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Breit-Wheeler pair production by high-energy bremsstrahlung and intense laser radiation

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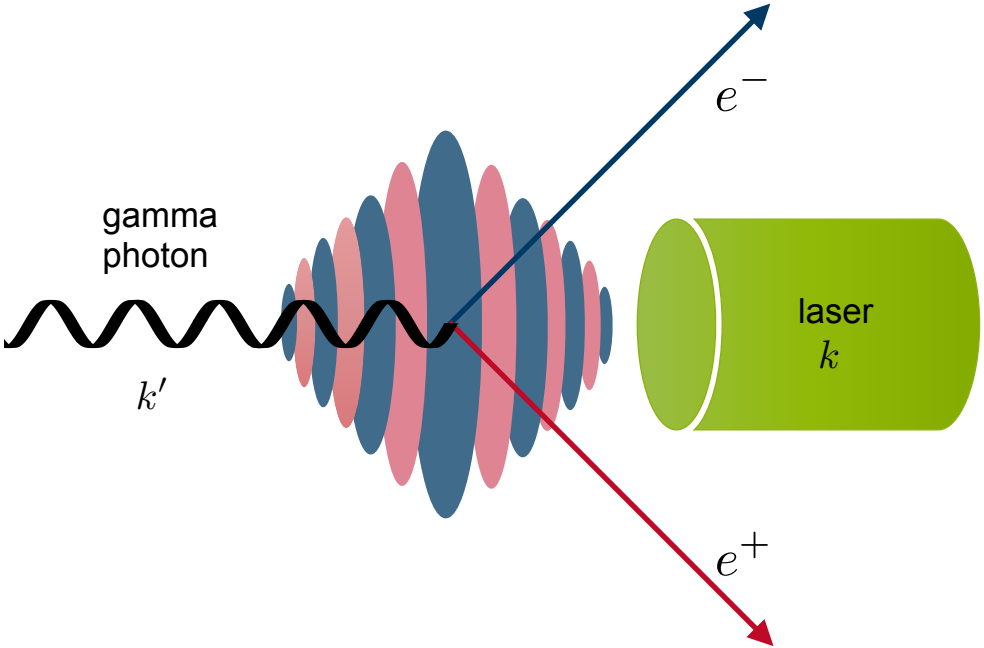
Overview

- Non-linear pair creation with optical laser and high energy bremsstrahlung photons
  - Bremsstrahlung and crossed fields
  - Bremsstrahlung and laser wave with Gaussian time profile
  - Bremsstrahlung and focused pulse
- Linear Breit-Wheeler pair creation with X-ray laser and bremsstrahlung photons
- Breit-Wheeler pair creation in 2+1 space-time dimensions

Breit-Wheeler pair production in a laser field



Breit-Wheeler pair production in a laser field

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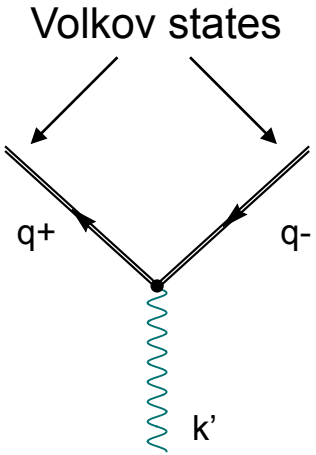


S-matrix element $S_{fi} = -\frac{ie}{\sqrt{2\omega' V_\gamma}} \int d^4x \; \bar{\psi}_{q^-} \not{\epsilon}\,' \psi_{q^+} \mathrm{e}^{-ik'x}$

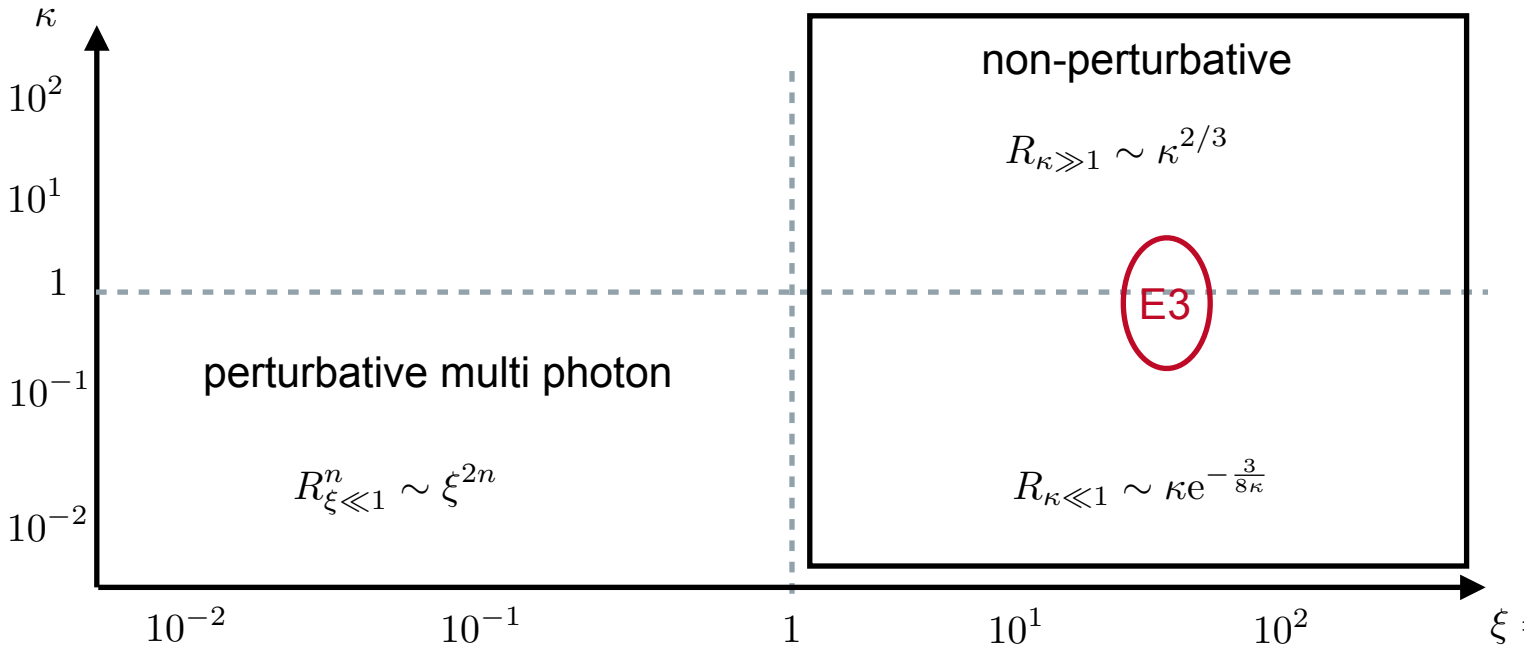
with Volkov states

Number of pairs per time and volume $R = \int V \frac{d^3q^-}{(2\pi)^3} V \frac{d^3q^+}{(2\pi)^3} \frac{|S_{fi}|^2}{TV}$

From now on we work in a unit system with $c = \hbar = \epsilon_0 = 1$

Breit-Wheeler pair production: regimes

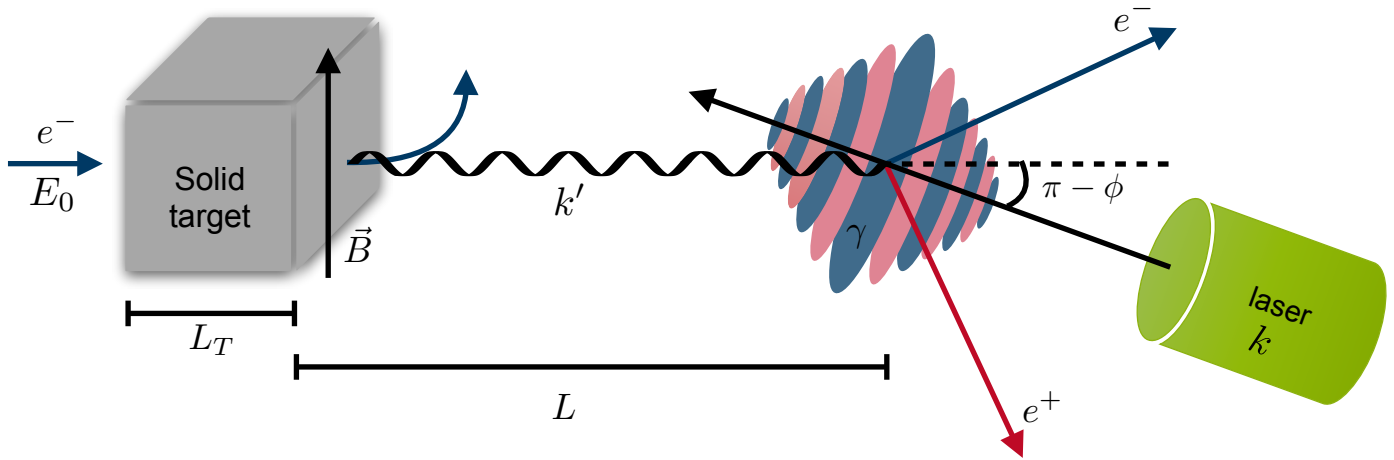
quantum non-linearity parameter $\kappa = \frac{e}{m^3}\sqrt{-(F_{\mu\nu}k'^{\nu})^2}$ intensity parameter $\xi = \frac{e\mathcal{E}}{m\omega}$



Breit-Wheeler pair production: our approach

Bremsstrahlung for highly energetic γ' quanta
GeV

Optical laser as a source for photons
eV



Breit-Wheeler pair production: bremsstrahlung

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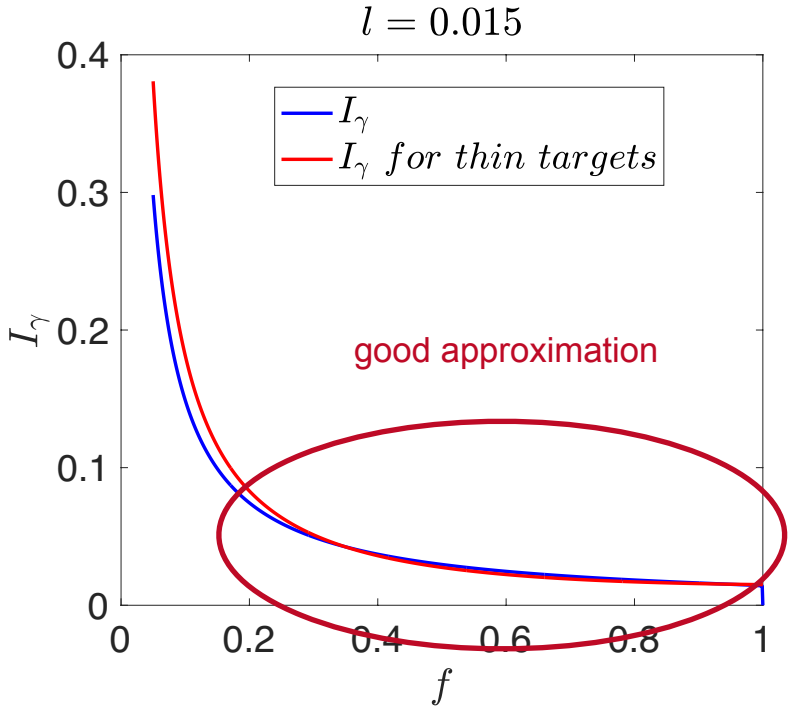
Photon spectrum for thick targets

$$I(f)_\gamma \approx \frac{(1-f)^{4l/3} - \mathrm{e}^{-7l/9}}{f(7/9 + 4/3\log(1-f))}$$

Photon spectrum for thin targets

$$I(f)_\gamma \approx \frac{l}{f}(4/3 - 4f/3 + f^2),$$

$$f = \frac{\omega'}{E_0},\ l = \frac{L_T}{L_{rad}}$$



- Pair production and bremsstrahlung of charged leptons, Y.S. Tsai, Rev. Mod. Phys. 46, 4 (1974)

Breit-Wheeler pair production with bremsstrahlung photons

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quasi-static field approximation: rate in crossed fields

$$R = -\frac{\alpha m^2}{6\sqrt{\pi}k_0' V_\gamma}\int_1^\infty du \frac{8u+1}{zu\sqrt{u(u-1)}}\Phi'(z)$$

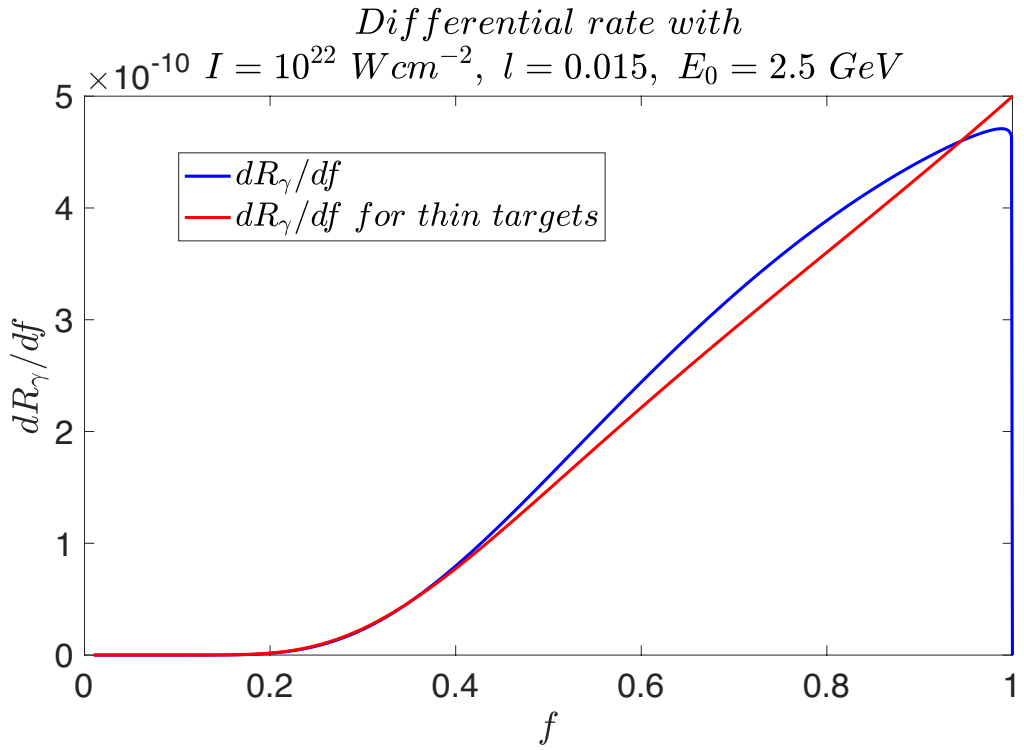
with an Airy function $\Phi(z)$

with Bremsstrahlung photon

$$R_\gamma = \int_0^1 df\, R\; I_\gamma(f,l)$$

- Radiative effects and their enhancement in an intensive electromagnetic field, V. I. Ritus, Zh. Eksp. Theor. Fiz. 57 (1969)

Breit-Wheeler pair production with bremsstrahlung photons



Rate of pair creation

$$R_\gamma = \int_0^1 df R\ I_\gamma(f,l)$$

Number of pairs

$$N \approx \frac{T_{int} V_{int}}{1-\cos(\phi)} R_\gamma$$

Breit-Wheeler pair production: volume effects

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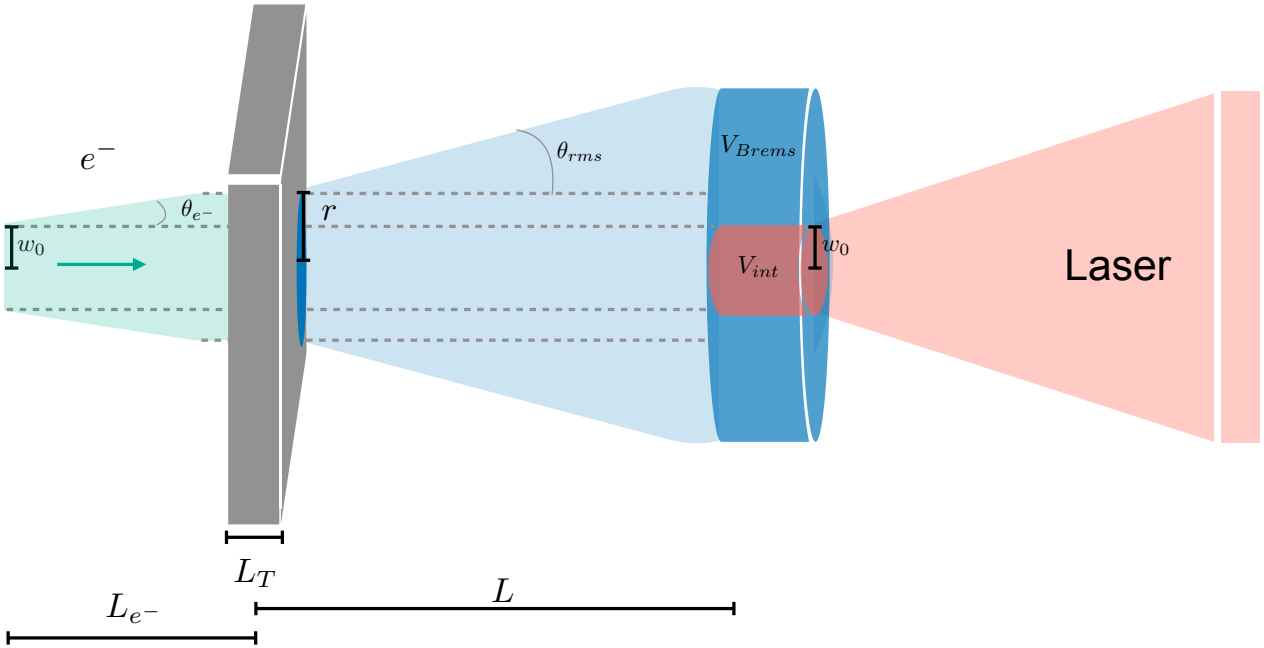
Number of pairs $$N \approx \frac{T_{int} V_{int}}{1-\cos(\phi)} R_\gamma \propto \frac{T_{int}}{1-\cos(\phi)} \frac{V_{int}}{V_\gamma} \propto \frac{w_0^2}{2(w_0 + L_{e^-}\theta_{e^-} + L\theta_{rms})^2}$$



Breit-Wheeler pair production with different field configurations

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Number of pairs in LCFA $$N = \frac{1}{1-\cos(\phi)} \int_{-\infty}^{\infty} dt \int dV R_\gamma\big(\kappa(t,x,y,z)\big)$$

quantum non-linearity parameter $$\kappa = \frac{e}{m^3}\sqrt{-(F_{\mu\nu}k'^{\nu})^2} \quad \rightarrow \quad \kappa(t,x,y,z)$$

CCF

$$N \approx \frac{T_{int}V_{int}}{1-\cos(\phi)} R_\gamma$$

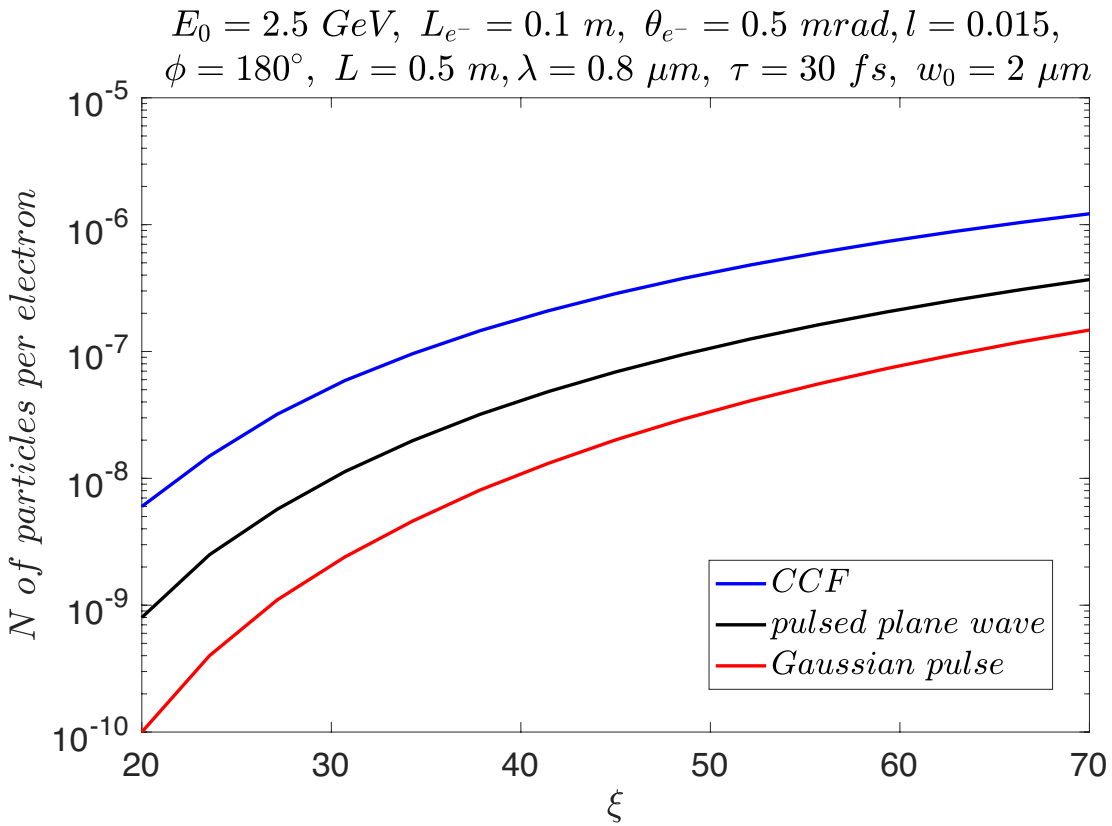
pulsed plane wave

$$N \approx \frac{A_{int}}{1-\cos(\phi)} \int_{-\infty}^{\infty} dt \int_{-z_R}^{z_R} dz R_\gamma\big(\kappa(t,z)\big)$$

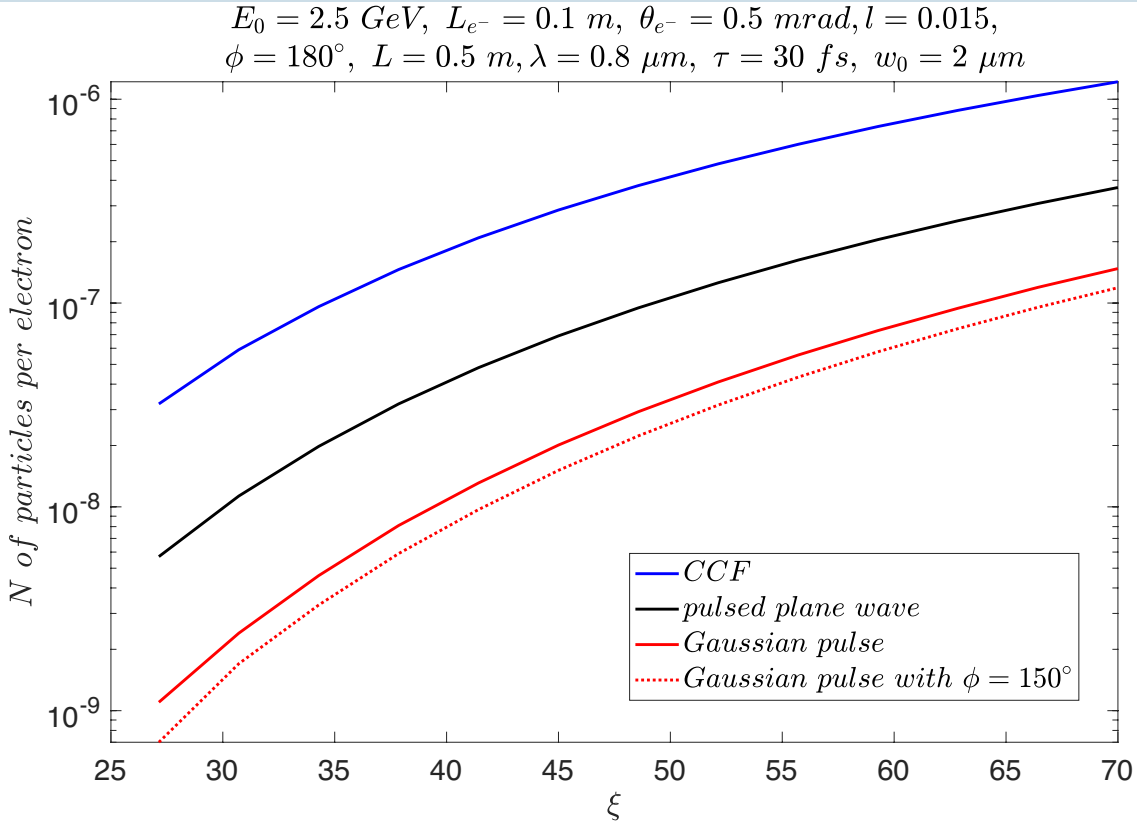
Gaussian pulse

$$N \approx \frac{2\pi}{1-\cos(\phi)} \int_{-\infty}^{\infty} dt \int_{-z_R}^{z_R} dz \int_{0}^{\infty} \rho d\rho R_\gamma\big(\kappa(t,z,\rho)\big)$$

Breit-Wheeler pair production with different field configurations



Breit-Wheeler pair production with different field configurations



Linear Breit-Wheeler pair production

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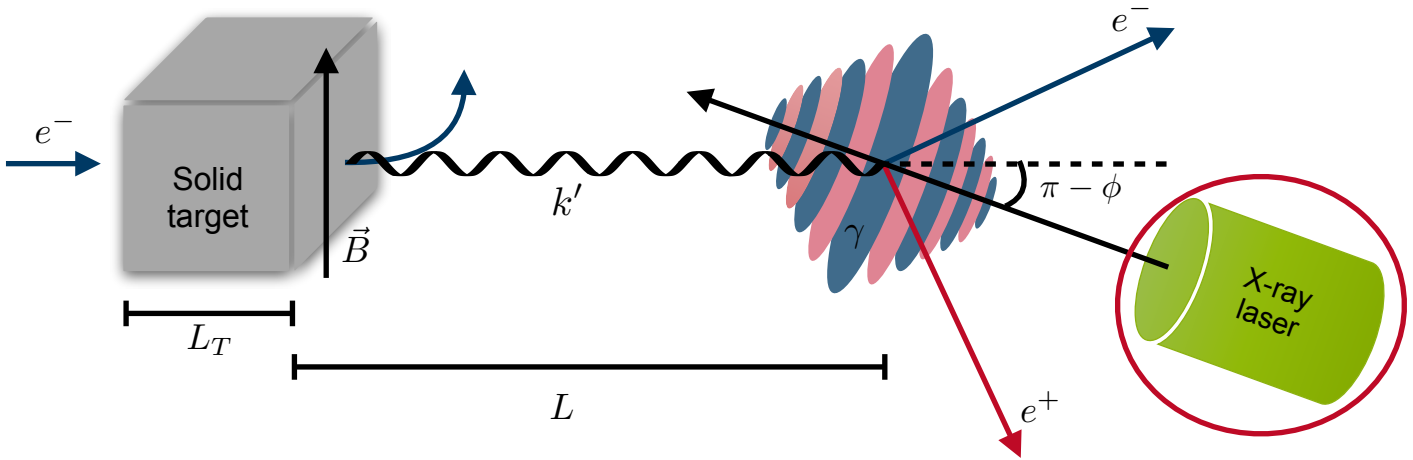
Bremsstrahlung for highly energetic γ' quanta
GeV

X-ray laser as a source for photons
keV

higher energy possible !



Linear Breit-Wheeler pair production

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Number of pairs per time and volume for two-photon process

ordinary linear BW rate

$$R = \int \frac{V d^3p^+}{(2\pi)^3} \frac{V d^3p^-}{(2\pi)^3} \frac{|S_{fi}|^2}{TV} = \int \frac{d^4\tilde{k}}{(2\pi)^4} |\tilde{a}_0(\tilde{k}, k)|^2 \frac{1}{TV} \frac{1}{N_\gamma^2} R_{BW}(\tilde{k}, k)$$

normalization of γ quantum

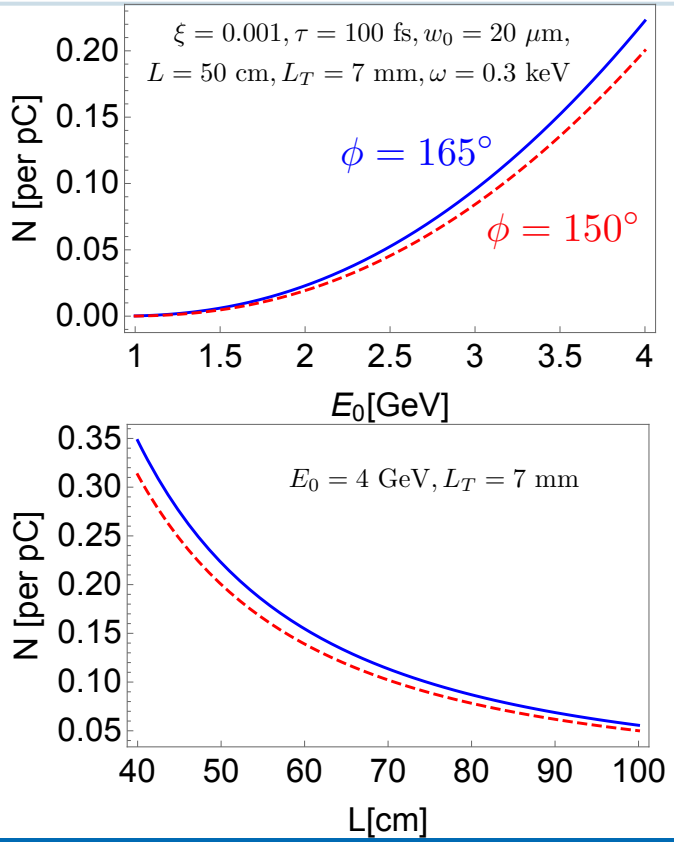
with Fourier transformed

$$\tilde{a}_0(\tilde{k}, k) = \int d^4x a_0(x, k) \mathrm{e}^{ix\tilde{k}}$$

When incorporating bremsstrahlung

$$R_\gamma = \int_0^1 df R\ I_\gamma(f, l)$$

Linear Breit-Wheeler pair production



- Linear Breit-Wheeler pair production by high energy bremsstrahlung photons colliding with an intense X-ray laser pulse,

  A. Golub, H. Ruhl, S. Villalba-Chavez,

  C. Müller, PRD 103, 016009 (2021)

Breit-Wheeler pair production in QED 2+1

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S-matrix in 2+1 dimensions

$$[e] = \mathcal{E}^{1/2} \qquad [a] = \mathcal{E}^{1/2} \qquad [\psi] = \mathcal{E}$$

$$S_{fi} = -ie \int d^3x \bar{\psi}_{p^-}(x) \not{a}'(x) \psi_{p^+}(x)$$

Rate in 2+1 dimensions

$$dR = \frac{|S_{fi}|^2}{TA} A^2 \frac{d^2q^-}{(2\pi)^2} \frac{d^2q^+}{(2\pi)^2}$$

$$\eta = \frac{ea_0}{m}$$

$$R = \frac{e^2 a_0^2 m^2}{8\pi^2} \sum_{n \geq n_0}^{\infty} \int_0^{2\pi} d\phi \int_0^{\infty} \frac{dq}{2q_0} \delta(q - q_n^*) \left(\tilde{J}_n^2 - \eta^2 \left(1 - \frac{(kk')^2}{4kq^+kq^-} \right) \left[(\tilde{\mathcal{J}}_n^1)^2 - \tilde{J}_n \tilde{\mathcal{J}}_n^2 \right] \right)$$

$$\left[R_{\parallel}^{3+1} = \frac{e^2 a_0^2 m^2}{8\pi^2} \sum_{n \geq n_0}^{\infty} \int_0^{\pi} d\theta \sin\theta \int_0^{2\pi} d\phi \int_0^{\infty} \frac{qdq}{2q_0} \delta(q - q_n^*) \left(\sigma \tilde{J}_n^2 - \xi^2 \left(1 - \frac{(kk')^2}{4kq^+kq^-} \right) \left[(\tilde{\mathcal{J}}_n^1)^2 - \tilde{J}_n \tilde{\mathcal{J}}_n^2 \right] \right) \right]$$

Breit-Wheeler pair production in QED 2+1

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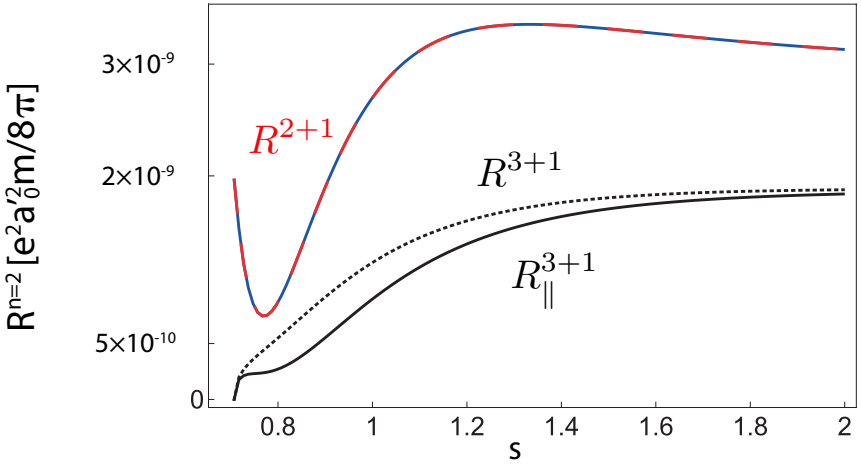
Energy threshold behavior $\tilde{J}_n(z_-, z_+) \to \tilde{J}_n(0, z_{+n}) = \begin{cases} J_{n/2}(z_{+n}), & n \text{ even}, \\ 0, & n \text{ odd}. \end{cases}$



$$R^{\eta\ll 1}_{q\to 0} \approx \frac{e^2 a_0^2 m}{8} \sum_{2\ell \geq n_0}^{\infty} \eta^{4\ell} \frac{\ell^{2(\ell-1)}}{2^{4\ell}\Gamma^2(\ell)}$$

Breit-Wheeler pair production in QED 2+1

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Asymptotic at strong fields for different $\chi = \frac{kk'}{m^2}\eta$

$$R_{\eta\gg1,\chi\ll1} \approx \frac{e^2 a_0^2 m}{8\pi}\frac{3}{8\sqrt{2}}\chi \mathrm{e}^{-\frac{8}{3\chi}}$$

$$\left[R_{\parallel}^{3+1} = \frac{\mathfrak{e}^2\mathfrak{a}_0^2 m^2}{8\pi}\frac{3}{32(2\pi)^{3/2}}\kappa^{3/2}\mathrm{e}^{-\frac{8}{3\kappa}}\right]$$

$$R_{\eta\gg1,\chi\gg1} \approx \frac{e^2 a_0^2 m}{8\pi}\frac{3^{11/6}}{2^{1/3}5\pi}\Gamma^2\left(\frac{2}{3}\right)\chi^{1/3}$$

$$\left[R_{\parallel}^{3+1} = \frac{\mathfrak{e}^2\mathfrak{a}_0^2 m^2}{8\pi}\frac{3^{11/3}}{14\ 2^{8/3}\pi^5}\Gamma^7\left(\frac{2}{3}\right)\kappa^{2/3}\right]$$

- Strong-field Breit-Wheeler pair production in QED 2+1,

  A. Golub, S. Villalba-Chavez and

  C. Müller, PRD 103, 096002 (2021)

Breit-Wheeler pair production in graphene

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$$\mathcal{L} = \sum_{\sigma=\pm 1} \bar{\Psi}_\sigma \left[i\tilde{\gamma}^0 \partial_t + v_F \tilde{\gamma}^j \left(i\partial_j - \frac{e}{c}\mathcal{A}_j \right) - \Delta \right] \Psi_\sigma$$

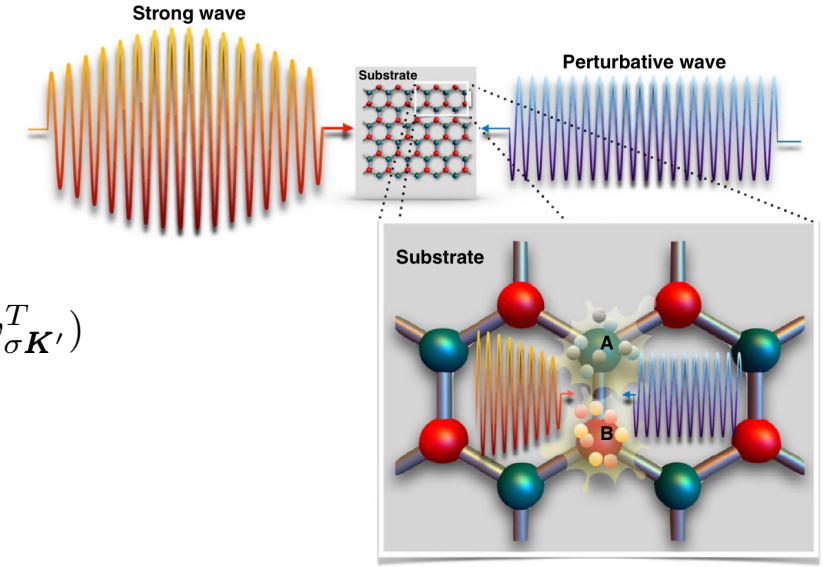
Fermi velocity $v_F \approx c/300$

Half bare gap $\Delta = m_g v_F^2 = 0.1\ \mathrm{eV}$

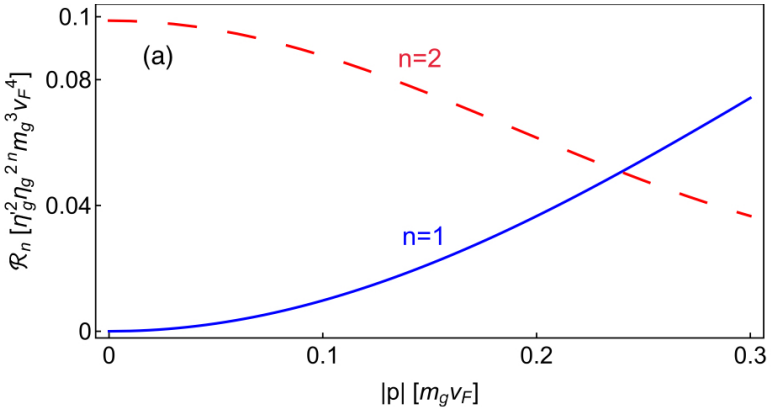
Four component spinors $\Psi_\sigma^T = (\psi_{\sigma \boldsymbol{K}}^T, \psi_{\sigma \boldsymbol{K}'}^T)$

Reducible four representation of matrices

$$\tilde{\gamma}^\mu = \sigma_3 \otimes (\sigma_3, i\sigma_2, -i\sigma_1)$$



Breit-Wheeler pair production in graphene



- Dimensionality-driven photoproduction of massive Dirac pairs near threshold in gapped graphene,

  A. Golub, R. Egger, C. Müller, S. Villalba-Chavez, PRL 124, 110403 (2020)

for $\eta_g = 10,\ \eta_g' = 0.1,\ \Delta = 0.1\ \mathrm{eV},$
$\omega\omega' = 0.25\ \mathrm{eV}^2,\ A_g = 10\ \mu\mathrm{m}^2$

$R_1 \approx 2 \times 10^{-2}\ \mathrm{pairs/fs}$

for $\omega\omega' = 0.01\ \mathrm{eV}^2$

$R_2 \approx 3.4 \times 10^{-7}\ \mathrm{pairs/fs}$

Summary

- Non-linear non-perturbative Breit-Wheeler pair creation with bremsstrahlung photons
- Linear Breit-Wheeler pair creation with bremsstrahlung photons
- Breit-Wheeler pair creation in 2+1 dimensional space-time