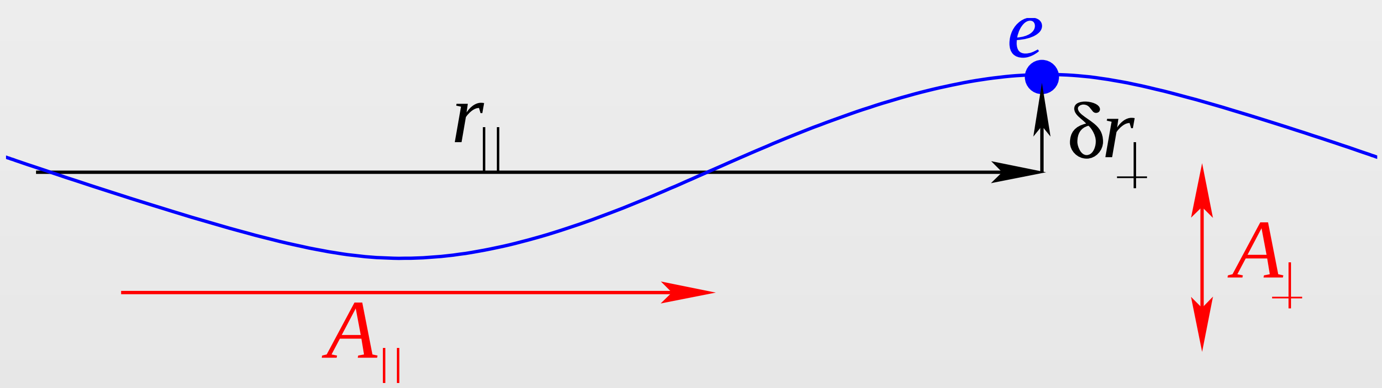
Spin- and energy-independent Thomson scattering

$$L_{\text{electron}} = -m_e\sqrt{1-\dot{\boldsymbol{r}}^2} - q_e\,\dot{\boldsymbol{r}}\cdot\boldsymbol{A}(\boldsymbol{r})$$

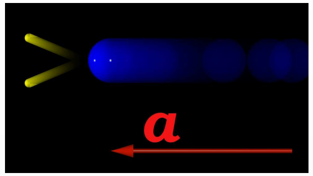
Split $\boldsymbol{A} = \boldsymbol{A}_{\|} + \boldsymbol{A}_{\perp} \rightsquigarrow \boldsymbol{r} = \boldsymbol{r}_{\|} + \delta\boldsymbol{r}_{\perp}$ yields

$$\mathcal{L}_{\perp} = \frac{1}{2}\left(\boldsymbol{E}_{\perp}^2 - \boldsymbol{B}_{\perp}^2\right) - \frac{g}{2}\,\boldsymbol{A}_{\perp}^2\,\delta^3(\boldsymbol{r}_{\|}[t]-\boldsymbol{r})\sqrt{1-\dot{\boldsymbol{r}}_{\|}^2[t]}$$

Planar Thomson $s$-wave scattering with $g = q_e^2/m_e$



# Two-photon Amplitude




Perturbation theory for small coupling $g = q_e^2/m_e$

$$|\mathrm{out}\rangle = |0\rangle + \sum_{\boldsymbol{k},\lambda,\boldsymbol{k'},\lambda'} \mathfrak{A}_{\boldsymbol{k},\lambda,\boldsymbol{k'},\lambda'} \, |\boldsymbol{k},\lambda,\boldsymbol{k'},\lambda'\rangle + \mathcal{O}(g^2)$$

Two-photon amplitude of created pairs

$$\mathfrak{A}_{\boldsymbol{k},\lambda,\boldsymbol{k'},\lambda'} = \frac{\boldsymbol{e}_{\boldsymbol{k},\lambda} \cdot \boldsymbol{e}_{\boldsymbol{k'},\lambda'}}{2iV\sqrt{kk'}} \int dt\, g\, \sqrt{1 - \dot{\boldsymbol{r}}_e^2[t]} \; \times$$
$$\times \exp\left\{i(k+k')t - i(\boldsymbol{k}+\boldsymbol{k'}) \cdot \boldsymbol{r}_e[t]\right\}$$

Depends on electron’s trajectory $\boldsymbol{r}_e[t]$

Always entangled photon pairs $\boldsymbol{e}_{\boldsymbol{k},\lambda} \cdot \boldsymbol{e}_{\boldsymbol{k'},\lambda'}$