Modelling trident pair production in laser-matter interactions

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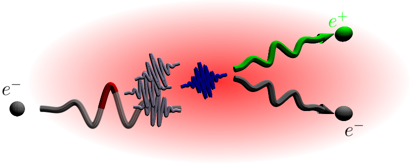
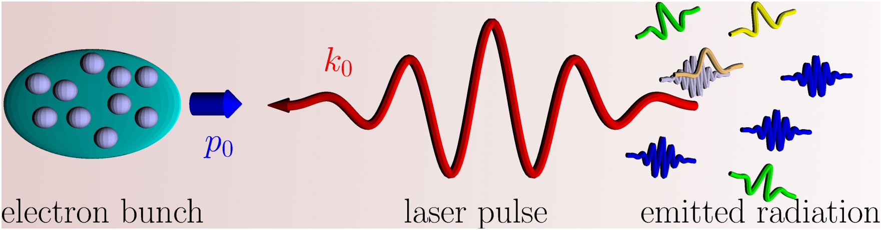


Motivation

Laser-matter interactions



- laser-matter quantum interactions

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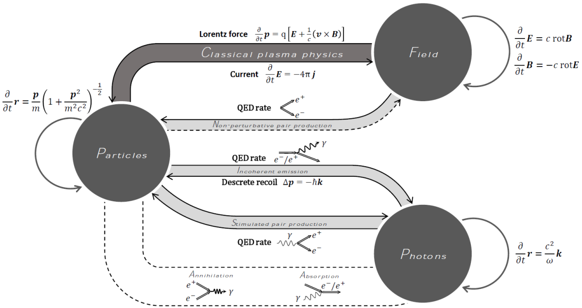

from Gonoskov et al. arXiv:1412.6426v1 (2014) - accepted in PRE

- laser-matter quantum interactions
- modelled by PIC schemes

Motivation

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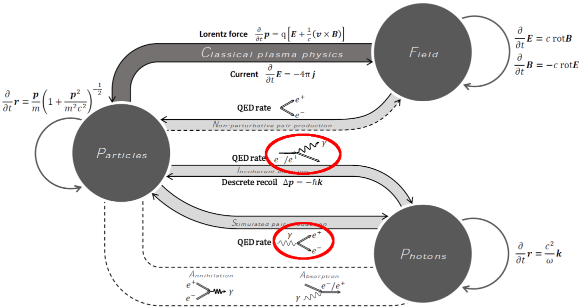

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- laser-matter quantum interactions
- modelled by PIC schemes
- Quantum rates needed

Outline

Nonlinear QED in strong laser fields

Condition for strong laser fields

$$\xi = \frac{eE}{m_e \omega_0} \gtrsim 1 \ , \ I \gtrsim 10^{18} \left[\frac{\omega}{\mathrm{eV}}\right]^2 \frac{\mathrm{W}}{\mathrm{cm}^2}$$

Quantum effects

$$\chi = \frac{(k_0 p)}{m \omega_0} \frac{E}{E_{\mathrm{cr}}} \gtrsim 1$$

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Quantum effects

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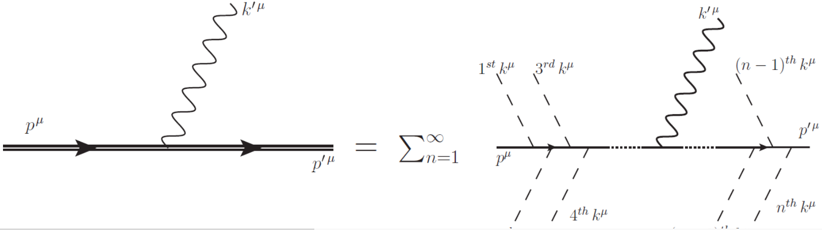
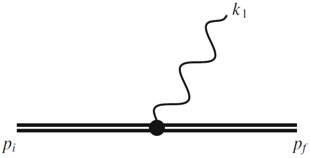
Volkov solution

$$\Psi_p(x) = \mathrm{e}^{-iS_V(x,p)} E_p\left(x^\eta\right) \frac{u_p}{\sqrt{2\varepsilon}}$$

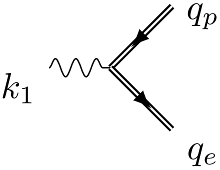


Quantum processes - laser dressed

Photon emission



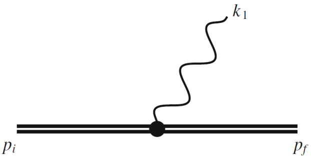
Partcicle production

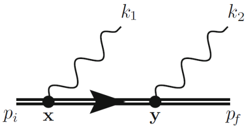


- first order processes (in PIC)

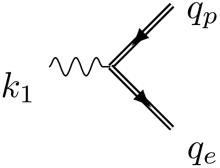
Quantum processes - laser dressed

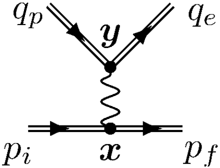
Photon emission





Partcicle production

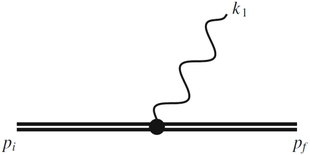


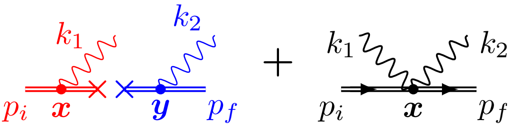


- first order processes (in PIC)
- second order processes

Quantum processes - laser dressed

Photon emission





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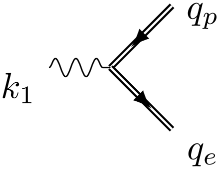
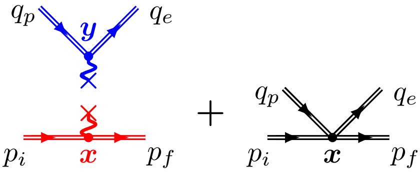
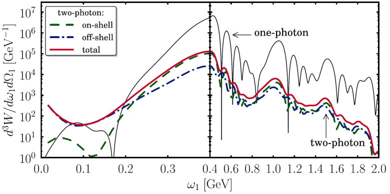




- first order processes (in PIC)
- second order processes approximated by cascades

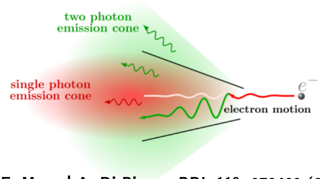
Nonlinear double Compton scattering

Double photon emission suppressed



from D. Seipt and B. Kämpfer, PRD 85, 101701 (2012)

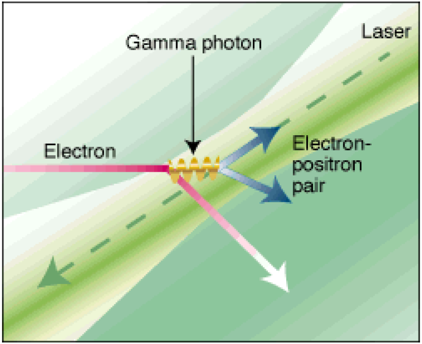
Angle separated signal **dominated by cascade**



see F. M. and A. Di Piazza, PRL 110, 070402 (2013)

Trident pair production

Photon emission with subsequent **pair production**
E-144 @ SLAC

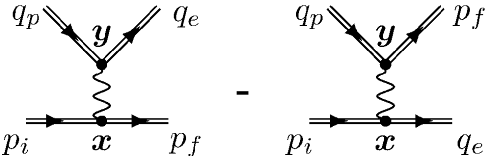


D.L. Burke, et al., PRL **79**, 1626 (1997)
C. Bamber et al., PRD **60**, 092004 (1999)

Trident pair production

Photon emission with subsequent **pair production**

H. Hu et al., PRL 105, 080401 (2010)



Scattering matrix element

$$S_{fi} = - e^2 \int d^4x d^4y \overline{\Psi}_{q_e}(y) \gamma_\mu \Psi_{-q_p}(y) \mathcal{D}^{\mu\nu}(y,x) \overline{\Psi}_{p_f}(x) \gamma_\nu \Psi_{p_i}(x)$$

Trident pair production

Photon emission with subsequent **pair production**

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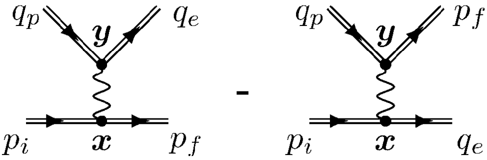

Scattering matrix element

$$
\begin{aligned}
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&= -\, e^2 \int dx^\eta dy^\eta M^y_\mu(y^\eta)\mathcal{D}^{\mu\nu}(y^\eta, x^\eta)M^x_\nu(x^\eta) \\
&\quad \times \delta^{(3)}\left(p_{i,\perp} - p_{f,\perp} - k_{\mathrm{int},\perp}\right)\delta^{(3)}\left(q_{p,\perp} + q_{e,\perp} - k_{\mathrm{int},\perp}\right)
\end{aligned}
$$

Trident pair production

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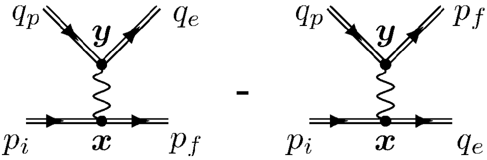

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$$= - e^2 \int dx^\eta dy^\eta M^y_\mu(y^\eta)\mathcal{D}^{\mu\nu}(y^\eta, x^\eta)M^x_\nu(x^\eta)$$

$$\times \delta^{(3)}(p_{i,\perp} - p_{f,\perp} - k_{\text{int},\perp})\delta^{(3)}(q_{p,\perp} + q_{e,\perp} - k_{\text{int},\perp})$$

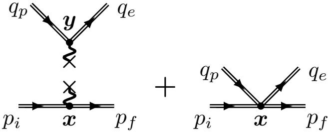
Dressed photon propagator

Partial channels

Photon propagator splits up (see A. Ilderton PRL 106, 020404 (2011))

$$\mathcal{D}^{\mu\nu}(y^\eta, x^\eta) = g^{\mu\nu}\left(C_d\delta(y^\eta - x^\eta) + C_c\Theta(y^\eta - x^\eta)\right)$$

Scattering amplitude alike



$$S_{fi} = \underbrace{\int dx^\eta dy^\eta \theta(y^\eta - x^\eta) M_{\mathrm{BW}}(y^\eta) M_{\mathrm{C}}(x^\eta)}_{\text{cascade}} + \underbrace{\int dx^\eta \tilde{M}^{(d)}(x^\eta)}_{\text{direct}}$$

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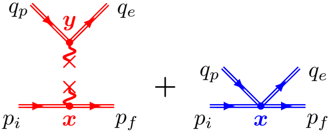

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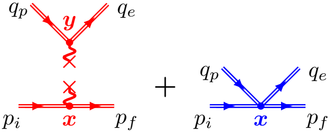

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Direct channel negligible?

Partial channels - estimates

NTPC partial channels

$$M_{fi}^{(c)} = \sum_{r,s=1}^{2} a_{r,s} \int d\eta_x d\eta_y \theta(\Delta\eta)\psi^s(\eta_x)\psi^r(\eta_y)\mathrm{e}^{-i(S_\mathbf{C}(\eta_x)+S_\mathbf{BW}(\eta_y))}$$

$$M_{fi}^{(d)} = \sum_{r=1}^{2} b_r \int d\eta\psi^r(\eta)\mathrm{e}^{-i(S_\mathbf{C}(\eta)+S_\mathbf{BW}(\eta))}$$

Cascade channel

- 2 interaction points
- Compton $\otimes$ Breit-Wheeler events

Direct channel

- 1 interaction point
- non-separable dynamical behaviour

Partial channels - estimates

NTPC partial channels

$$M_{fi}^{(c)} = \sum_{r,s=1}^{2} a_{r,s} f_{r,s}$$

$$M_{fi}^{(d)} = \sum_{r=1}^{2} b_r f_r$$

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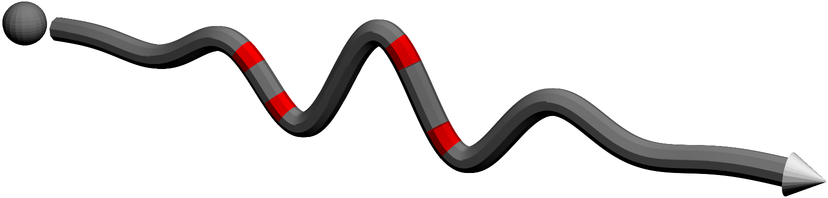
Partial channels - estimates

Formation lengths $\delta_{C/BW} \sim \lambda_0/\xi$ $(\xi = {}^{eE}/_{m_e\omega_0})$



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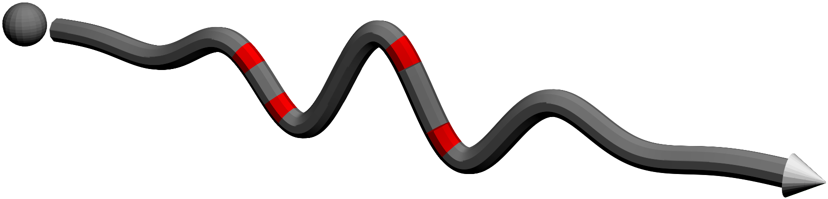

Cascade channel

- 2 interaction points
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- $P^{(c)} \sim (\xi\omega_0\tau)^2$

Direct channel

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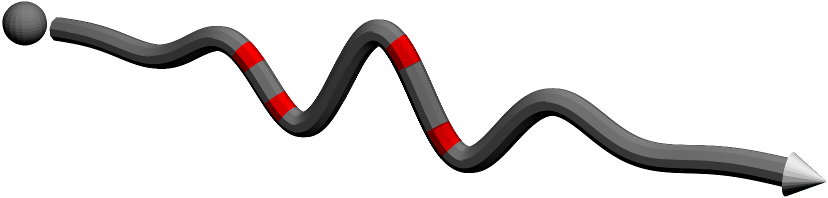

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Direct channel

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- non-separable dynamical behaviour
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Consider short $\tau \sim \omega_0^{-1}$, not too intense $\xi \gtrsim 1$ pulses!

Pair production probability

Typical parameters:

$\varepsilon = 10$ GeV e^- - $I_0 = 2 \times 10^{21} \frac{\text{W}}{\text{cm}^2} (\xi \approx 20)$ - $\chi \approx 2.5$

$\omega_0 = 1.55$ eV, $\tau = 5$ fs laser $(\omega_0 \tau \approx 10)$

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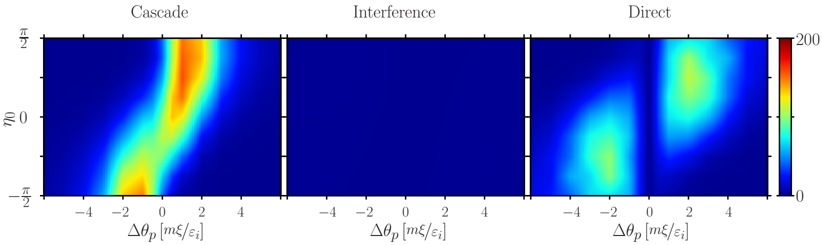

F.M. et al., to be published

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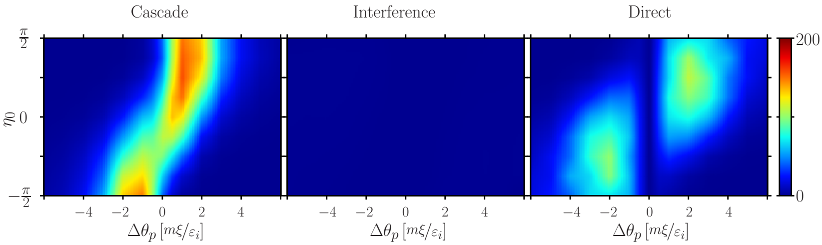

F.M. et al., to be published

- Channels of comparable amplitude

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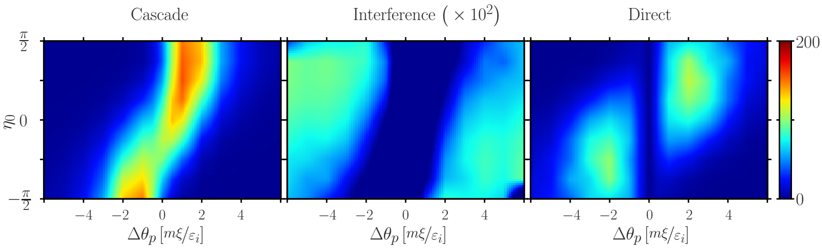

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- Channels of comparable amplitude
- Interference term suppressed $P^{\text{tot}} \approx P^{(\text{c})} + P^{(\text{d})}$

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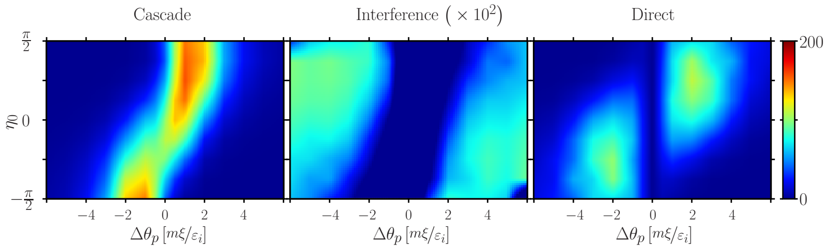

F.M. et al., to be published

- Channels of comparable amplitude
- Interference term suppressed $P^{\text{tot}} \approx P^{(\text{c})} + P^{(\text{d})}$
- Suppression of $\Delta\theta_p = 0$ in direct channel: Quantum interferences

Disentangling NTPC channels

Asymmetry of relative yield

$$\mathcal{R} = \frac{P^{(\mathrm{d})} - P^{(\mathrm{c})}}{P^{(\mathrm{d})} + P^{(\mathrm{c})}}$$

Disentangling NTPC channels

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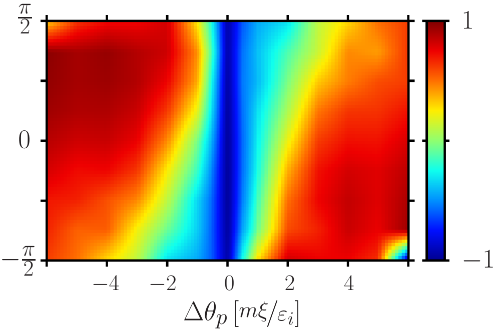

F.M. et al., to be published

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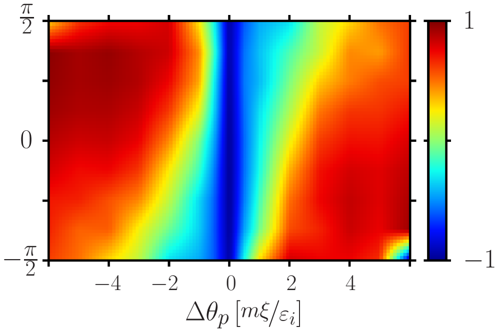

F.M. et al., to be published

Disentangling of separate pair production channels

Angular distribution - Quasiclassical picture

Quantum interaction, classical particle motion

- cascade: (2 interaction points)
  - 1st field maximum: photon emission ($\boldsymbol{k}_{\text{int}} = {}^{p_i}/_2$)
  - 2nd field maximum: pair creation ($\boldsymbol{p}_p = {}^{k_i}/_2$)
- direct: (1 interaction point)
  - overall field maximum: pair creation
  - $\boldsymbol{p}_p = {}^{p_i}/_7$ (numerical)

Angular distribution - Quasiclassical picture

Quantum interaction, classical particle motion

- cascade: (2 interaction points)
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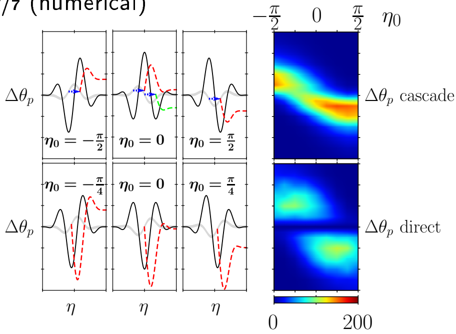


F.M. et al., to be published

Summary

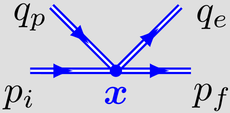
Take home

- quantification of trident pair production
- quasi-classical angular distribution
- **coherent channel has to be taken into account**
- quantum interferences in coherent channel

Summary

Take home

- quantification of trident pair production
- quasi-classical angular distribution
- **coherent channel can be taken into account**

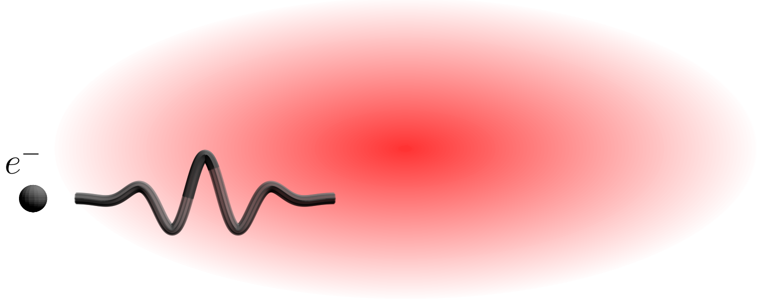


- quantum interferences in coherent channel

Thank you

Motivation

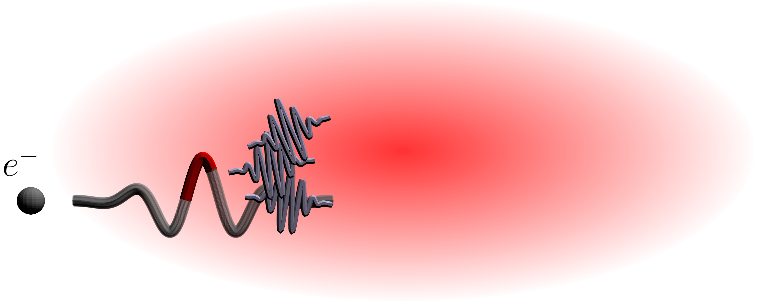
Laser-matter interactions



Electron inside a laser field

Motivation

Laser-matter interactions

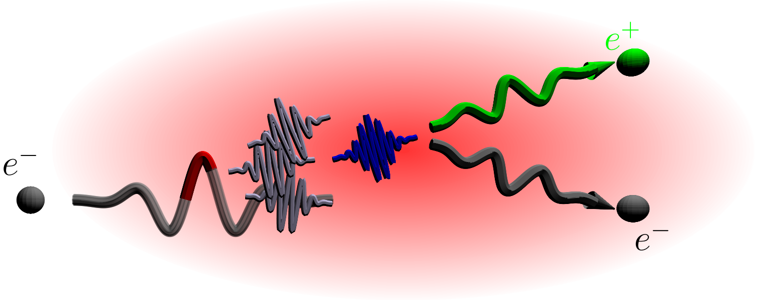


Photon emission inside a laser field

- photons emitted by electron inside laser field

Motivation

Laser-matter interactions

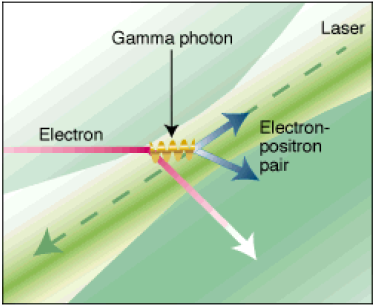


Pair production inside a laser field

- photons emitted by electron inside laser field
- e^+-e^--pair created by high-energy photon inside laser field

Motivation

Laser-matter interactions



Matter production (SLAC experiment E-144)

- photons emitted by electron inside laser field
- e^+-e^--pair created by high-energy photon inside laser field
- **provide closed analysis of matter production**

Nonlinear QED in strong laser fields

Condition for strong laser fields

$$\xi = \frac{eE}{m_e \omega_0} \gtrsim 1 \;, \; I \gtrsim 10^{18} \left[\frac{\omega}{\mathrm{eV}}\right]^2 \frac{\mathrm{W}}{\mathrm{cm}^2}$$

Quantum effects

$$\chi = \frac{(k_0 p)}{m\omega_0} \frac{E}{E_{\mathrm{cr}}} \gtrsim 1$$

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Light cone coordinate $a^\eta = (k_0 a)$ **,** $a^\mu = (a^\eta, a^\perp)$

Nonlinear QED in strong laser fields

Condition for strong laser fields

$$\xi = \frac{eE}{m_e \omega_0} \gtrsim 1 \ , \ I \gtrsim 10^{18} \left[\frac{\omega}{\text{eV}}\right]^2 \frac{\text{W}}{\text{cm}^2}$$

Quantum effects

$$\chi = \frac{(k_0 p)}{m\omega_0} \frac{E}{E_{\text{cr}}} \gtrsim 1$$

Light cone coordinate $a^\eta = (k_0 a)$, $a^\mu = (a^\eta, a^\perp)$

Volkov solution

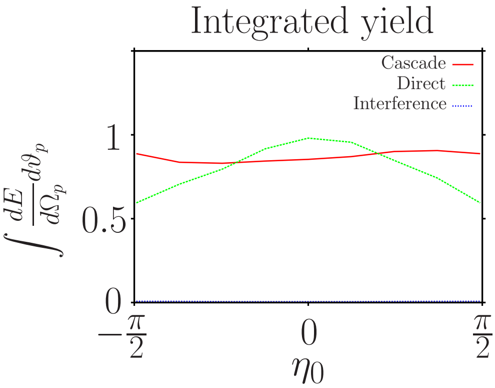
$$\Psi_p(x) = \mathbf{e}^{-iS_V(x,p)} E_p(x^\eta) \frac{u_p}{\sqrt{2\varepsilon}}$$

photon propagator

$$\mathcal{D}^{\mu\nu}(y,x) = \lim_{\epsilon \to 0} \int \frac{d^4 q}{(2\pi)^4} \frac{4\pi g^{\mu\nu}}{q^2 + i\epsilon} \mathbf{e}^{-iq(y-x)}$$

Disentangling NTPC channels

Quite **robust** with changing CEP



F.M. et al., to be published

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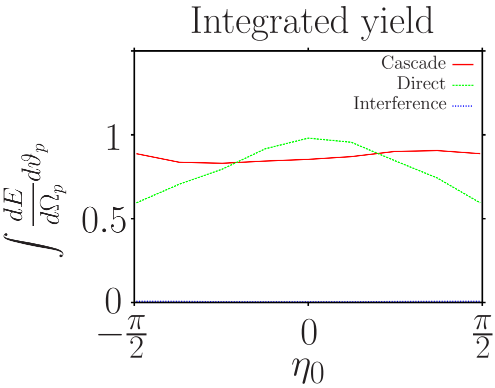


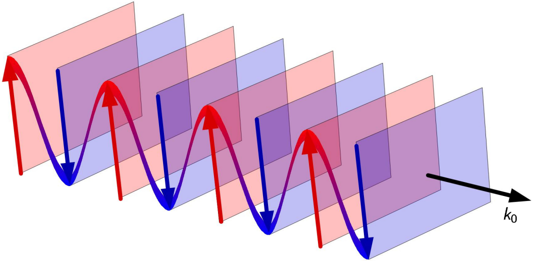
F.M. et al., to be published

Disentangling of separate pair production channels

Nonlinear QED in strong laser fields

Model laser pulse as **plane wave** (neglect focusing)

$$A(\boldsymbol{x}, t) = A(k_0 x =: x^\eta)$$



Nonlinear QED in strong laser fields

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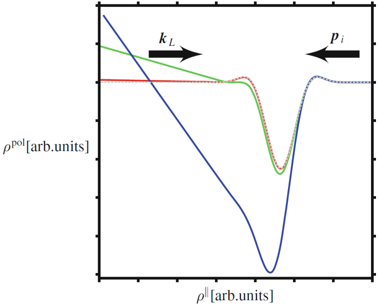
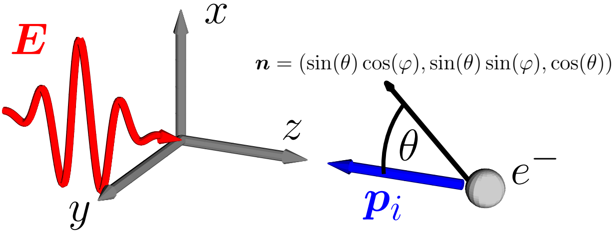


$\lambda_0 = 800$ nm
$w_0 = 2\lambda_0$ (red)
$w_0 = \lambda_0$ (red)
$w_0 = \lambda_0/2$ (blue)

Nonlinear QED in strong laser fields

Model laser pulse as **plane wave** (neglect focusing)

Scattering geometry



Light cone coordinate $a^{\eta} = (k_0 a)$, $a^{\mu} = (a^{\eta}, a^{\perp})$

Nonlinear QED in strong laser fields

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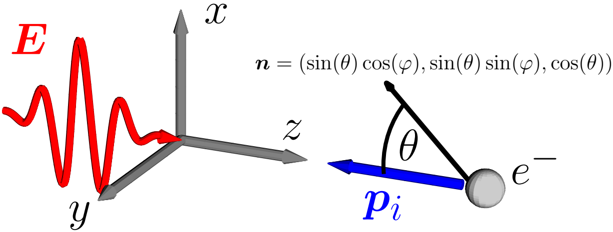


Light cone coordinate $a^\eta = (k_0 a)$, $a^\mu = (a^\eta, a^\perp)$

Volkov solution

$$\Psi_p(x) = e^{-iS_V(x,p)} E_p(x^\eta) \frac{u_p}{\sqrt{2\varepsilon}}$$

Classical action

$$p^\mu_{\text{class}}(x) = \frac{\partial}{\partial x_\mu} S_V(x, p)$$

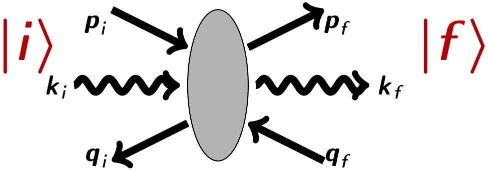
Scattering matrix elements

Initial & final states

$$|i\rangle = \prod_{\boldsymbol{k}_i} a^\dagger_{\boldsymbol{k}_i} \prod_{\boldsymbol{p}_i} c^\dagger_{\boldsymbol{p}_i} \prod_{\boldsymbol{q}_i} d^\dagger_{\boldsymbol{q}_i} |0\rangle$$

$$|f\rangle = \prod_{\boldsymbol{k}_f} a^\dagger_{\boldsymbol{k}_f} \prod_{\boldsymbol{p}_f} c^\dagger_{\boldsymbol{p}_f} \prod_{\boldsymbol{q}_f} d^\dagger_{\boldsymbol{q}_f} |0\rangle$$

Scattering matrix



Perturbative order: n vertices

Scattering matrix elements

Initial & final states

$$|i\rangle = \prod_{k_i} a^\dagger_{k_i} \prod_{p_i} c^\dagger_{p_i} \prod_{q_i} d^\dagger_{q_i} |0\rangle$$

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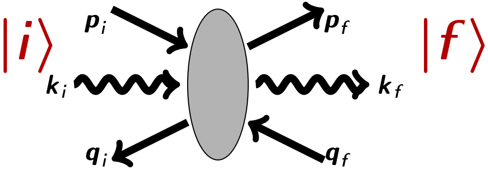
Scattering matrix



Perturbative order: n vertices - consider tree-level processes

$$S^n_{fi} = \int d^4x_1 \cdots d^4x_n \overline{\Psi}_{p_f} \gamma_{\mu_n} \Psi_{-q_f} \cdots (\mathcal{G}(x_i, x_{i-1}), \mathcal{D}^{\mu_i \mu_{i-1}}(x_i, x_{i-1})) \overline{\Psi}_{q_i} \gamma_{\mu_1} \Psi_{p_i}$$

Disentangling NTPC channels

Direct channel suppression in forward direction Stationary phase in cascade channel: small stationary phase imaginary parts

$$\psi(\eta_0) \approx -\frac{\alpha_{\mathrm{C/BW}}}{2\beta_{\mathrm{C/BW}}}$$

Direct channel:

$$\psi(\eta_0) \approx -\frac{\alpha_{\mathrm{C}} + \alpha_{\mathrm{BW}}}{2\left(\beta_{\mathrm{C}} + \beta_{\mathrm{BW}}\right)} + i\mathcal{C}$$

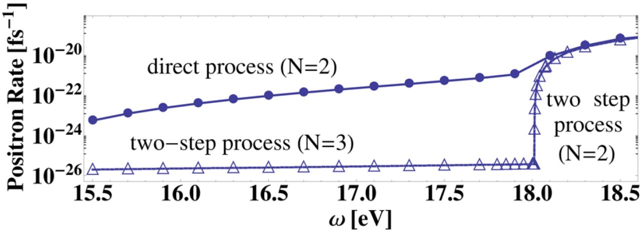
$$\mathcal{C} \approx \frac{p_i^- p_f^- p_p^- p_e^- \left(p_f^- \boldsymbol{p}_i^\perp - p_i^- \boldsymbol{p}_f^\perp - p_e^- \boldsymbol{p}_p^\perp - p_p^- \boldsymbol{p}_e^\perp\right)^2}{(m\xi)^2 \left(p_i^- p_e^- p_p^- - p_f^- p_e^- p_p^- + p_i^- p_e^- p_f^- + p_i^- p_f^- p_p^-\right)^2}$$

$$\stackrel{\boldsymbol{p}_p^\perp = 0}{\approx} \frac{p_i^- p_f^- p_p^- p_e^- \left((p_f^- - p_p^-)\boldsymbol{p}_i^\perp - (p_i^- - p_p^-)\boldsymbol{p}_f^\perp\right)^2}{(m\xi)^2 \left(p_i^- p_e^- p_p^- - p_f^- p_e^- p_p^- + p_i^- p_e^- p_f^- + p_i^- p_f^- p_p^-\right)^2}$$

$\Rightarrow \boldsymbol{p}_f^\perp \equiv 0$ favoured

Experimental evidence

E-144 experiment @ SLAC:
$\varepsilon = 46.6$ GeV e^- & $I = 10^{18}\,\frac{\mathrm{W}}{\mathrm{cm}^2}$, $\omega = 2.35$ eV, $\tau = 40$ fs laser
Laser approx. monochromatic, divergences regularised "by hand"



Hu et al., Phys. Rev. Lett. 105, 080401 (2010)