Boiling the Vacuum in Photon Laser Collisions

Laser-assisted Bremsstrahlung Photon Pair Production

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LUXE Workshop
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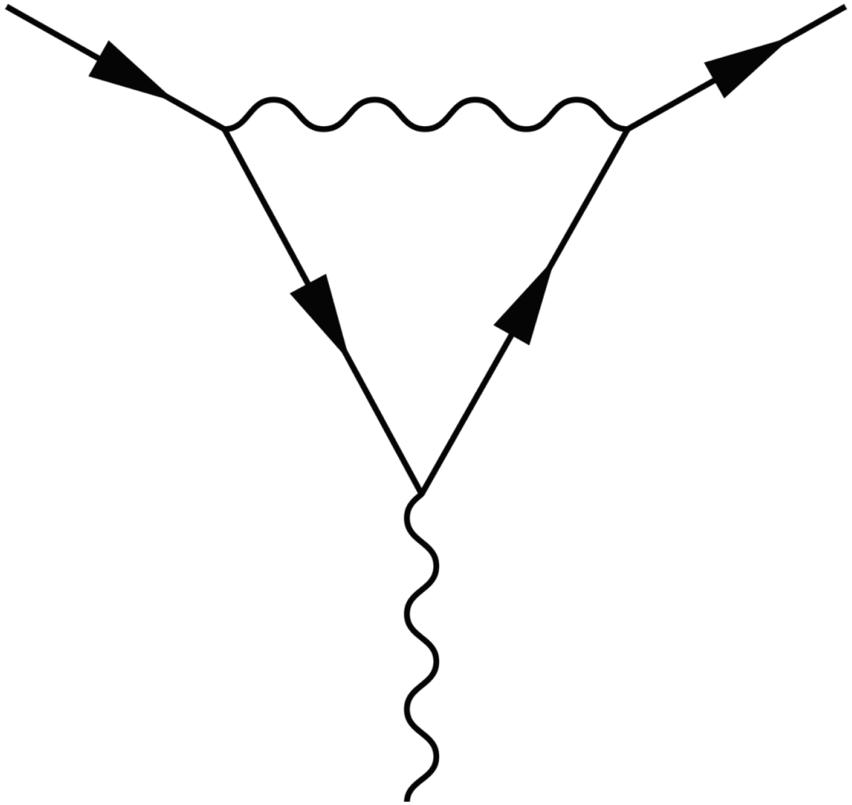
[Anthony Hartin, AR, Natalia Tapia, Phys.Rev. D99 (2019) no.3, 036008 [arXiv:1807.10670 [hep-ph]]

Motivation

QED beyond ordinary perturbation theory

- Quantum Electrodynamics (QED) is the most accurately tested theory in physics
- Its predictions, for observables accessible by ordinary perturbation theory, have been verified up to very high accuracy
  - Anomalous magnetic moment of electron



[wikipedia]

$$a_e = \frac{\alpha}{2\pi} \approx 0.001\ 161\ 4$$

[Schwinger 48]

$$\alpha \equiv e^2/4\pi$$

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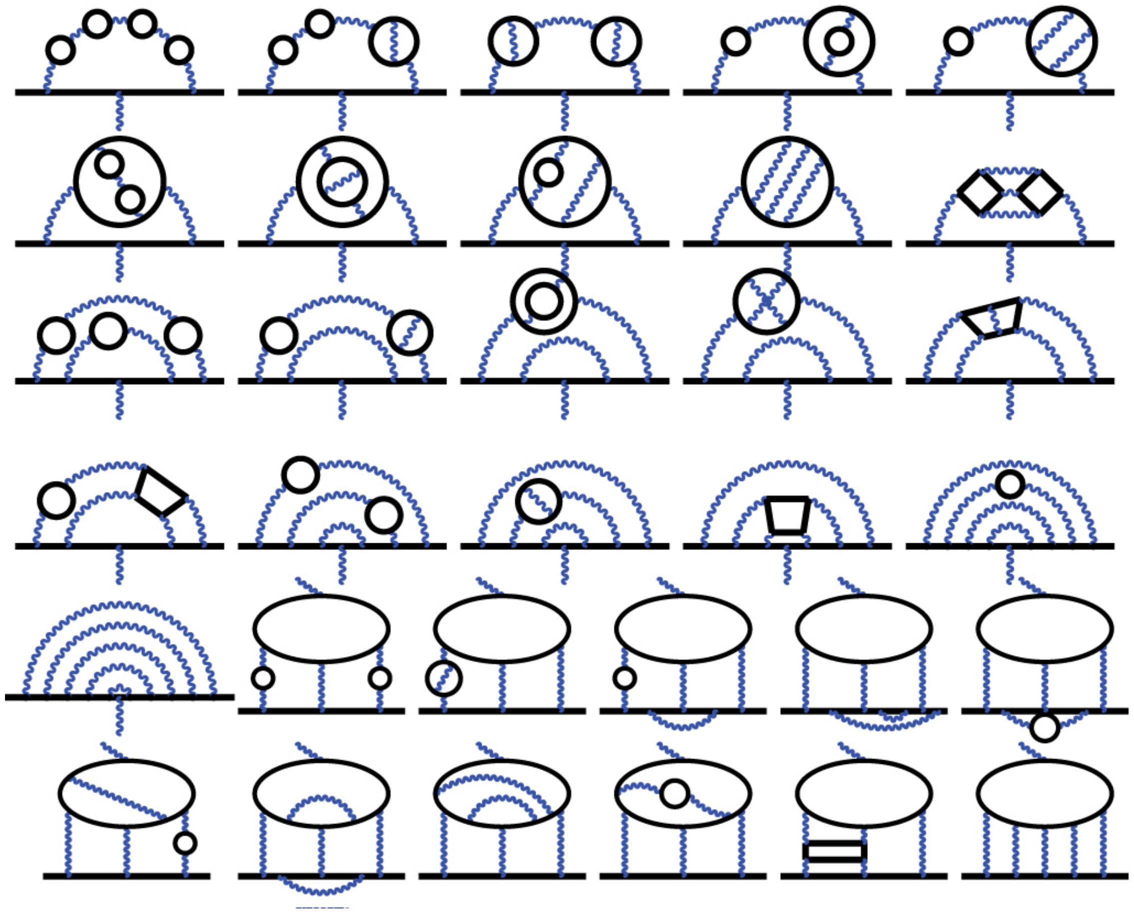
    - Anomalous magnetic moment of electron: theory (five loop) agrees with experiment to more than 10 significant digits



[phys.org 2012]

Theory: $a_e = 0.001\,159\,652\,181\,643(764)$

[Aoyama,Hayakawa,Kinoshita,Nio 12,15]

Experiment: $a_e = 0.001\,159\,652\,180\,73(28)$

[Hanneke,Fogwell Hoogerheide,Gabrielse 11]

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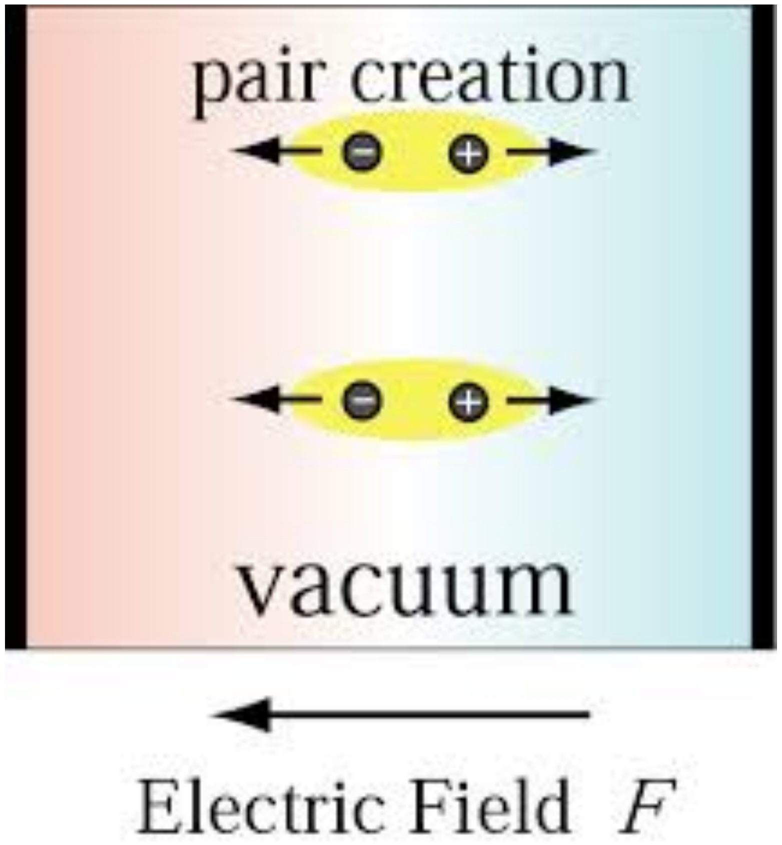
- Its predictions, for observables accessible by ordinary perturbation theory, have been verified up to very high accuracy
  - Anomalous magnetic moment of electron:
    theory (five loop) agrees with experiment to more than 10 significant digits
- There are, however, also observables which are inaccessible by ordinary perturbation theory and whose prediction lacks an experimental verification
  - Vacuum electron-positron pair production (VPP) in a strong static electric field

[Sauter 31;Euler,Heisenberg 36;Schwinger 51]



Motivation

QED beyond ordinary perturbation theory

- Rate per unit volume: [Schwinger 51]

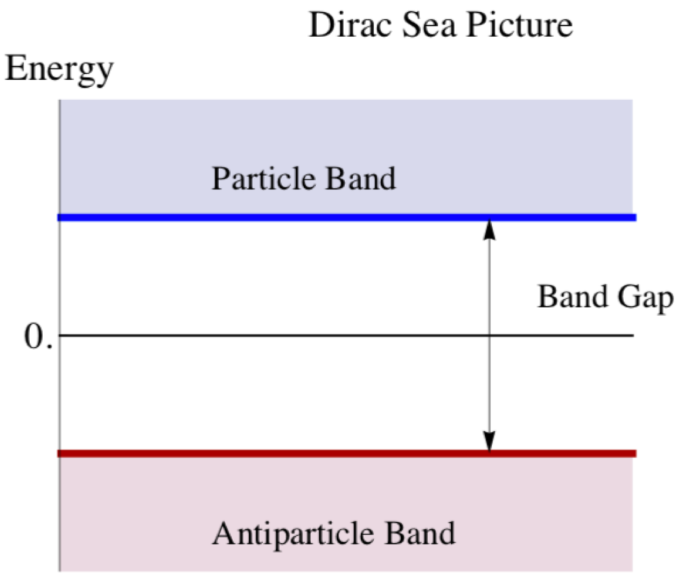
$$\frac{\Gamma_{\rm VPP}}{V} = \frac{m_e^4}{(2\pi)^3}\left(\frac{|\mathbf{E}|}{\mathrm{E_c}}\right)^2 \exp\left(-\pi\frac{\mathrm{E_c}}{|\mathbf{E}|}\right)$$

  - Schwinger critical field

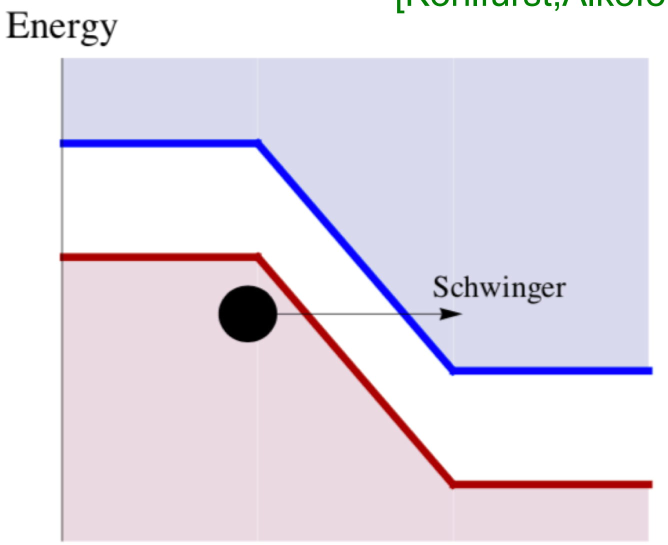
$$\mathrm{E}_c \equiv \frac{m_e^2}{e} \simeq 1.3\times 10^{18}\ \mathrm{V/m}$$

- Rate for VPP non-perturbative in QED coupling e, as typical for process which can occur, for $|\mathbf{E}| \lesssim \mathrm{E}_c$, only via quantum tunnelling:

$$\Gamma_{\rm VPP} \propto \exp\left(-\pi\frac{m_e^2}{e|\mathbf{E}|}\right)$$



[Kohlfürst,Alkofer,Gies 13]

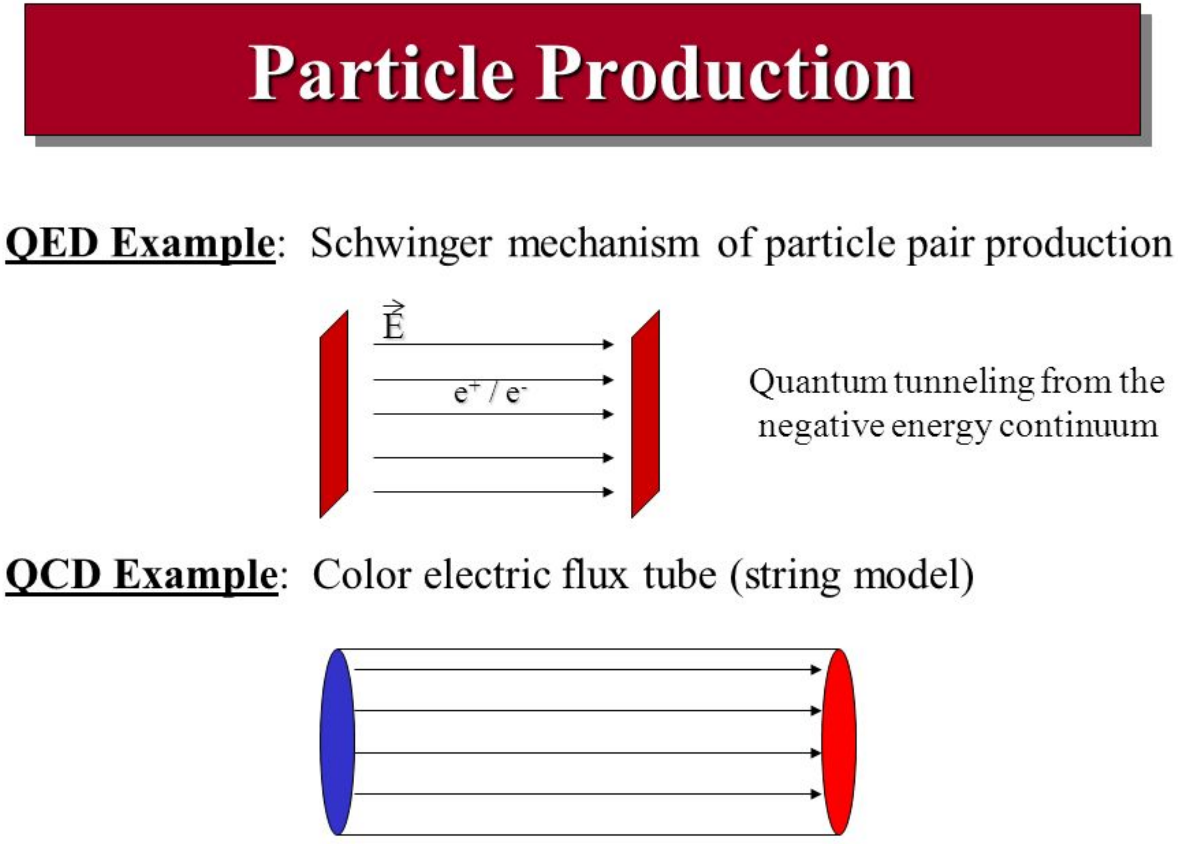


Motivation

Beyond QED

- Schwinger effect and its analogues have been suggested to play a role in many problems of phenomenological and cosmological interest:
  - Particle production in hadronic collisions

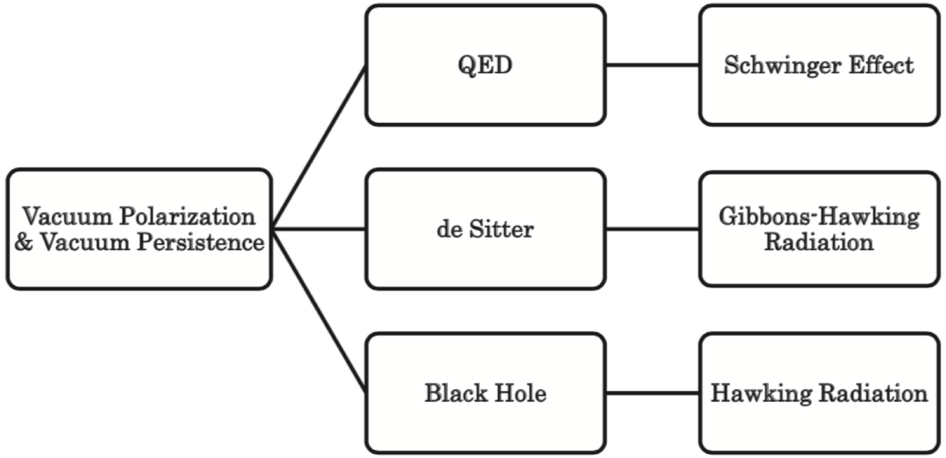
[Casher,Neuberger,Nussinov 79]



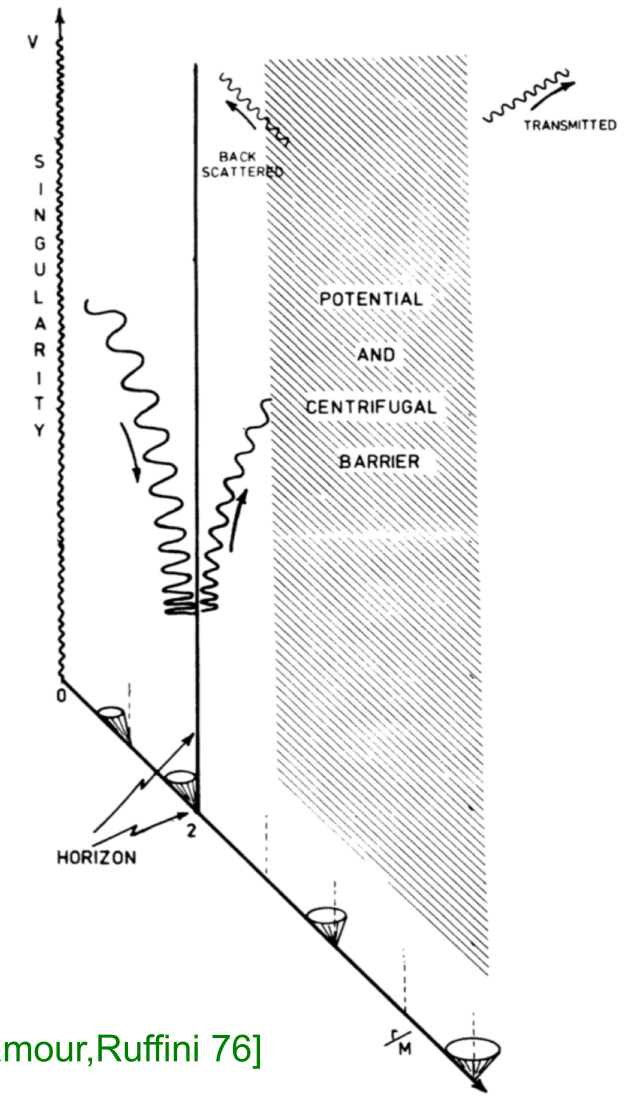
Motivation

Beyond QED

- Schwinger effect and its analogues have been suggested to play a role in many problems of phenomenological and cosmological interest:
  - Particle production in hadronic collisions [Casher,Neuberger,Nussinov 79]
  - Black hole quantum evaporation [Hawking 75]
  - Gibbons-Hawking radiation during inflation



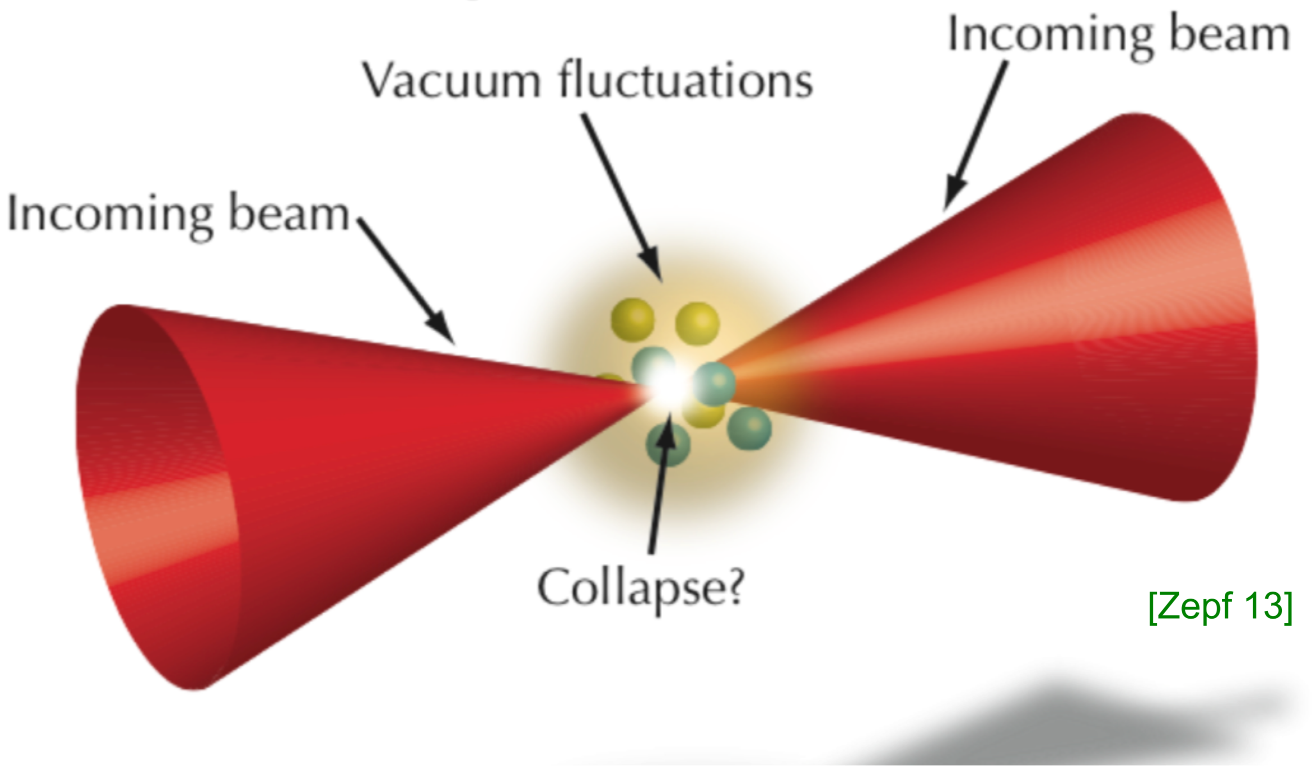
[S.P. Kim 15]



[Damour,Ruffini 76]

Laser-Assisted Vacuum Pair Production

- Direct laboratory test of prediction of VPP in strong static E field utopic
- Consider vacuum pair production at the focus of an intense laser:



[Zepf 13]

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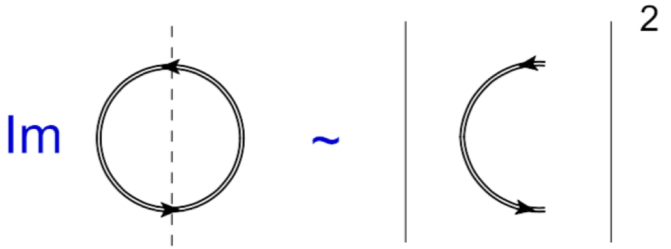
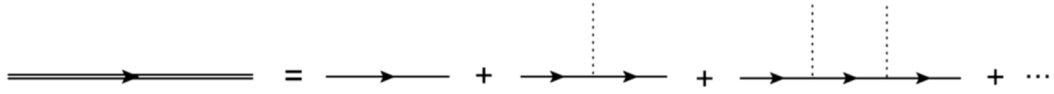


[Heinzl 11]

- Electron propagator in laser background: 

- Rate:

$$\frac{\Gamma_{\rm laVPP}}{V} = \frac{m_e^4}{(2\,\pi)^3} \begin{cases} \sqrt{2\pi}\left(\frac{\omega}{m_e}\right)^{\frac{5}{2}} \mathrm{e}^{4\frac{m_e}{\omega}} \sum_{n>2\frac{m_e}{\omega}} \mathrm{Erfi}\left(\sqrt{2\left(n-2\frac{m_e}{\omega}\right)}\right)\left(\frac{\xi}{4}\right)^{2n} & : \quad \xi \ll 1\,, \\ \frac{2\sqrt{2}}{\pi}\left(\frac{|\mathbf{E}|}{\mathrm{E_c}}\right)^{\frac{5}{2}} \exp\left[-\pi\,\frac{\mathrm{E_c}}{|\mathbf{E}|}\left(1-\frac{1}{8}\xi^{-2}+\mathcal{O}(\xi^{-4})\right)\right] & : \quad \xi \gg 1 \end{cases}$$

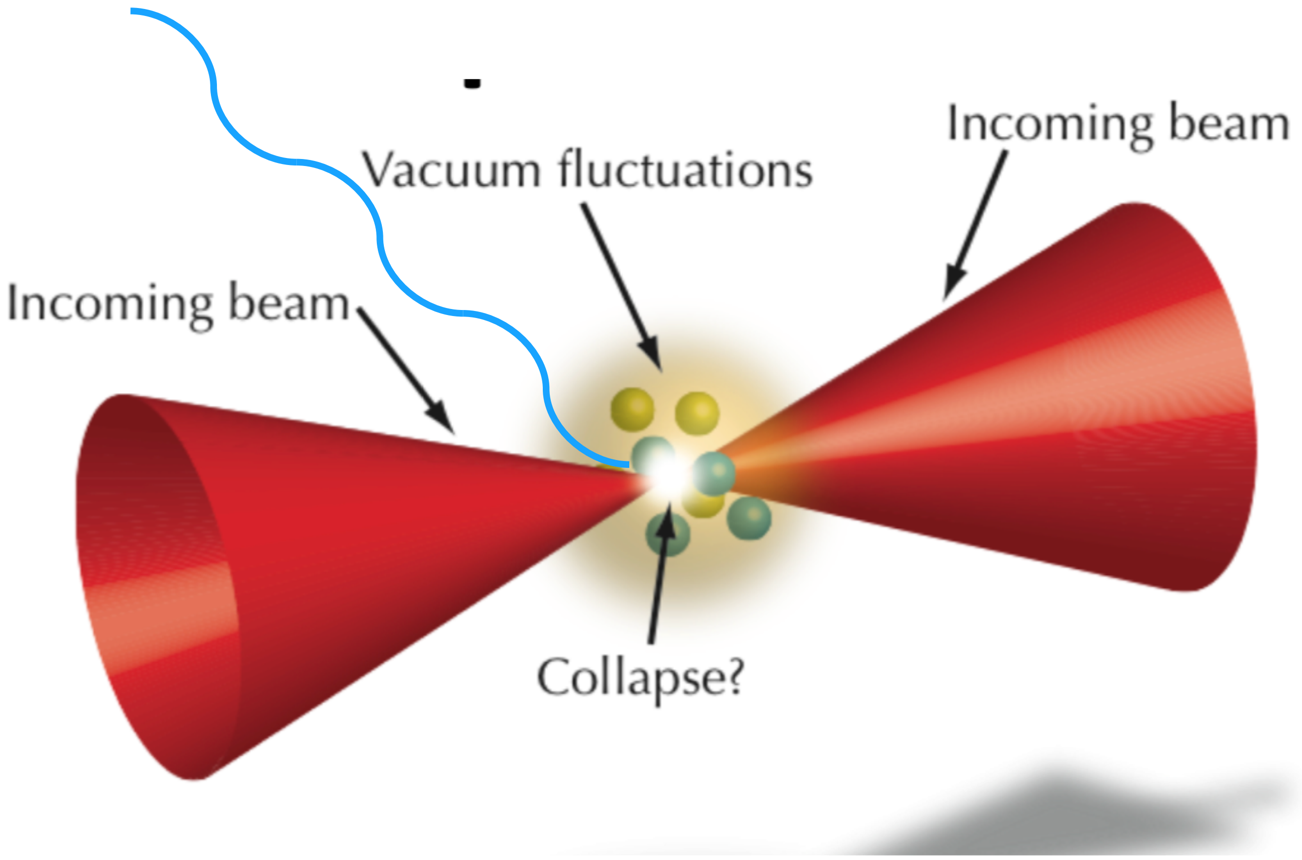
[AR 01, Popov 01]

- Laser intensity parameter: $\xi \equiv \frac{e\,|\mathbf{E}|}{\omega m_e} = \frac{m_e}{\omega}\frac{|\mathbf{E}|}{\mathrm{E}_c} \simeq 7.5\left(\frac{I}{10^{20}\,\mathrm{W/cm^2}}\right)^{1/2}\left(\frac{\mathrm{eV}}{\omega}\right)$
- Need optical laser in hundreds of exawatt range to have observable effect!
- Required power can be reduced if one superimposes the field at the focus with further weak HF field

[Schützhold,Gies,Dunne 08]

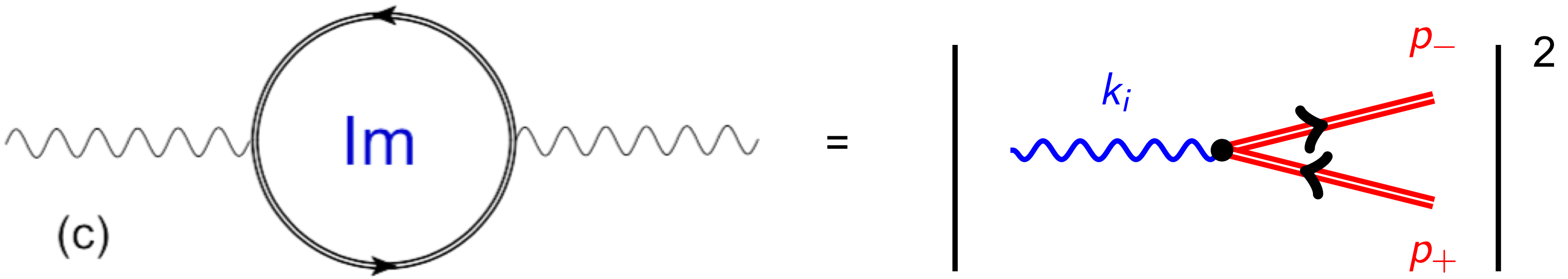
Laser-Assisted One Photon Pair Production

- Consider one photon pair production at the focus of an intense laser:



Laser-Assisted One Photon Pair Production

- Consider one photon pair production at the focus of an intense laser: [Reiss 62, Narozhnyi,Nikishov,Ritus 65]



[Heinzl 11]

- Rate: $\Gamma_{\mathrm{laOPPP}} = \dfrac{\alpha m_e^2}{4\,\omega_{\mathrm{i}}}\, F_\gamma(\xi,\chi_\gamma)$ (circular polarisation, infinite plane wave approximation)

[Narozhnyi,Nikishov,Ritus 65]

$$F_\gamma(\xi,\chi_\gamma) = \sum_{n>n_0}^{\infty} \int_1^{v_n} \frac{dv}{v\sqrt{v(v-1)}} \left[2\,J_n^2(z_v) + \xi^2(2v-1)\left(J_{n+1}^2(z_v) + J_{n\text{-}1}^2(z_v) - 2J_n^2(z_v)\right)\right]$$

$$n_0 \equiv \frac{2\xi\,(1+\xi^2)}{\chi_\gamma}, \qquad z_v \equiv \frac{4\xi^2\sqrt{1+\xi^2}}{\chi_\gamma}\left[v\,(v_n - v)\right]^{1/2}, \qquad v_n \equiv \frac{\chi_\gamma\, n}{2\xi(1+\xi^2)}$$

- Photon recoil parameter: $\chi_\gamma \equiv (1+\cos\theta)\,\dfrac{\omega_i}{m_e}\,\dfrac{|\mathbf{E}|}{\mathrm{E}_c} \simeq 0.5\,(1+\cos\theta)\left(\dfrac{\omega_i}{17.5\,\mathrm{GeV}}\right)\left(\dfrac{I}{10^{20}\mathrm{W/cm^2}}\right)^{1/2}$

Laser-Assisted One Photon Pair Production

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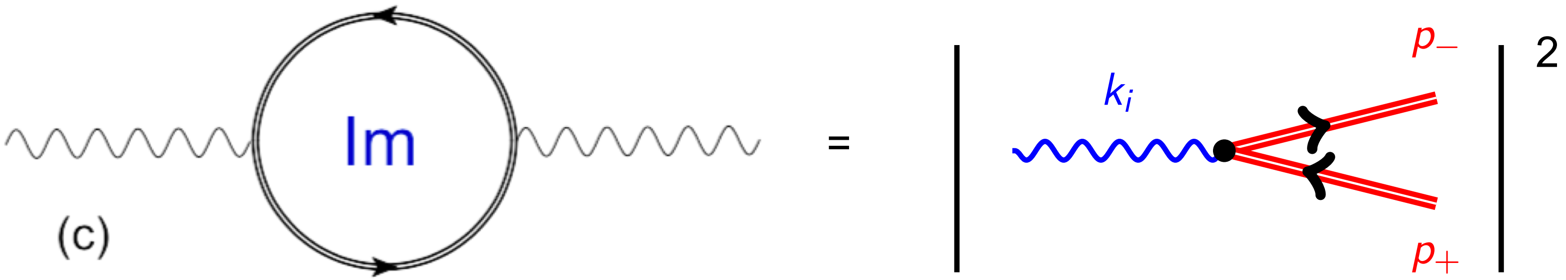

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[Ritus 85]

$$F_\gamma(\xi,\chi_\gamma) = \begin{cases} 2\,\xi^2\left[\log\left(\frac{2\chi_\gamma}{\xi}\right)-1\right] + \mathcal{O}\left(\xi^3\log\,\xi\right) & : \quad \xi \ll 1\,, \\ \frac{3}{4}\sqrt{\frac{3}{2}}\,\chi_\gamma\,\exp\left[-\frac{8}{3\chi_\gamma}\left(1-\frac{1}{15}\xi^{-2}+\mathcal{O}(\xi^{-4})\right)\right] & : \quad \xi \gtrsim 1/\sqrt{\chi_\gamma} \gg 1 \end{cases}$$

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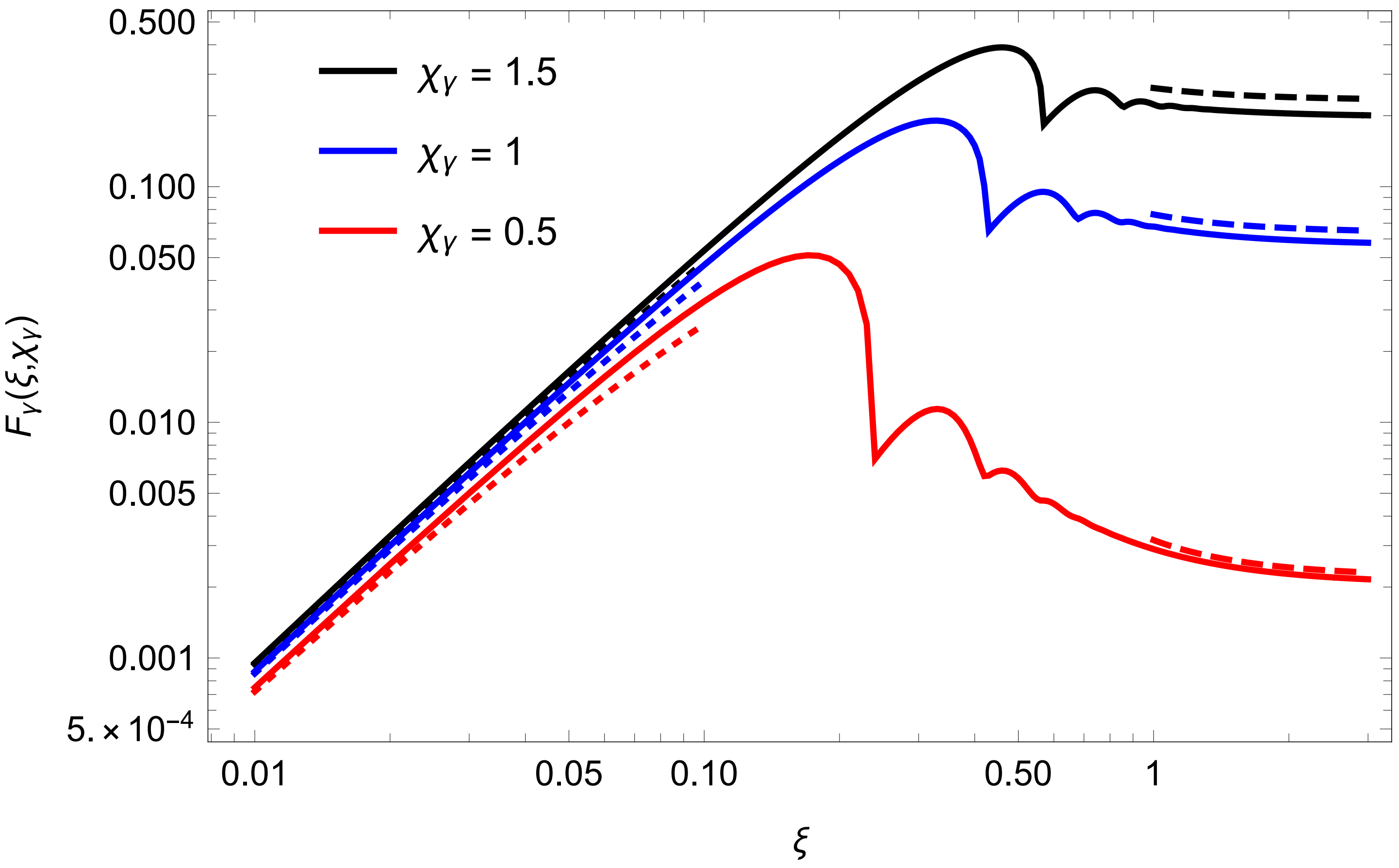
$$\Gamma_{\mathrm{laOPPP}} = \frac{\alpha m_e^2}{4\,\omega_{\mathrm{i}}}\, F_\gamma(\xi,\chi_\gamma)$$



$$F_\gamma(\xi,\chi_\gamma) = \begin{cases} 2\,\xi^2\left[\log\left(\frac{2\chi_\gamma}{\xi}\right) - 1\right] + \mathcal{O}\left(\xi^3 \log\,\xi\right) & : \quad \xi \ll 1\,, \\ \frac{3}{4}\sqrt{\frac{3}{2}}\,\chi_\gamma\ \exp\left[-\frac{8}{3\chi_\gamma}\left(1 - \frac{1}{15}\xi^{-2} + \mathcal{O}(\xi^{-4})\right)\right] & : \quad \xi \gtrsim 1/\sqrt{\chi_\gamma} \gg 1 \end{cases}$$

Laser-Assisted One Photon Pair Production

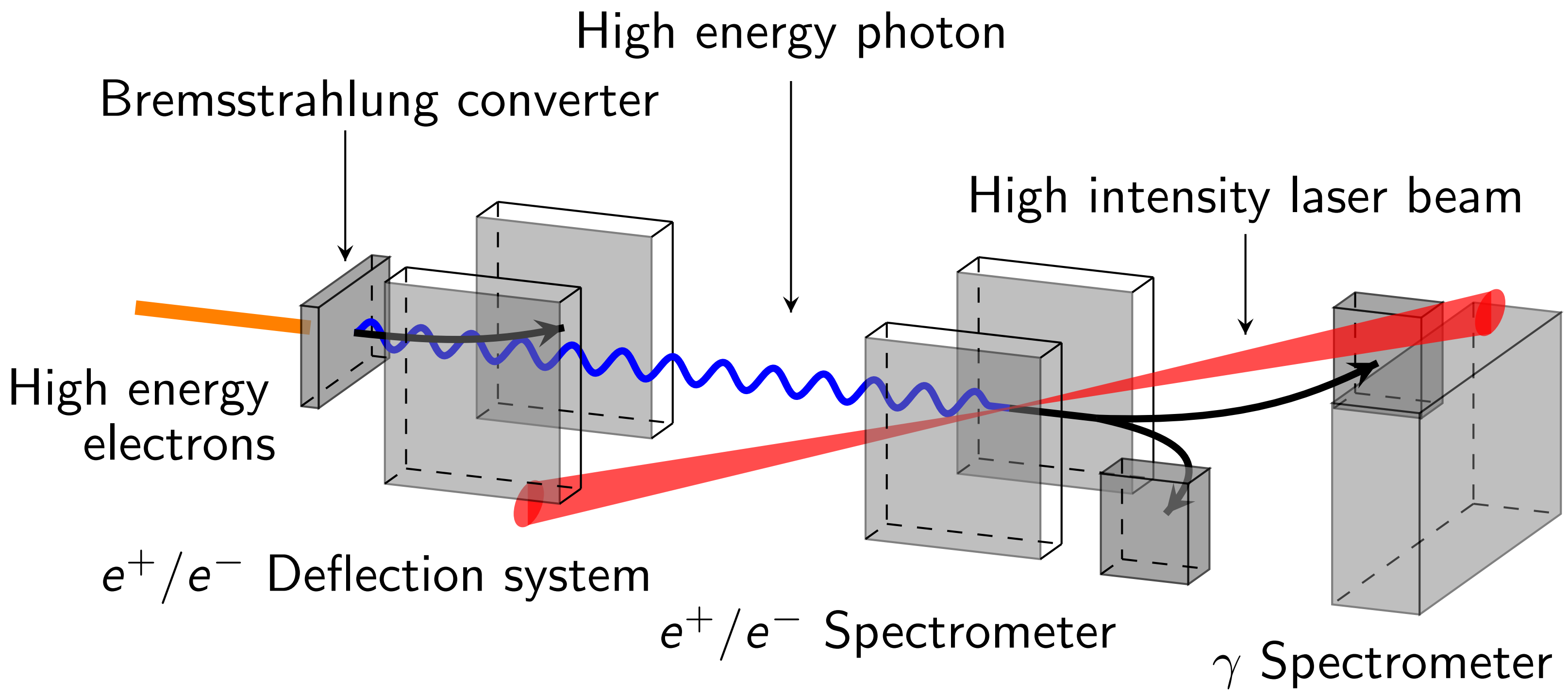
- At $\xi \gtrsim 1/\sqrt{\chi_\gamma} \gg 1$, rate asymptotes to

$$\Gamma_{\rm laOPPP} \to \frac{3}{16}\sqrt{\frac{3}{2}}\,\alpha\, m_e\,(1+\cos\theta)\;\;\frac{|\mathbf{E}|}{\mathrm{E}_c}\exp\left[-\frac{8}{3}\frac{1}{1+\cos\theta}\frac{m_e}{\omega_i}\frac{\mathrm{E}_c}{|\mathbf{E}|}\right]$$

  - Ressembles rate of VPP in constant electric field
  - In fact, $\xi \gg 1$ corresponds to quasi-static electric field, $\omega \ll e\,|\mathbf{E}|\,/m_e$
  - Rate enhanced tremendously in OPPP in comparison to VPP due to boost factor $\omega_i/m_e \gg 1$

Laser-Assisted Bremsstrahlung Photon Pair Production

- Experimental set up to measure laser assisted one photon pair production: [Reiss 71,Keitel et al.. 10,Turcu et al. 16]



[Hartin,AR,Tapia 1807.10670]

Laser-Assisted Bremsstrahlung Photon Pair Production

- Rate:

$$\Gamma_{\rm laBPPP} = \frac{\alpha\, m_e^2}{4} \int_0^{E_e} \frac{{\rm d}\omega_i}{\omega_{\rm i}} \frac{{\rm d}N_\gamma}{{\rm d}\omega_i} F_\gamma(\xi, \chi_\gamma(\omega_i))$$

- For a thin target, $X \ll X_0$, and high laser intensity, $\xi \gtrsim 1/\sqrt{\chi_e} \gg 1$, with $\chi_e \equiv (1+\cos\theta)\omega E_e \xi/m_e^2$:

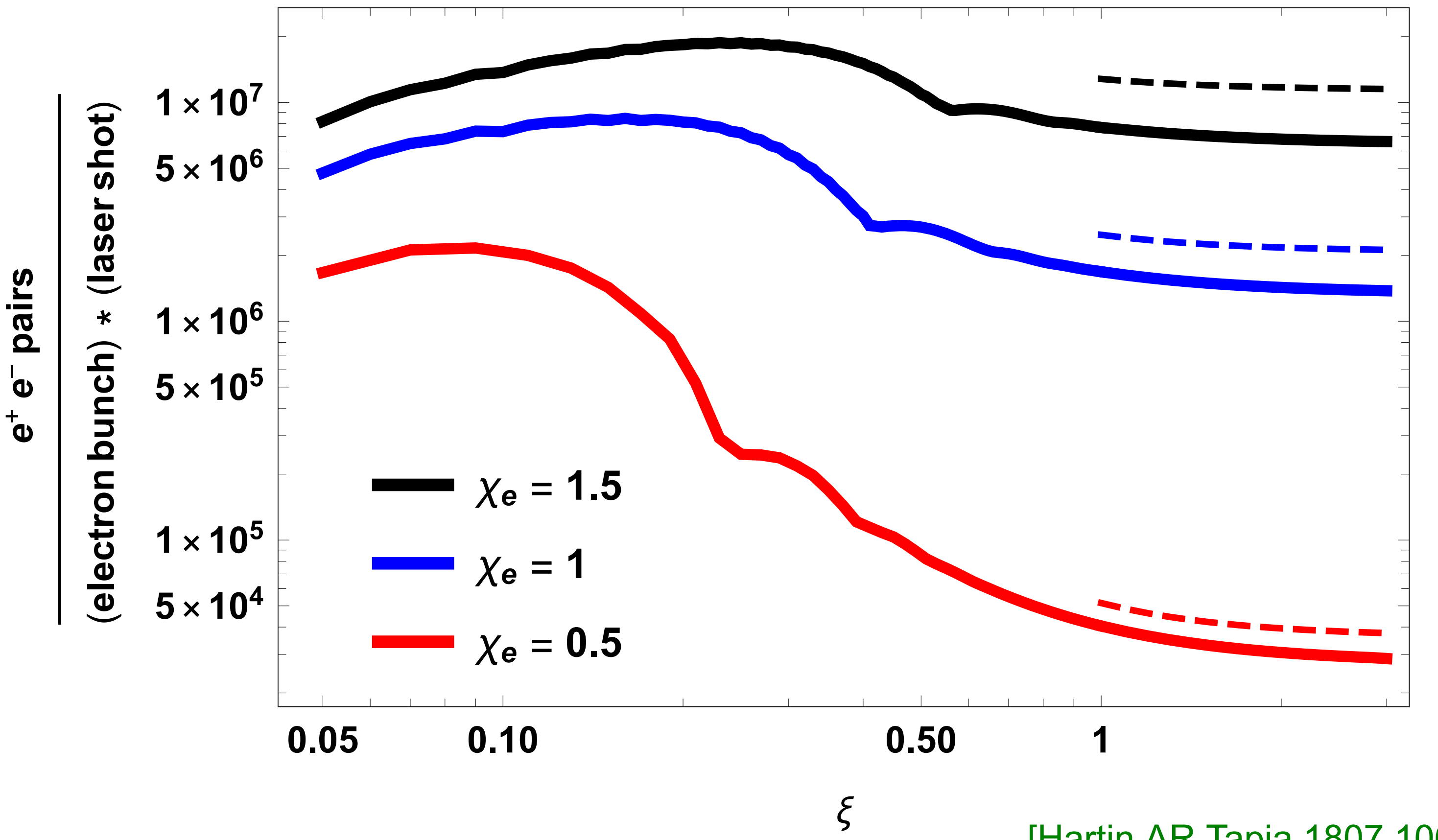
$$\Gamma_{\rm laBPPP} \to \frac{\alpha\, m_e^2}{E_e} \frac{9}{128} \sqrt{\frac{3}{2}}\, \chi_e^2\, e^{-\frac{8}{3\chi_e}\left(1-\frac{1}{15\xi^2}\right)} \frac{X}{X_0}$$

[Hartin,AR,Tapia 1807.10670]

$$\to \frac{9}{128}\sqrt{\frac{3}{2}}\, \alpha\, E_e\, (1+\cos\theta)^2 \left(\frac{|\mathbf{E}|}{{\rm E}_c}\right)^2 \exp\left[-\frac{8}{3}\frac{1}{1+\cos\theta}\frac{m_e}{E_e}\frac{{\rm E}_c}{|\mathbf{E}|}\right] \frac{X}{X_0}$$

Laser-Assisted Bremsstrahlung Photon Pair Production

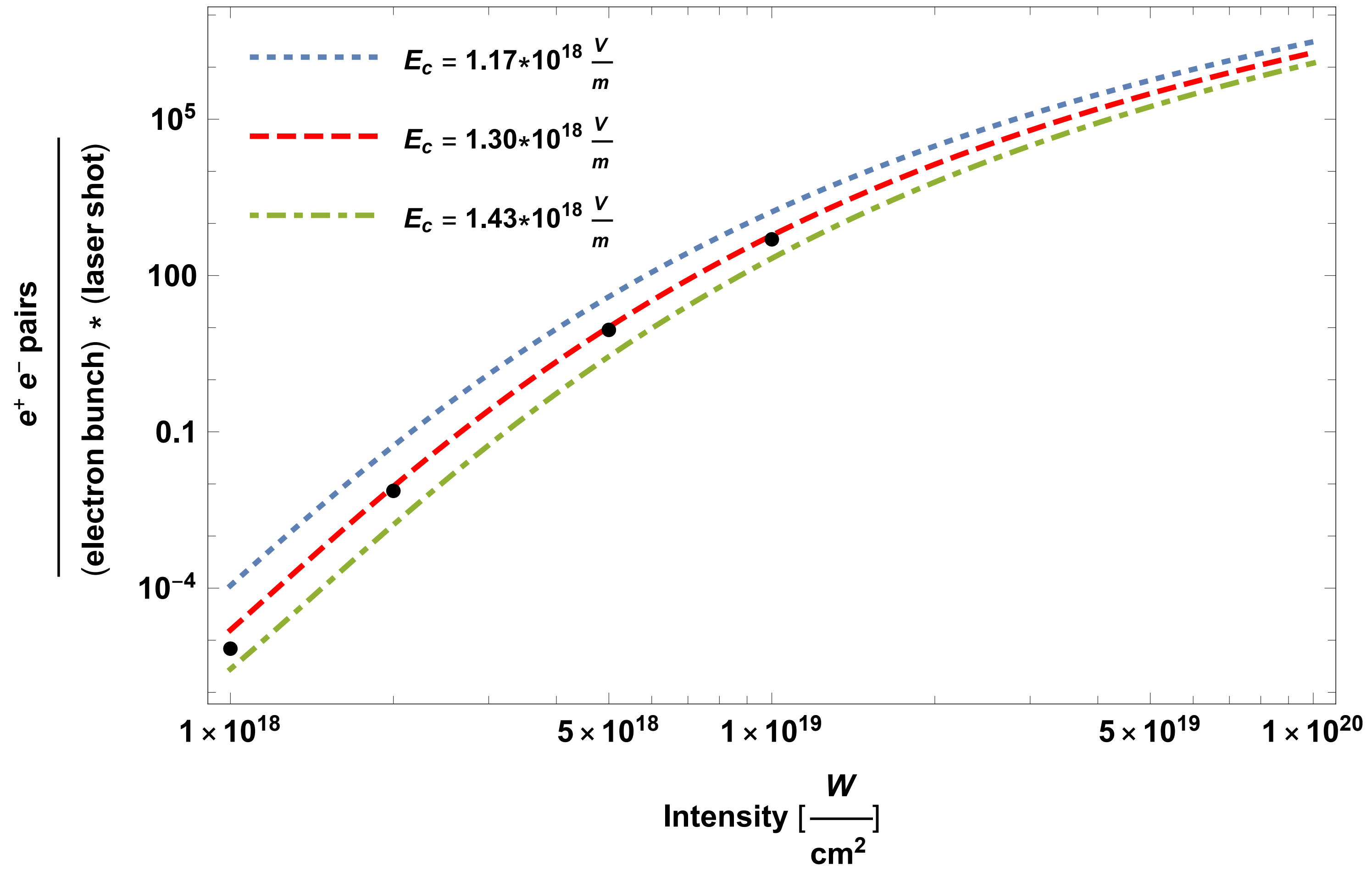
E_e=17.5 GeV, e^- bunch = $6*10^9$, $\frac{X}{X_0}$ = 0.01, Laser shot= 35 fs



[Hartin,AR,Tapia 1807.10670]

Laser-Assisted Bremsstrahlung Photon Pair Production

E_e=17.5 GeV, e^- b.=$6*10^9$, $\frac{X}{X_0}$=0.01, L. s.=35 fs, $\theta = \frac{\pi}{12}$, w=1.053 eV



Summary and Outlook

- Measurement of laser-assisted bremsstrahlung photon pair production exploiting primary electron beam from European XFEL and optical laser with intensity above about $10^{19}\,\mathrm{W/cm^2}$ range allows test of QED in the non-perturbative tunneling regime (sub-Schwinger electric fields involved)
- Ongoing:
  - GEANT model of converter target (cf. Sasha´s talk)
  - Strong field QED particle-in-cell simulation (cf. Tony´s talk)
  - Study effects of finite pulse length

BackUp: Infinite plane wave approximation

- The infinite plane wave approximation (IPWA) which we have exploited in order to determine the OPPP transition rate neglects the finite length and shape of the laser pulse.
- If the pulse length is not too short in comparison to the laser wavelength, the slowly varying envelope approximation (SVEA) can be employed. This requires the assumption that the pulse envelope does not change much over the course of one wavelength of the laser field. For LUXE, an 800 nm laser with a 35 fs pulse length is envisaged. This gives around N=12 periods within the pulse, meaning that the SVEA may be a reasonable assumption.
- In [Nousch:2012xe,Titov:2012rd,Titov:2013kya,Titov:2015pre] it was shown that the IPWA is a very good assumption if the pulse length is above N=10