Strong-field pair production:

An introduction with applications to two-color laser fields

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Outline

- Introduction:

  From quantum mechanics to QED

  From “ordinary” QED to strong-field QED

- e^+e^- pair creation in strong laser fields:

  The three “standard” mechanisms

  Theoretical description and experimental observations

  Recent developments: More complex field configurations

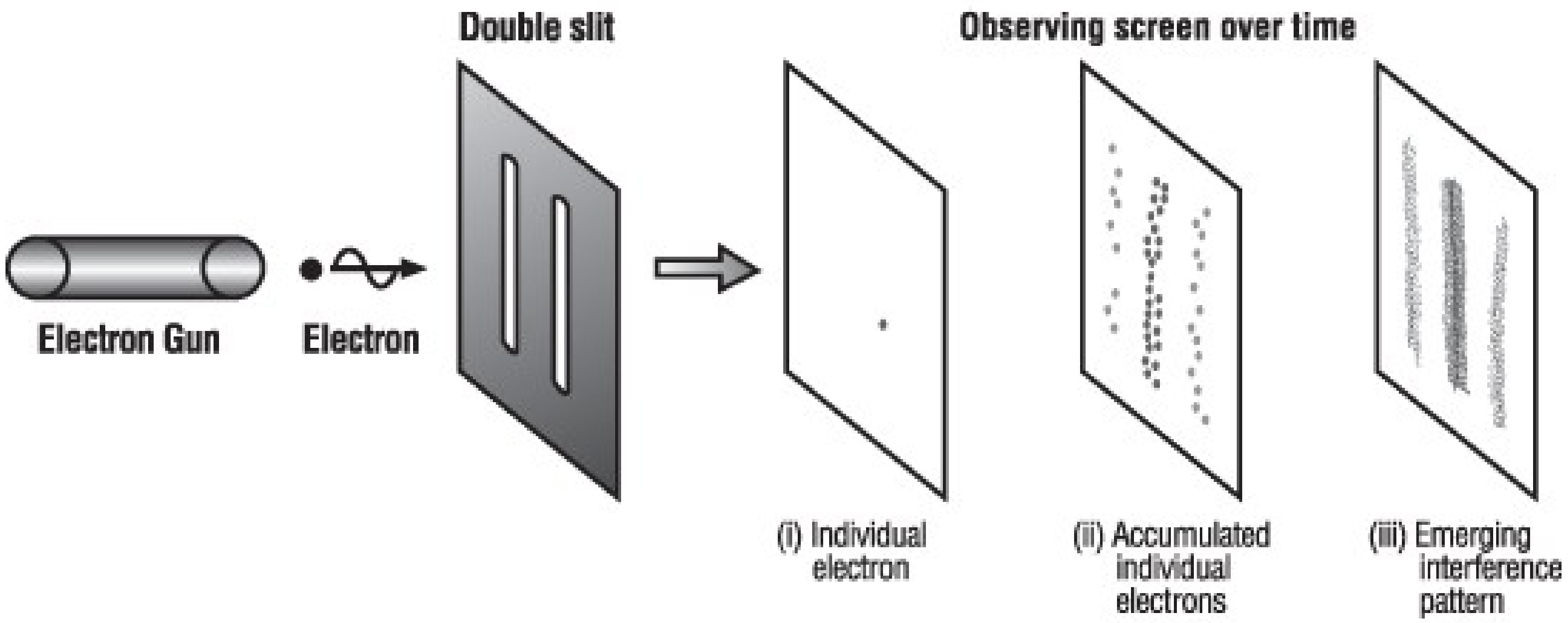
- e^+e^- pair creation in two-color laser fields:

  Further variants and getting back to where we started

Introduction part I:

From quantum mechanics to QED

The double-slit experiment with electrons



Double-slit apparatus showing the pattern of electron hits on the observing screen building up over time.

$$W = |A_1 + A_2|^2$$

Wave-particle duality

2-pathway interference

Davisson & Germer (1927)

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We used to think that if we knew one, we knew two, because one and one are two. We are finding that we must learn a great deal more about 'and'.

(Sir Arthur Eddington)

Development of quantum theory in the 1920s

Schrödinger equation (1926)

$$i\hbar\frac{\partial\Psi}{\partial t} = \frac{1}{2m}\left(\hat{\vec{p}} - \frac{e}{c}\vec{A}\right)^2\Psi$$

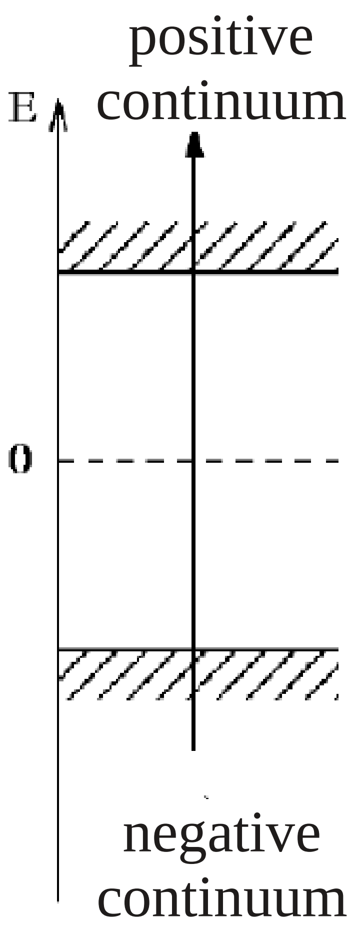
→ Hydrogen atom

Quantized radiation field (1927):
→ absorption & emission of **photons**

$$\hat{\mathbf{A}}_\gamma(\mathbf{r},t) = \sum_{\mathbf{k},\rho}\sqrt{\frac{2\pi c^2}{V\omega_k}}\,\mathbf{e}_{\mathbf{k},\rho}\left(c^+_{\mathbf{k},\rho}\,e^{i(\omega_k t-\mathbf{k}\cdot\mathbf{r})} + \text{C.C.}\right)$$

Relativistic generalization:
Dirac equation (1928) → antimatter

$$\left(ic\gamma^\mu\partial_\mu - e\gamma^\mu A_\mu - mc^2\right)\Psi = 0$$



Development of QED in the 1940s

Tomonaga, Schwinger, Feynman, Dyson (1948/49):

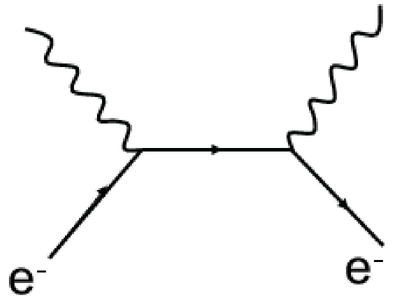
- Second-quantize fermion field to describe creation/annihilation of e$^+$ and e$^-$
- Introduce propagators (2-point correlation functions of field operators):

$$\left[\gamma^\mu \left(i\hbar\partial'_\mu - \frac{e}{c} A_\mu(x')\right) - mc\right] \underbrace{\mathcal{G}(x';x)}_{4\times 4-\text{Matrix}} = \hbar\, \delta^4(x'-x)\cdot \mathbb{1}$$

Evolution of fermion state:

$$\Psi_i^{(+)}(x') = \Phi_i(x') + \frac{e}{\hbar c}\int d^4x\ \mathcal{G}_0(x'-x)\ \left(\gamma A(x)\right)\ \Psi_i^{(+)}(x)$$

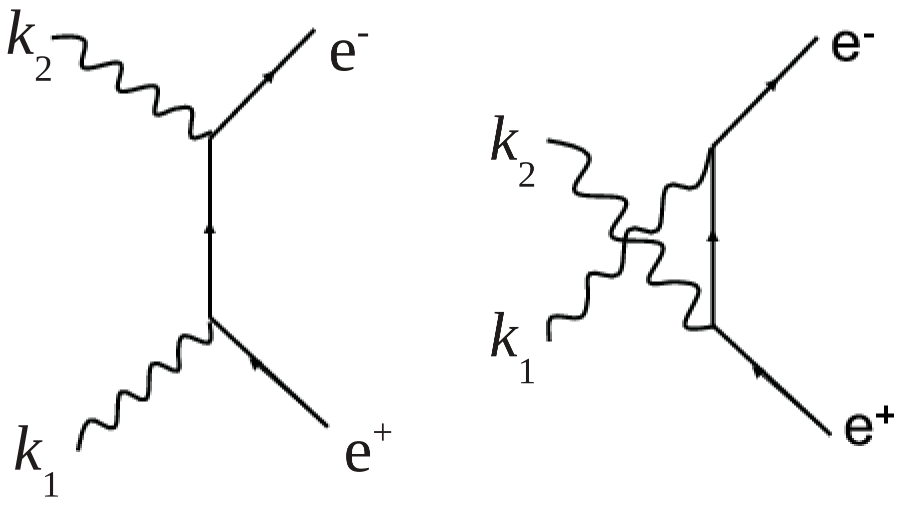
Photon-electron scattering:



Example: e^+e^- pair creation from photons

[Breit & Wheeler (1934)]

$$(k_1+k_2)^2 \geq (2mc)^2$$



NOTE that single photon cannot create pairs

Transition amplitude in momentum space

$$S_{fi} = -i\left(\frac{e}{\hbar c}\right)^2 \frac{2\pi\hbar c^2}{V\sqrt{\omega_1\omega_2}}\,\overline{u^{(+)}}(\vec{p}_-,s_-)\left\{(\gamma\varepsilon_2)\,\mathcal{G}_0(p_- - \hbar k_2)\,(\gamma\varepsilon_1)\right.$$
$$\left.+(\gamma\varepsilon_1)\,\mathcal{G}_0(p_- - \hbar k_1)\,(\gamma\varepsilon_2)\right\}u^{(-)}(-\vec{p}_+,-s_+)$$
$$\times(2\pi\hbar)^4\delta^{(4)}(p_- + p_+ - \hbar k_1 - \hbar k_2)$$

Introduction part II:

From QED to strong-field QED

Development of strong-field QED in the 1960s

Maiman (1960): “Stimulated optical radiation in ruby”

Franken et al. (1961): First observation of 2nd harmonic
“...exploiting extraordinary ruby laser intensities of 10^6 W/cm^2 “

Intriguing question for theory:

How to generalize newly established QED to electron-laser interactions?

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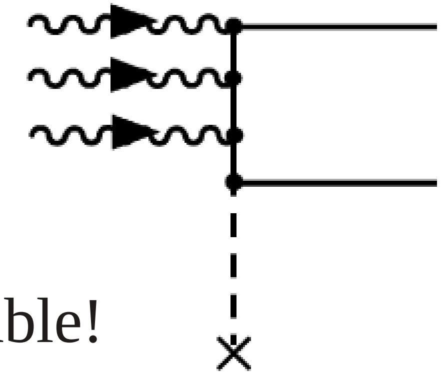
In principle, one can calculate in ordinary QED processes with N>1 photons, but becomes tedious very quickly...



Besides, perturbative expansion not always applicable!

Furry picture (1951)

$$\left[\mathrm{i}c\gamma^\mu \partial_\mu - e\gamma^\mu \left(A_\mu + A_\mu^{(\mathrm{ext})} \right) - mc^2 \right] \Psi = 0$$

Ordinary QED: Let free states interact with $A_\mu + A_\mu^{(\mathrm{ext})}$

Furry picture (1951)

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Ordinary QED: Let <u>free</u> states interact with $A_\mu + A_\mu^{(\mathrm{ext})}$

Alternatively, IF you can solve

$$\left(\mathrm{i}c\gamma^\mu \partial_\mu - e\gamma^\mu A_\mu^{(\mathrm{ext})} - mc^2 \right) \Psi = 0$$

you may use these solutions as basis states which interact with A_μ only!

→ Strong-field QED

(also applied in “bound-state QED” to calculate, e.g., Lamb shift in high-*Z* ions)

Strong-field QED in laser physics

Dirac equation: $$\left(\mathrm{i}c\gamma^\mu\partial_\mu - e\gamma^\mu A^{(\mathrm{ext})}_\mu - mc^2\right)\Psi = 0$$

classical plane wave

relative coupling strength $\xi = eA^{(\mathrm{ext})}/mc^2$

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Volkov solutions (1935):

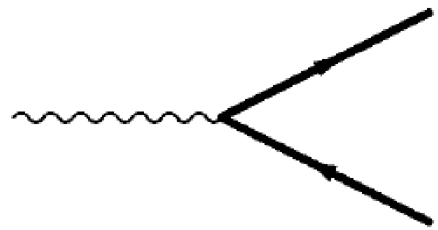
$$\Psi_{p,s}(x) = \left(1 - \frac{e \not{k} \not{A}}{2c(kp)} \right) u_{p,s} \, \mathrm{e}^{-\mathrm{i}(px)} \mathrm{e}^{\mathrm{i}f(x)}$$

free solution

$$f(x) = \frac{e}{c(kp)} \int^{(kx)} \left[p \cdot A(\eta) + \frac{e}{2c} A^2(\eta) \right] d\eta$$

How to formulate your transition amplitude

Example: Strong-field Breit-Wheeler process
(pair production by γ-photon + laser wave)



$$S_{fi} = -\frac{ie}{\hbar}\int d^4x\,\overline{\Psi}_{p_-,s_-}(\gamma^\mu A_\mu)\Psi_{p_+,s_+}$$

Volkov electron | **Quantized γ-photon** | **Volkov positron**

Produce pair in photon-multiphoton collision: $(k_\gamma + \mathrm{n}k_L)^2 \geq (2m_*c)^2$

Reiss (1962); Nikishov & Ritus (1964)

Why laser field not quantized?

Volkov states can also be formulated for a quantized laser field.

However, one can show that in the limit of

- **large** initial laser **photon numbers**

and

- **small depletion** of the laser wave

quantum and classical descriptions coincide ($\rightarrow$ **external-field approx.**)

Note that 800 nm laser pulse of 1 J energy contains ~ 10^{20} photons

Bergou & Varro, JPA (1980) + (1981)

e^+e^- pair creation in strong laser fields

Typical energy scales in laser physics

Photon energy	Electric work	Ponderomotive energy
$\hbar\omega$	$eE\Delta r$	$U_p = e^2E^2/4m\omega^2$

Efficient coupling of a laser field with a quantized system is possible when its level spacing $\Delta\varepsilon$ compares with one of these scales:

$\Delta\varepsilon \sim \hbar\omega$	Resonant (multiphoton) transition
$\Delta\varepsilon \sim eE\Delta r$	Quasistatic tunneling process
$\Delta\varepsilon \sim U_p$	Fast electron-induced reaction

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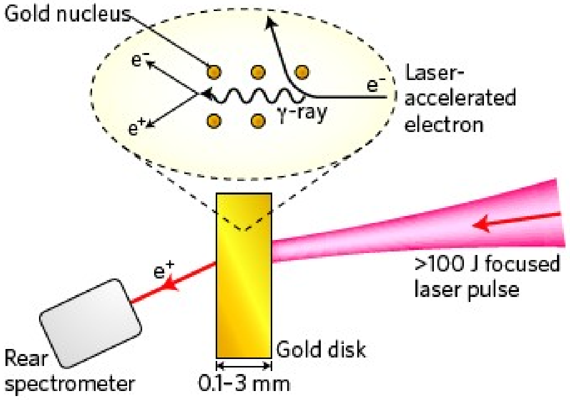
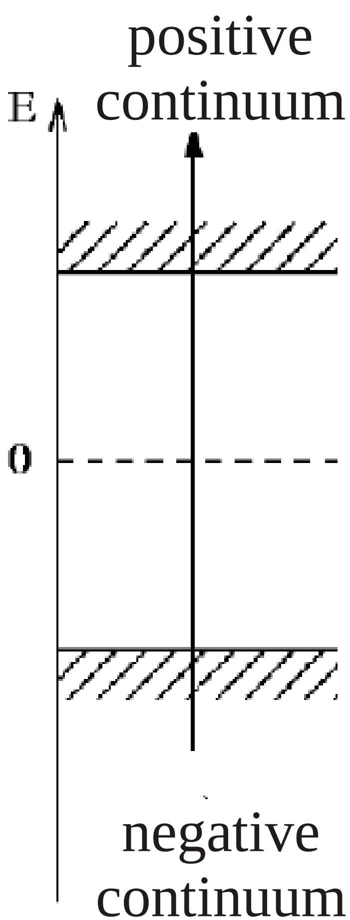
Pair creation experiments by powerful laser-solid interaction (Gahn/Chen/Sarri) where $\Delta\varepsilon \sim 1$ MeV have relied on U_p of secondary electrons



Direct laser-induced e^+e^- pair creation from vacuum?



Pair creation requires

$\hbar\omega \approx mc^2 \sim 1$ MeV

or

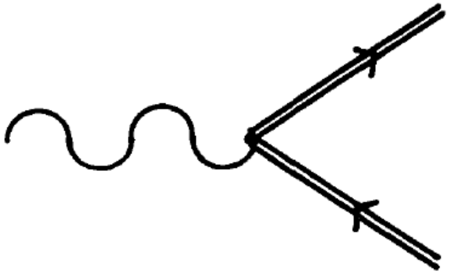
$E \approx E_{cr} = mc^2/e\lambda_C \approx 10^{16}$ V/cm

A single (plane) laser wave

does not polarize the vacuum

since $E^2 - B^2 = \mathbf{EB} = 0$

(J. Schwinger, 1951)



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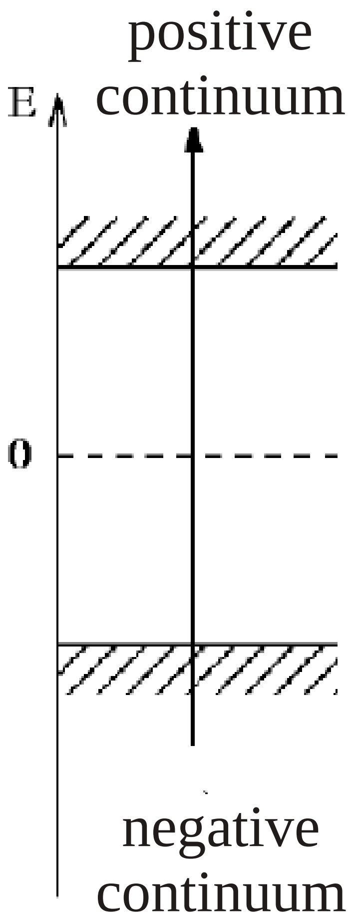

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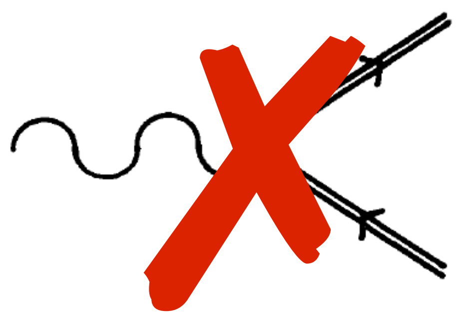


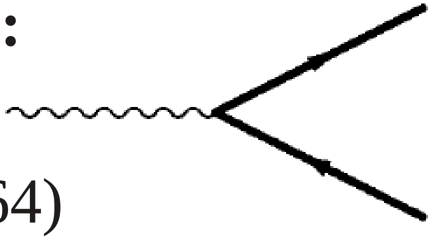
Early theoretical investigations:

The three "standard" mechanisms

Pair creation by high-energy photon + laser field:

Reiss, J. Math. Phys. 3, 59 (1962)

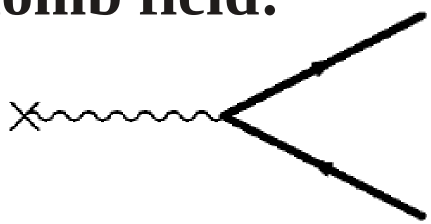
Nikishov & Ritus, Zh. Eksp. Teor. Fiz. 46, 776 (1964)



Pair creation in combined laser and nuclear Coulomb field:

Yakovlev, Zh. Eksp. Teor. Fiz. 49, 318 (1965)

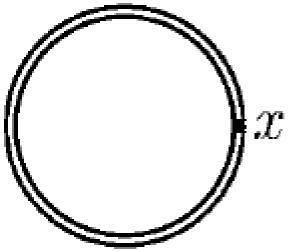
Mittleman, Phys. Rev. A 35, 4624 (1987)



Pair creation in a standing laser wave:

Brezin & Itzykson, Phys. Rev. D 2, 1191 (1970)

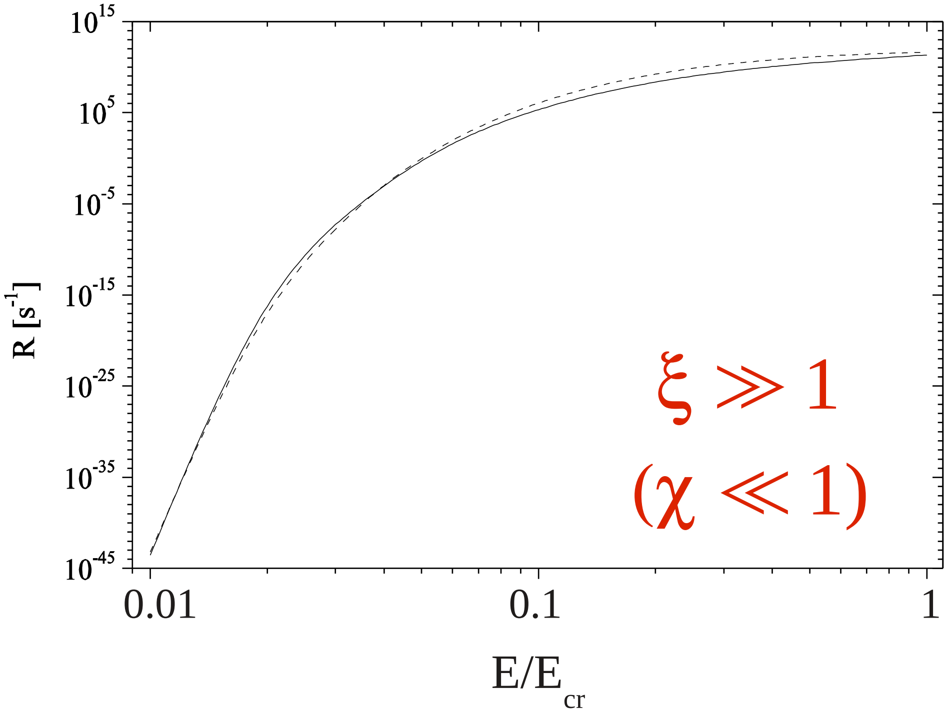
Popov, Pis'ma Zh. Eksp. Teor. Fiz. 13, 261 (1971)



Tunneling and multiphoton pair creation

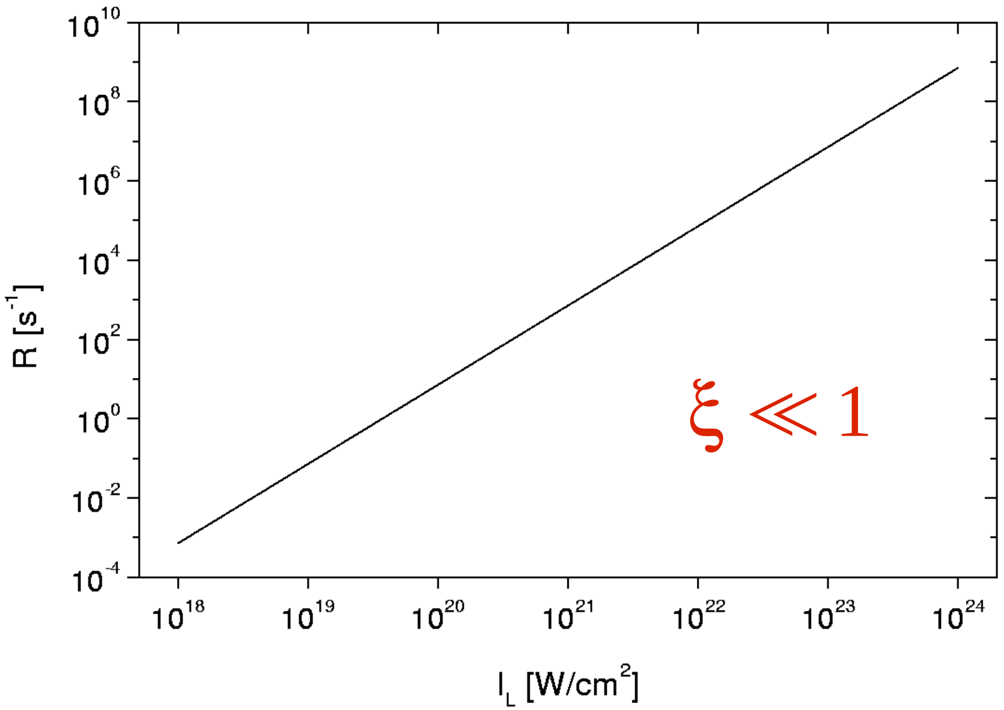
inverse Keldysh parameter for pair creation: $\xi = eA / mc^2$

Tunneling rate: $R \sim \exp(-E_{cr}/E)$



Nonperturbative tunneling regime

n-photon rate: $R \sim \xi^{2n} \sim I^n$

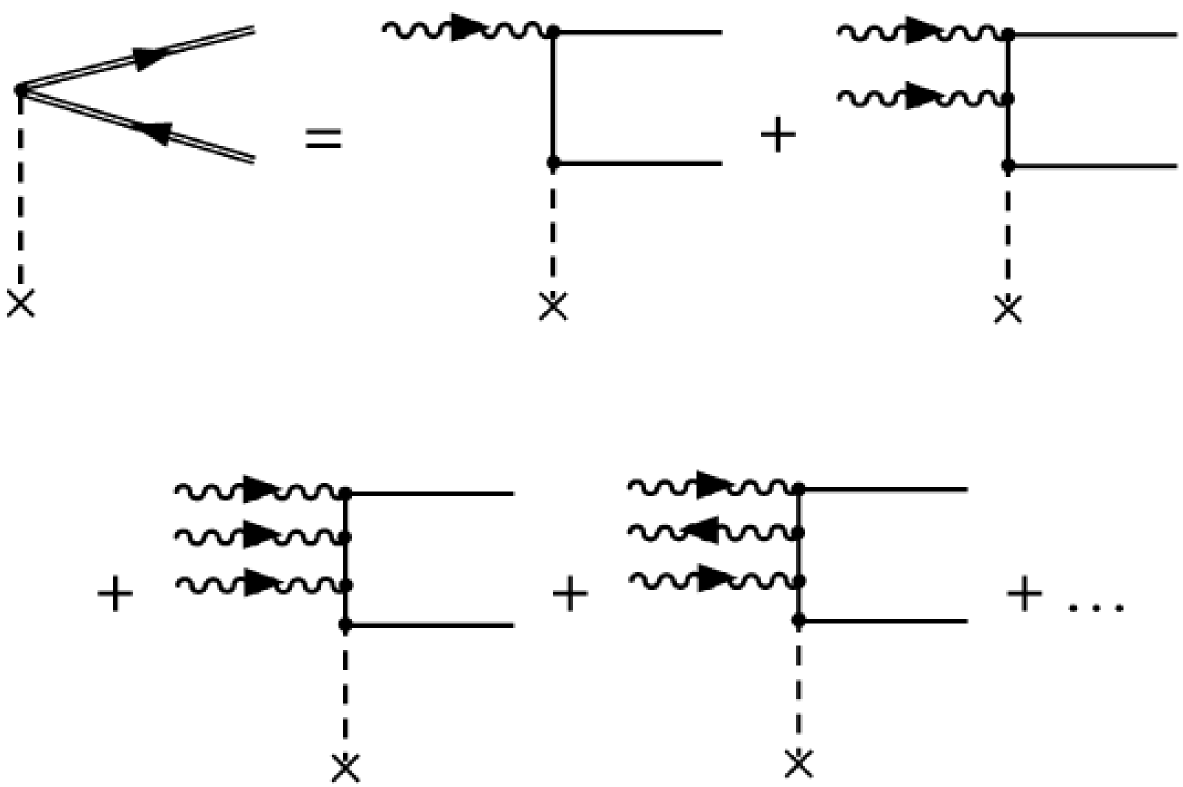


Perturbative multiphoton regime

Example of pair creation amplitude

$$S_{fi} = -\frac{ie}{\hbar}\int d^4x\, \overline{\Psi}_{p_-,s_-}(\gamma^\mu A_\mu)\Psi_{p_+,s_+}$$

Furry-Feynman diagram:



In the weak-field limit, equivalent to perturbative expansion in $\xi = eA/mc^2 \ll 1$

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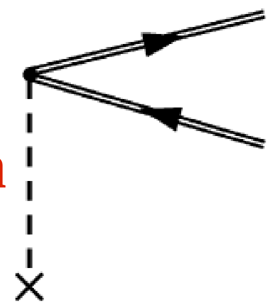
Furry-Feynman diagram:



Plug in Volkov states and
Fourier-expand oscillating terms:

$$S_{fi} \sim \sum_n \mathcal{M}_n(p_+,p_-)\int d^4x\,\mathrm{e}^{i(q_+ + q_- - k_\gamma - nk)\cdot x}$$

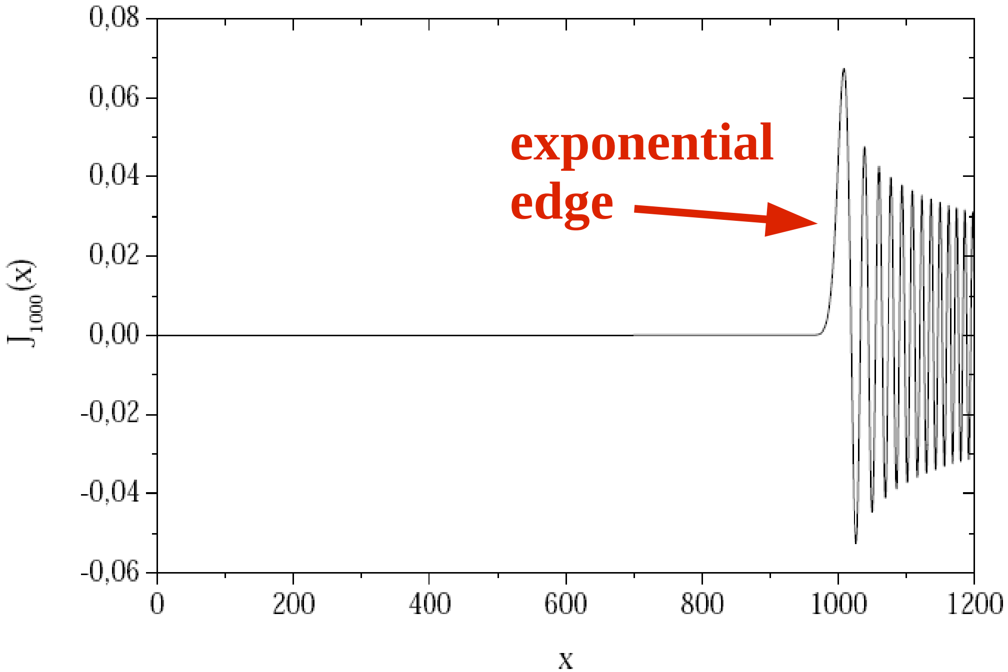
$$\delta\left(q_+^\mu + q_-^\mu - k_\gamma^\mu - nk^\mu\right)$$

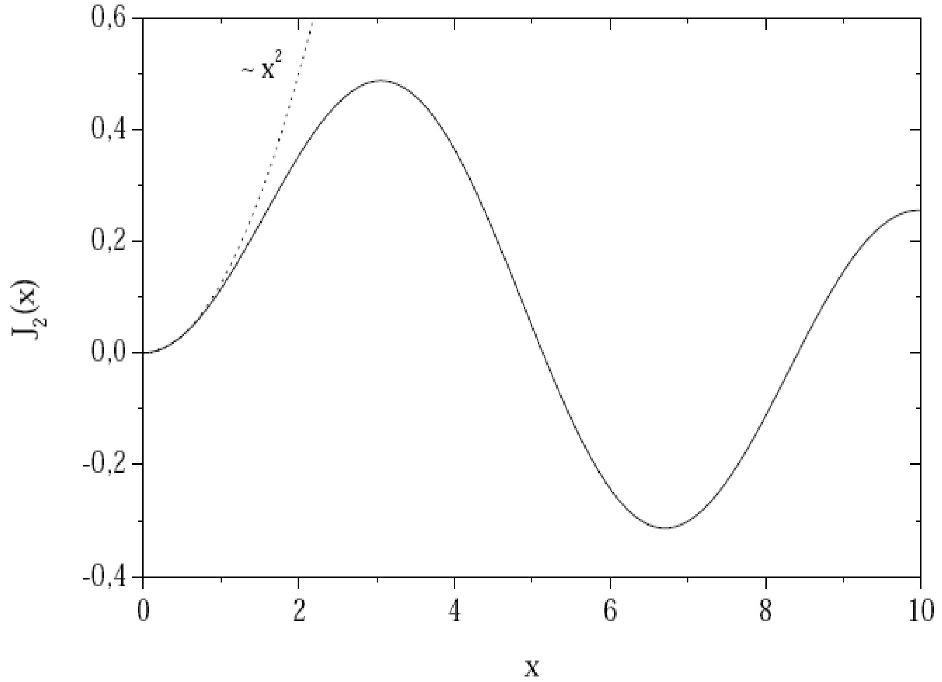
summation index counts number of laser photons!

Fourier coefficients = Bessel functions

$$e^{i f(x)} = \sum_n J_n(\alpha) e^{in(kx)}$$

number of photons!





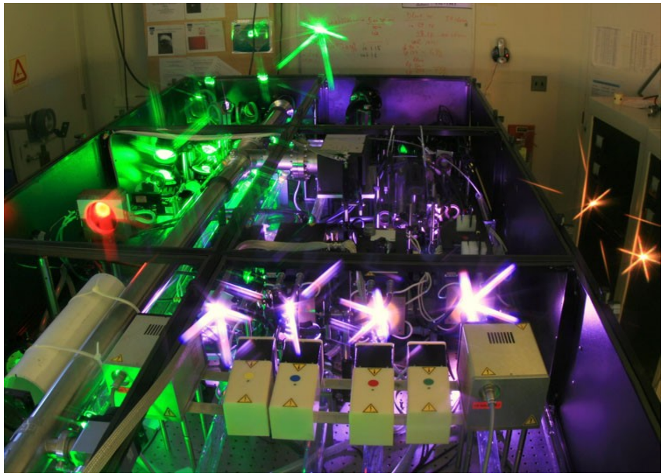
tunneling process

rate ~ $\exp(-E_{cr}/E_L)$

multiphoton process

rate ~ I^n

Can it be measured?



HERCULES Petawatt laser:
10^{22} W/cm^2 at 800 nm

$$\mathbf{E \sim 10^{-4}\, E_{cr}}$$

Free Electron Laser FLASH:
100 eV at 10^{17} W/cm^2

$$\hbar\omega \sim 10^{-4} mc^2$$

Tunneling regime:

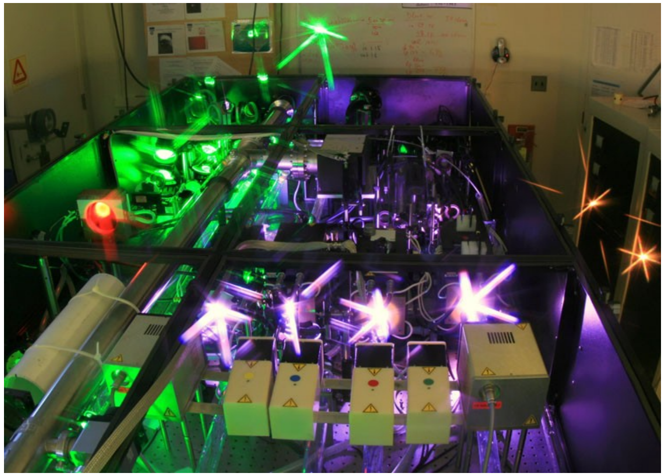
$$R \sim \exp(-E_{cr} / E) \sim 10^{-5000}$$

Multiphoton regime:

$$R \sim \xi^{4mc^2/\hbar\omega} \sim 10^{-100000}$$

Available laser field strengths and frequencies by 4 orders too small...

Can it be measured?



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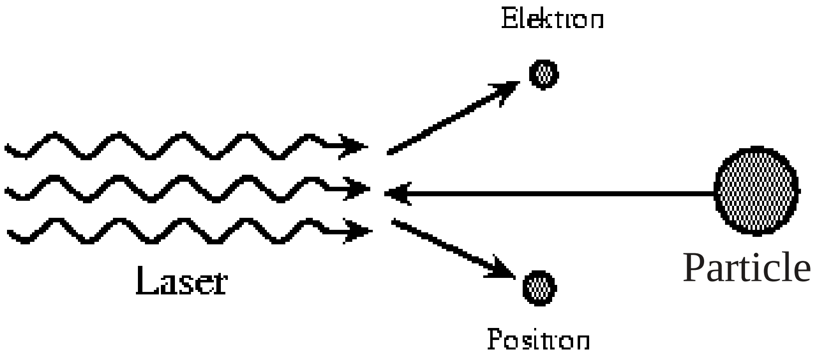
"The cross section for this process at optical frequencies or below is so small at any laser intensity as to make it completely negligible. It may be the smallest (nonzero) cross section on record."

(M. Mittleman, 1987)

Relativistic particle beam colliding with laser pulse

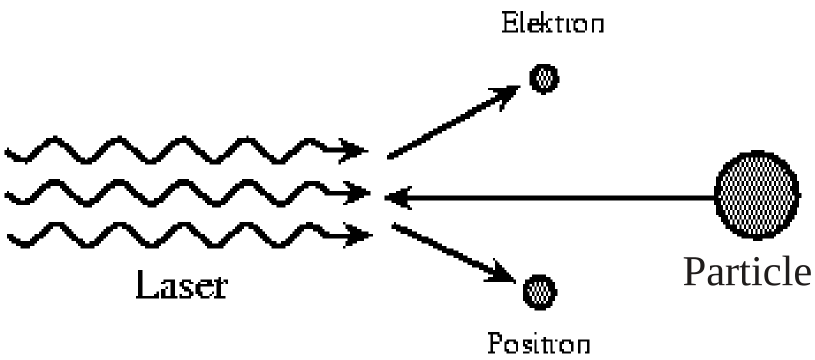


Exploit relativistic Doppler shift

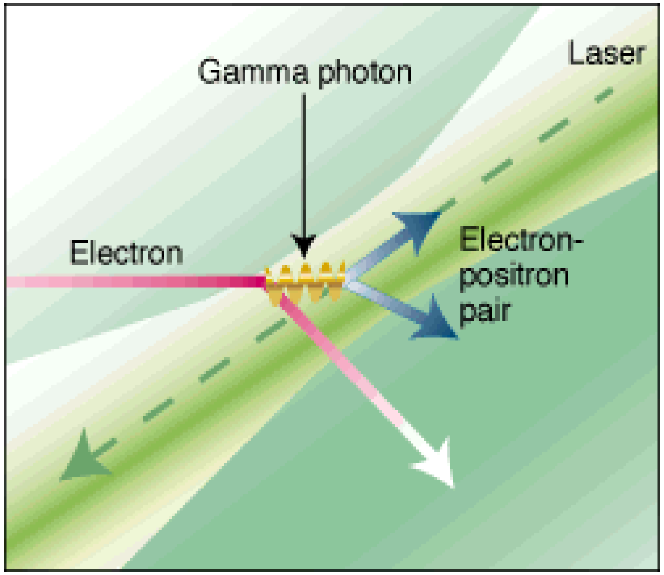
lab frame: $\hbar\omega \approx 100$ eV , $E \approx 10^{12}$ V/cm

rest frame: $\hbar\omega'$ and E' enhanced by 2γ

Relativistic particle beam colliding with laser pulse



SLAC experiment:
46 GeV electron + optical laser pulse
(D. Burke et al., PRL 1997)



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Pairs were produced in two-step process through an intermediate high-energy Compton photon:

$$\mathbf{\Omega_c + n\omega \rightarrow e^+e^-}$$

(strong-field Breit-Wheeler process)

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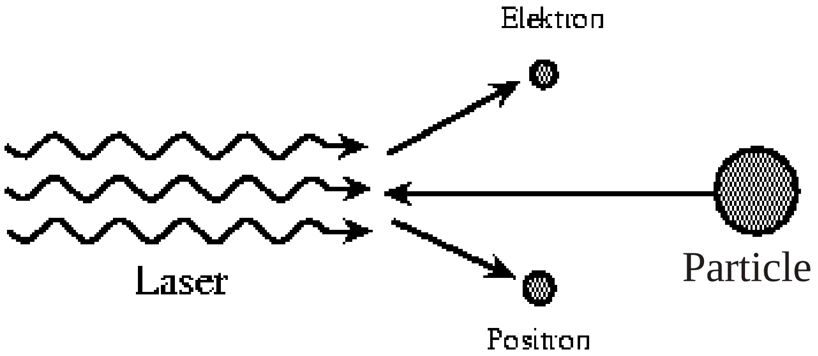

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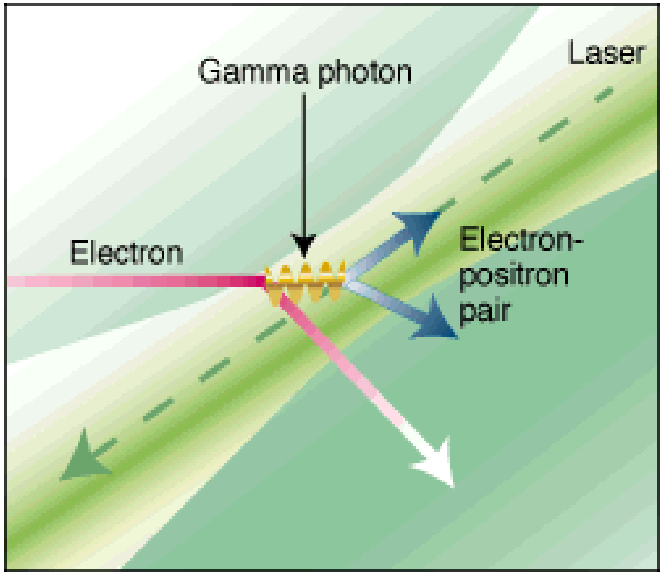

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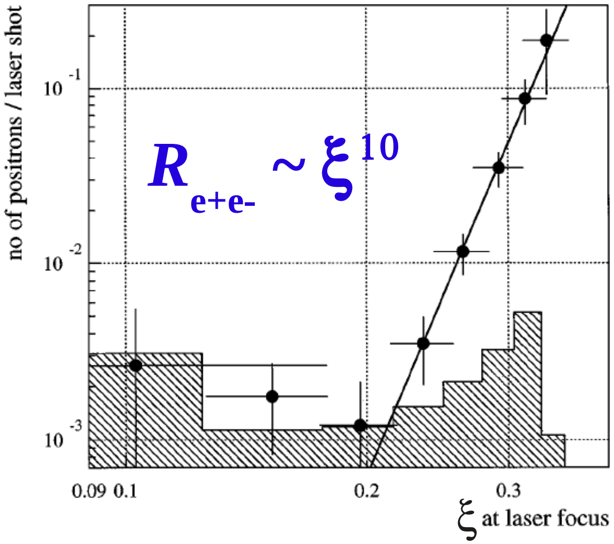

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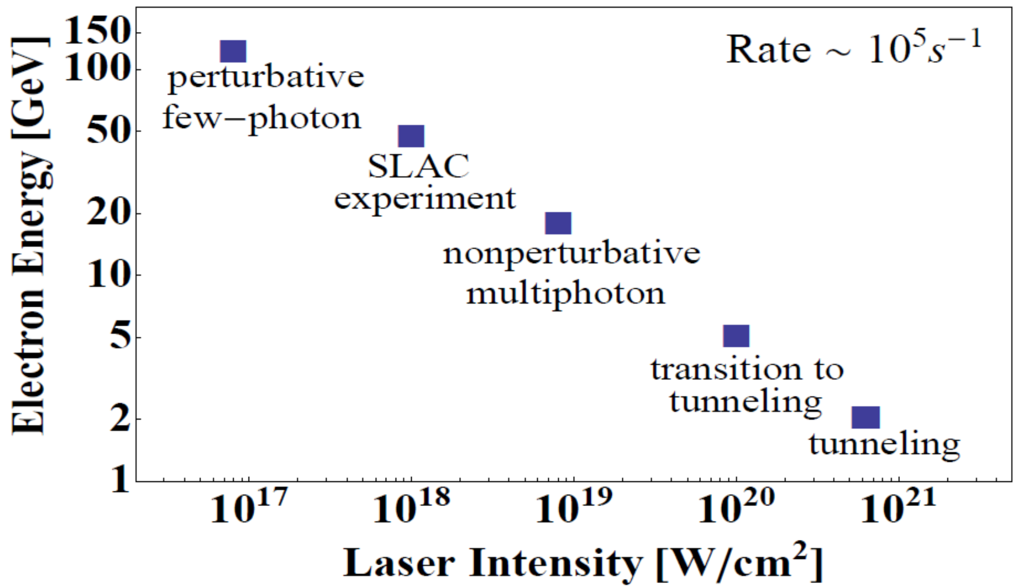
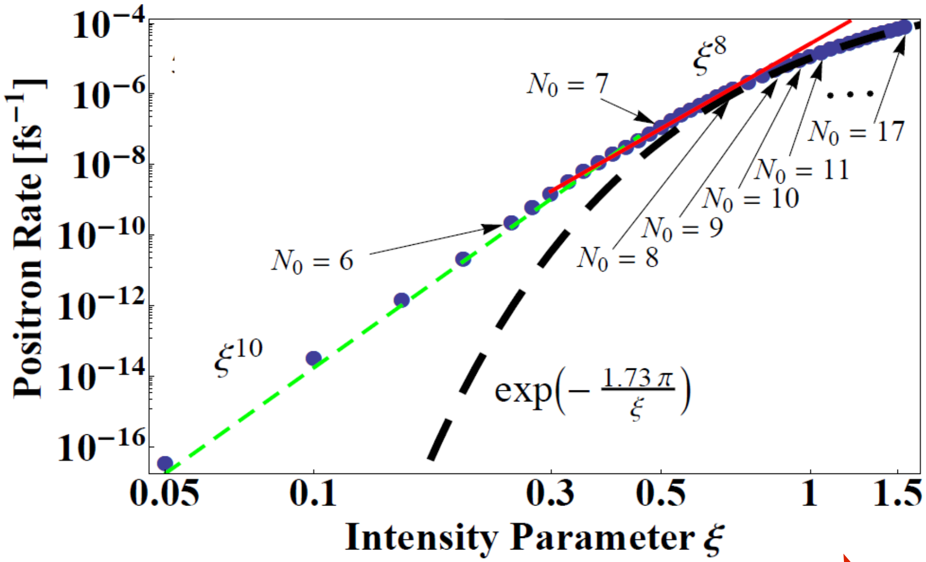
Transition from perturbative to nonperturbative regime



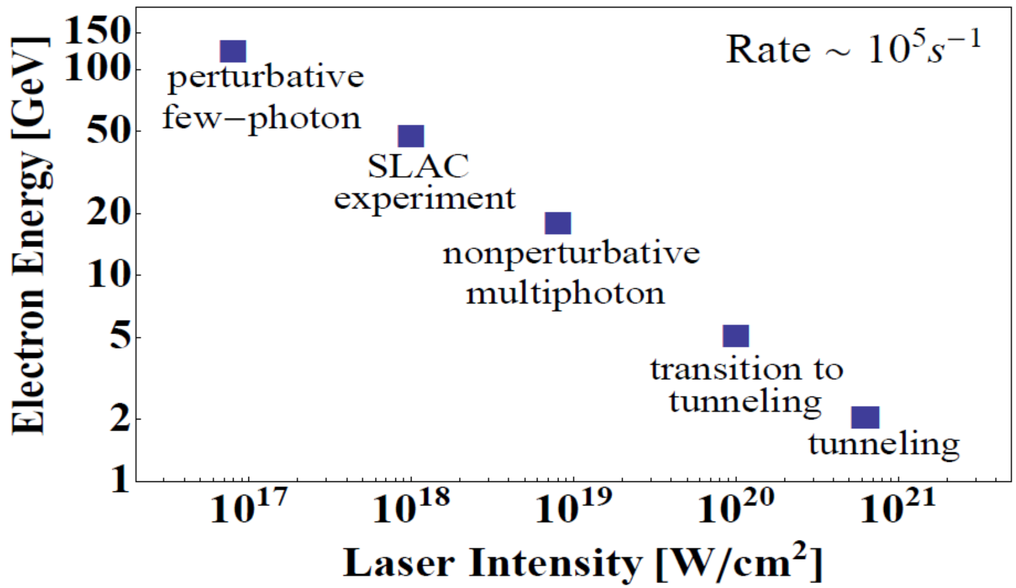


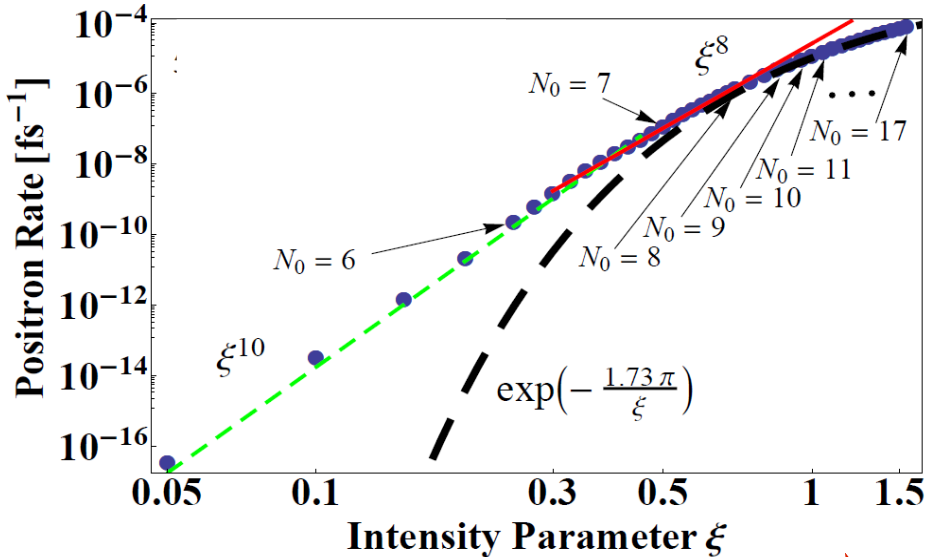
Hu, Müller & Keitel,
PRL **105**, 080401 (2010)

perturbative domain

nonperturbative domain

Transition from perturbative to nonperturbative regime





Hu, Müller & Keitel,
PRL **105**, 080401 (2010)

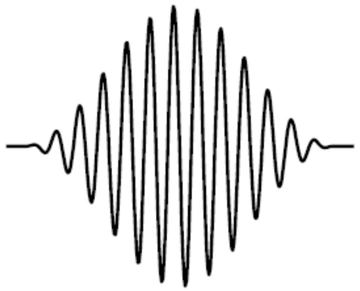
perturbative domain

nonperturbative domain

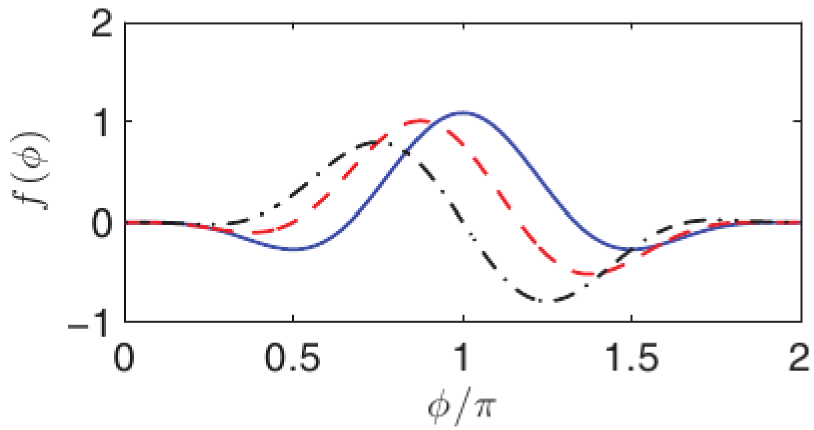
Combine laser-accelerated electron beam with second counter-propagating laser pulse: All-optical realization of SLAC experiment to probe the tunneling regime

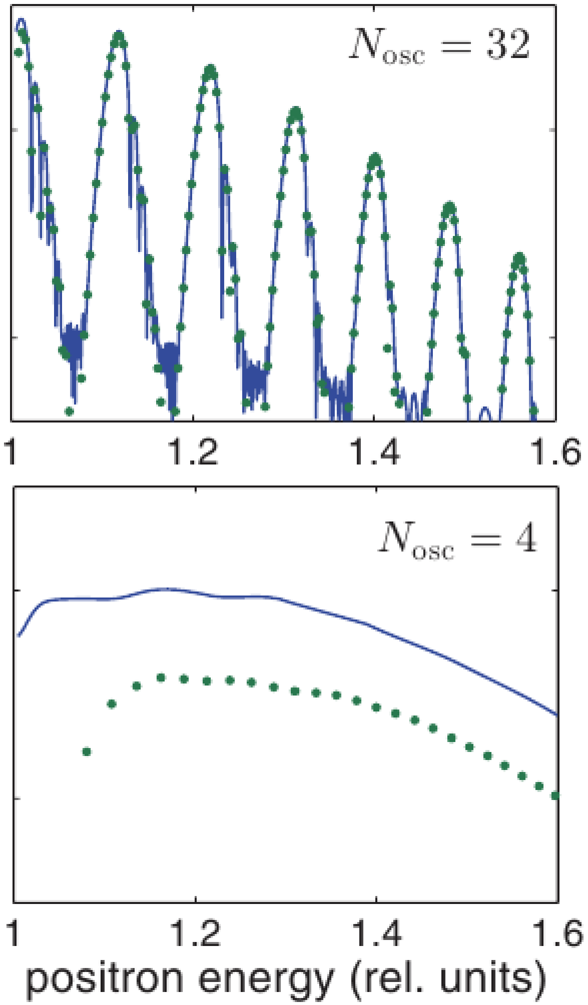
Recent developments in laser-induced e^+e^- pair creation

Pair creation in finite laser pulses



$$\vec{A}(k \cdot x) = A_0 \, \vec{\varepsilon} \, f(k \cdot x) \, \cos(k \cdot x)$$

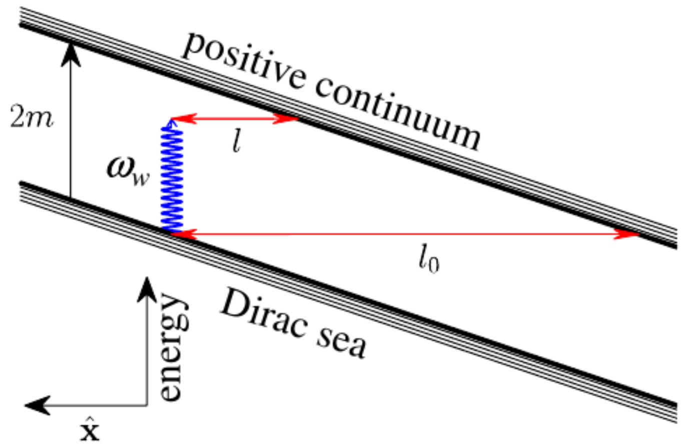




Boca & Florescu, PRA (2009)
Mackenroth, Di Piazza & Keitel, PRL (2010)
Heinzl, Seipt & Kämpfer, PRA (2010)
Heinzl, Ilderton & Marklund, PLB (2010)
Ipp, Evers, Keitel & Hatsagortsyan, PLB (2011)
Titov, Takabe, Kämpfer & Hosaka, PRL (2012)
Krajewska & Kaminski, PRAs (2012) + (2013)
Jiang, Lv, Liu, Grobe & Su, PRA (2014)
Meuren, Hatsagortsyan, Keitel & Di Piazza, PRD (2015)

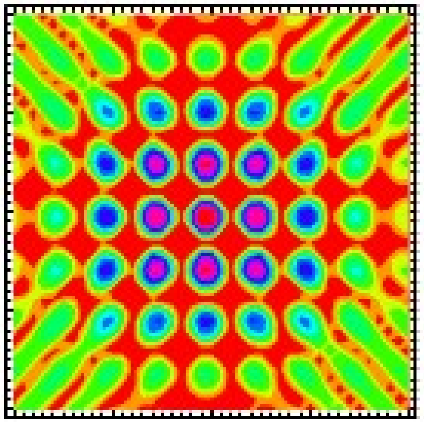
Enhancement of pair creation

Dynamical assistance:
add high-frequency component



Schützhold, Gies & Dunne, PRL (2008)
Di Piazza, Lötstedt, Milstein & Keitel, PRL (2009)
Orthaber, Hebenstreit & Alkofer, PLB (2011)
Jiang, Su, Lv, Lu, Li, Grobe & Su, PRA (2012)

Multiple-beam or multiple-center setups

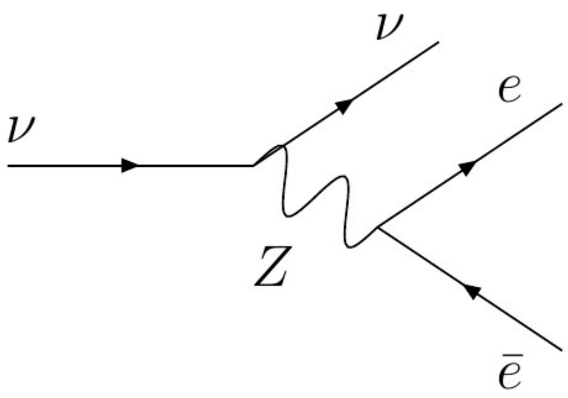


Bulanov, Mur, Narozhny, Nees & Popov, PRL (2010)
Fillion-Gourdeau, Lorin & Bandrauk, PRL (2013)

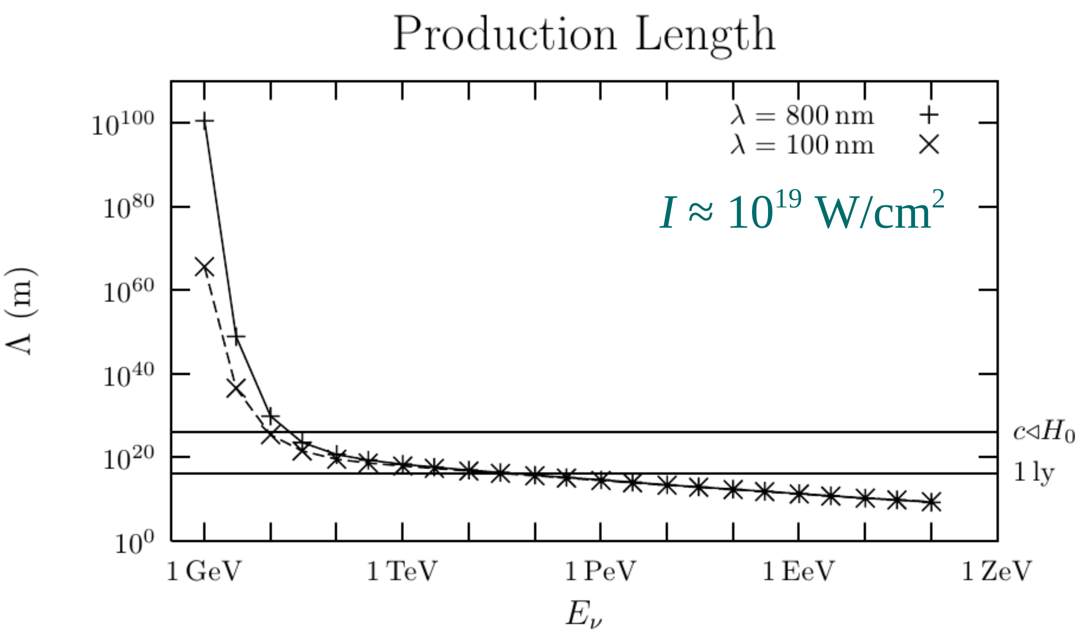
QED cascades

Bell & Kirk, PRL (2008)
Nerush, Kostyukov,
Fedotov, Narozhny,
Elkina & Ruhl, PRL (2011)

Pair creation in neutrino-laser collisions



$$\hat{S} = -\frac{\imath}{\hbar^8}\frac{4\pi\alpha}{2^2\cos^2\theta_W\sin^2\theta_W} \times \int d^4x\overline{\psi}_e(x)\gamma^\mu\left(-\frac{1}{2}+2\sin^2\theta_W+\frac{1}{2}\gamma^5\right)\psi_e(x)Z_\mu(x) \times \int d^4y\overline{\psi}_\nu(y)\gamma^\sigma\left(\frac{1}{2}-\frac{1}{2}\gamma^5\right)\psi_\nu(y)Z_\sigma(y)$$



creation length at E_ν ~ 10 GeV:
size of the universe....

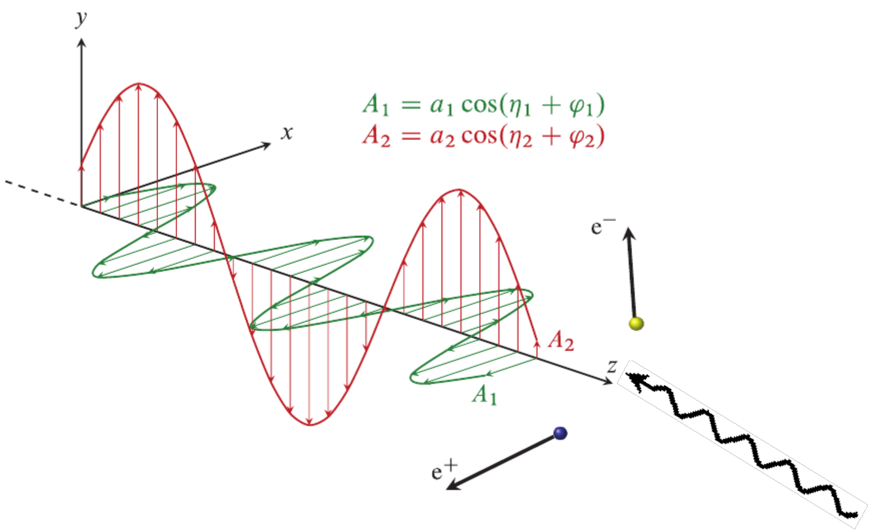
Tinsley, PRD 71, 073010 (2005)

e^+e^- pair creation in two-color laser fields

Dynamically assisted Breit-Wheeler pair creation

$$\mathcal{R} = \frac{3^2 \alpha m^2}{2^7 \sqrt{2\pi}\,\omega_\gamma} \left(\frac{E'}{E_{\rm cr}}\right)^{3/2} \exp\left(-\frac{8}{3}\frac{E_{\rm cr}}{E'}\right)$$

(Reiss 1962)



Dynamically assisted Breit-Wheeler pair creation

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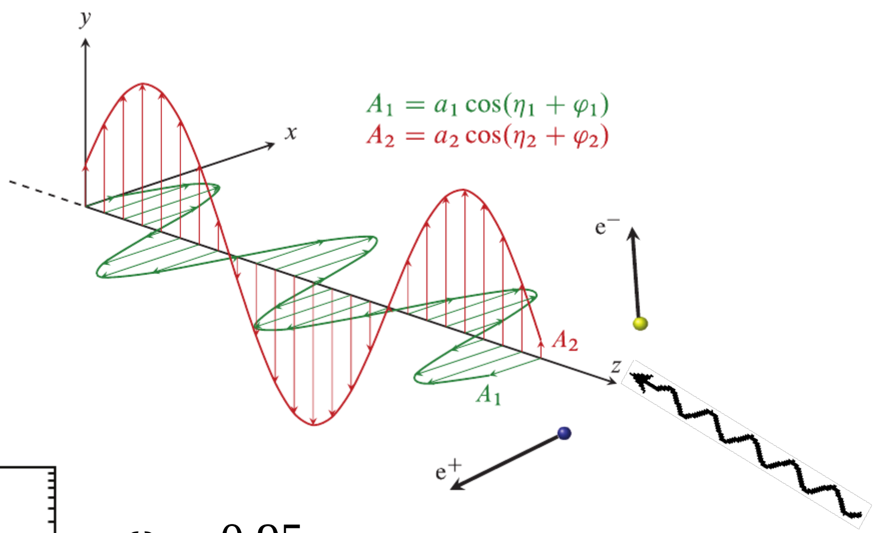
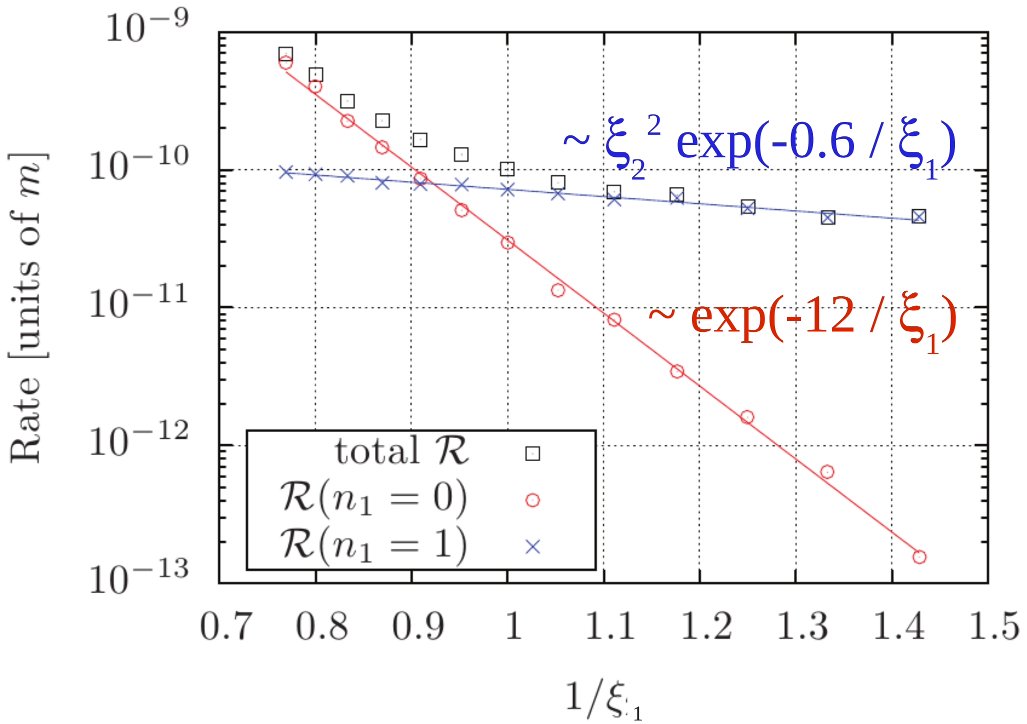
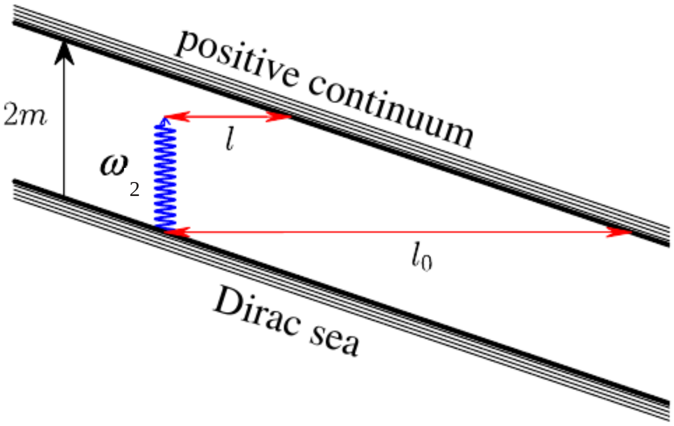




$\omega_\gamma = 0.95\,m$

$\omega_1 = 0.1\,m$

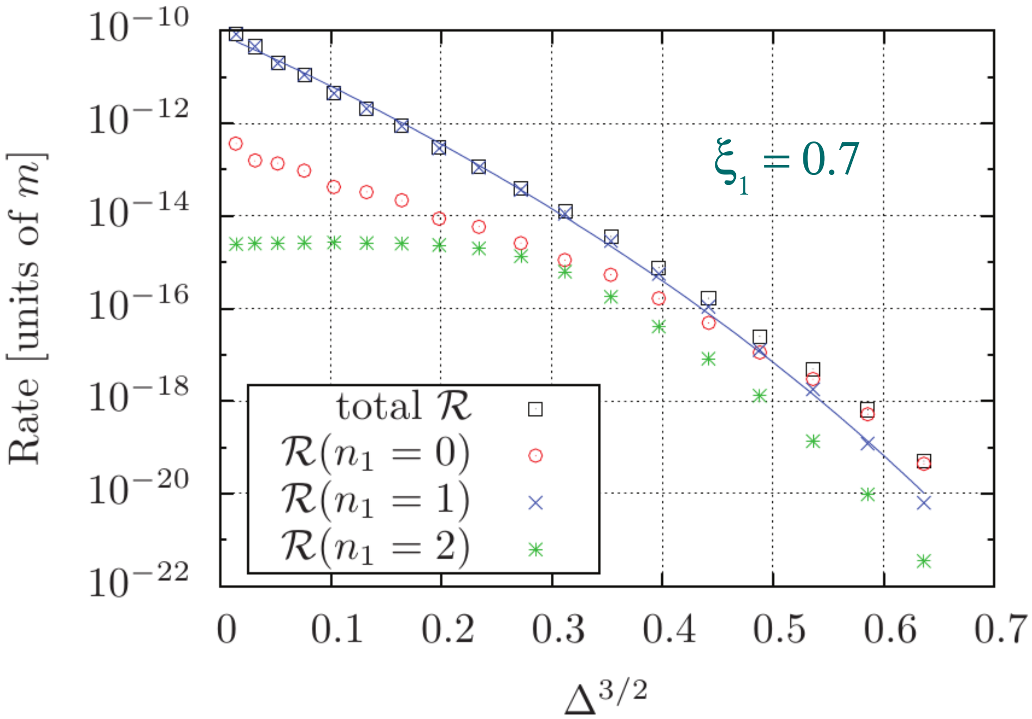
$\omega_2 = \omega_\gamma$, $\xi_2 = 0.002$



unassisted and assisted channels compete

Dynamically assisted Breit-Wheeler pair creation

Depencence on energy gap



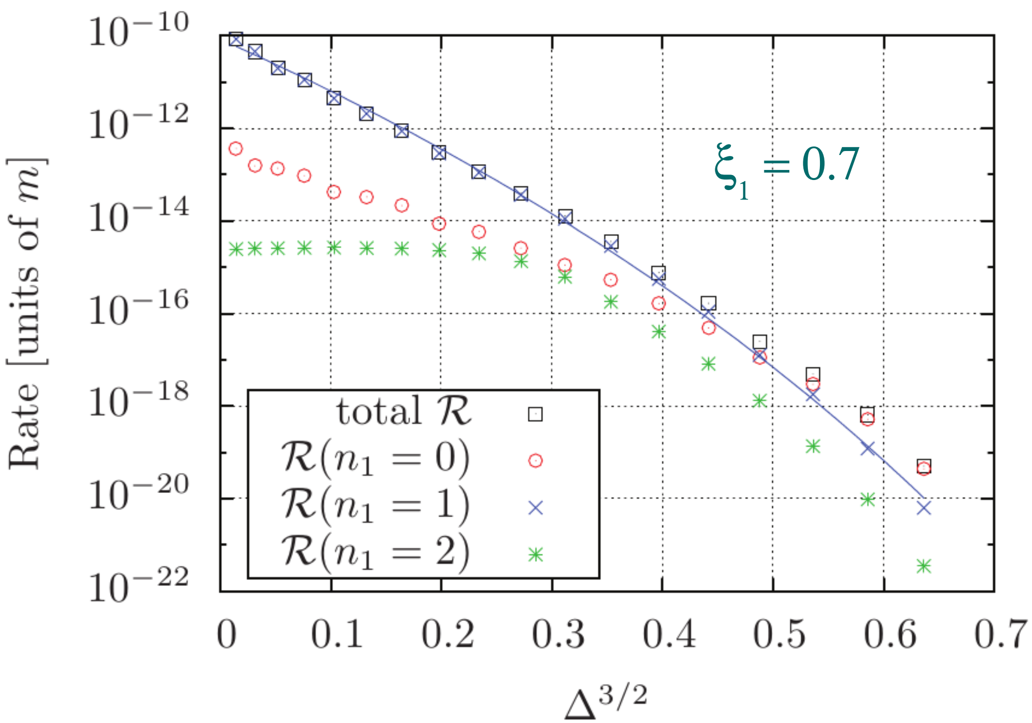
$$(k_2 + k_\gamma)^2 = 4m^2(1 - \Delta)$$

Jansen & Müller, PRA 88, 052125 (2013)

[see also Wu & Xue, PRD 90, 013009 (2014); Narozhny & Fofanov, JETP 90, 415 (2000)]

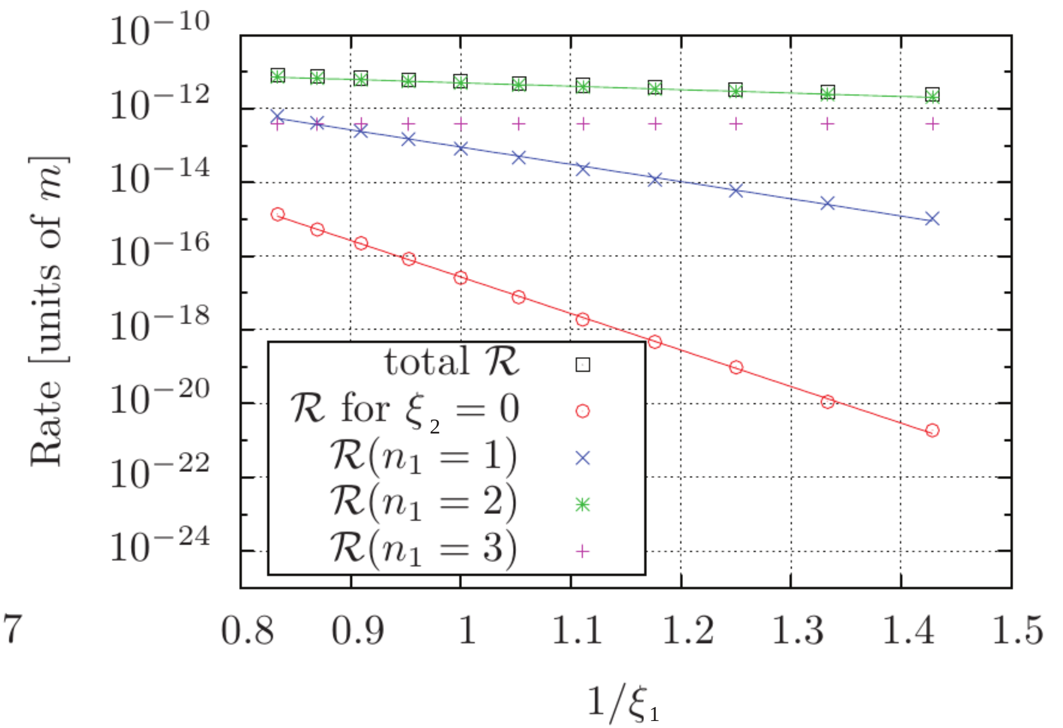
Dynamically assisted Breit-Wheeler pair creation

Depencence on energy gap



$$(k_2 + k_\gamma)^2 = 4m^2(1 - \Delta)$$

Assistance by two high-frequency photons dominates



$\omega_\gamma = 0.95\,m$

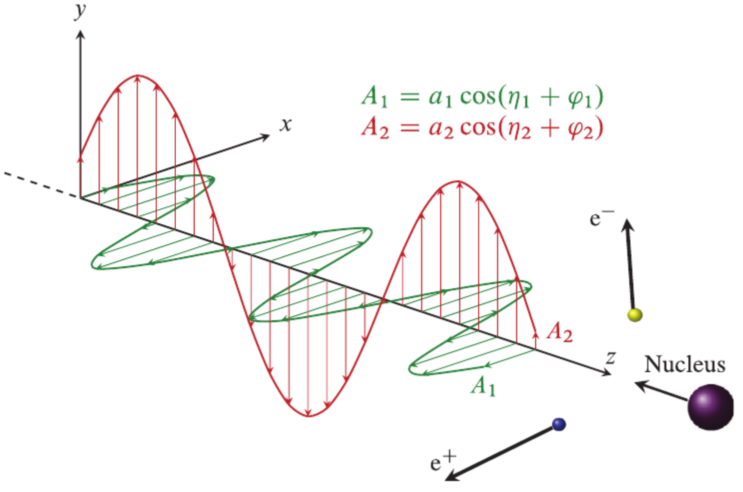
$\omega_1 = 0.05\,m$

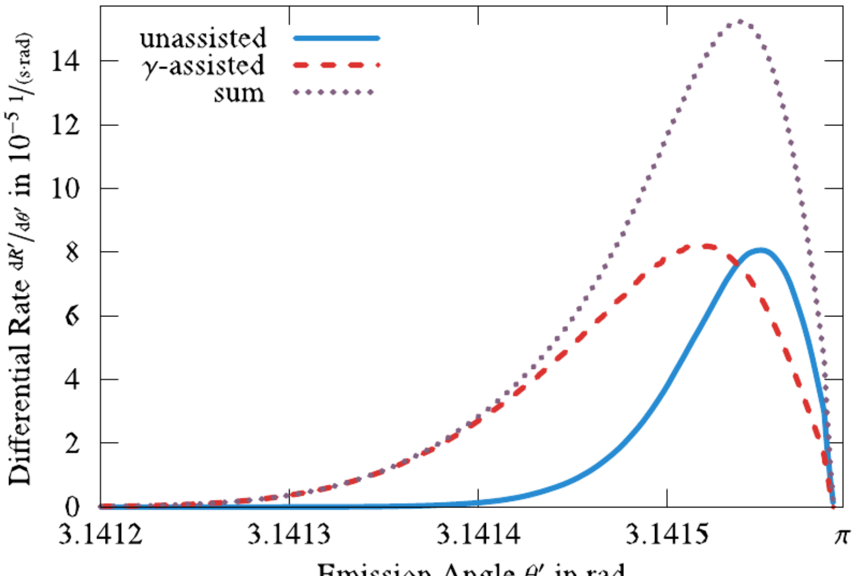
$\omega_2 = \omega_\gamma / 2$, $\xi_2 = 0.045$

Jansen & Müller, PRA 88, 052125 (2013)

[see also Wu & Xue, PRD 90, 013009 (2014); Narozhny & Fofanov, JETP 90, 415 (2000)]

Dynamically assisted Bethe-Heitler pair creation





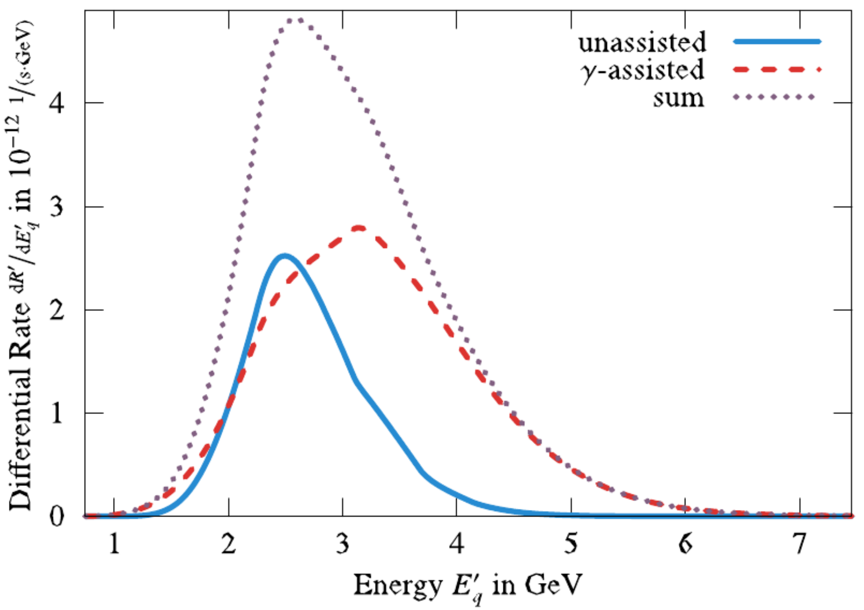
(b) Laboratory Frame

Angular & energy distributions of e^+ may differ even when total contributions similar in size

$\omega_1 = 2.3$ eV , $\xi_1 \approx 1$

$\omega_2 = 70$ eV , $\xi_2 \approx 10^{-8}$

$\gamma = 7000$

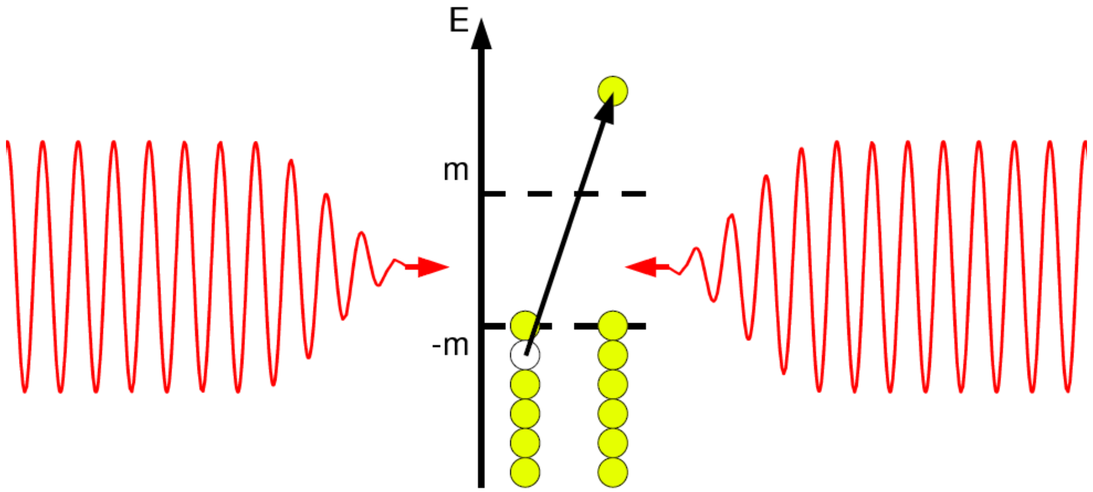


(b) Laboratory Frame

Augustin & Müller, PLB 737, 114 (2014)

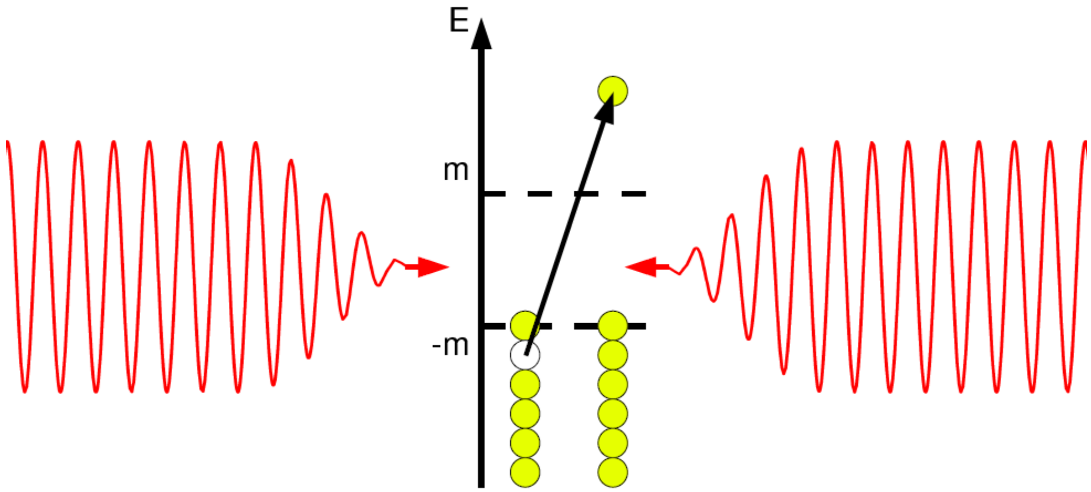
[see also Di Piazza et al., PRL 103, 170403 (2009)]

Pair creation in oscillating *E*-field

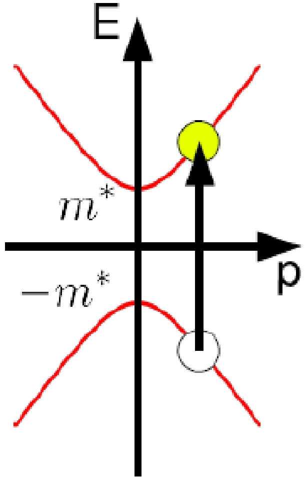


$$A = A_0 \,[\, \sin(\omega t - kz) + \sin(\omega t + kz) \,] = 2A_0 \sin(\omega t)\cos(kz) \approx 2A_0 \sin(\omega t)$$

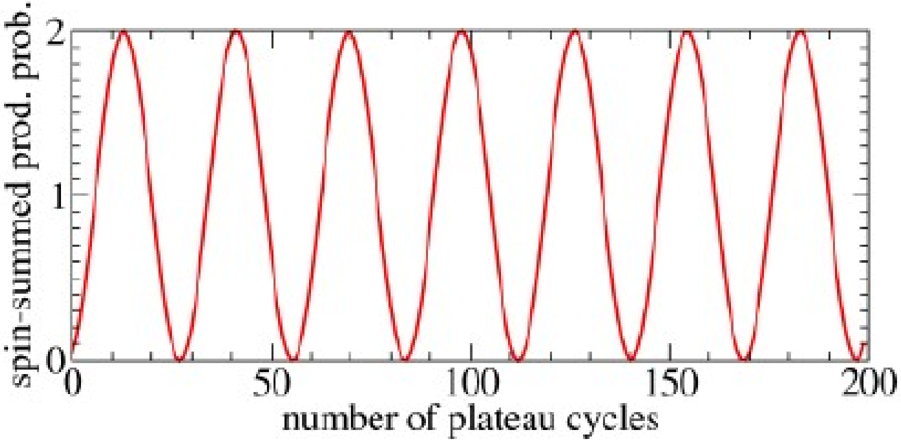
Pair creation in oscillating *E*-field



$$A = A_0 \, [\, \sin(\omega t - kz) + \sin(\omega t + kz) \,] = 2A_0 \sin(\omega t)\cos(kz) \approx 2A_0 \sin(\omega t)$$



Momentum conservation reduces the problem to a two-level system, which undergoes Rabi oscillations at certain frequencies.

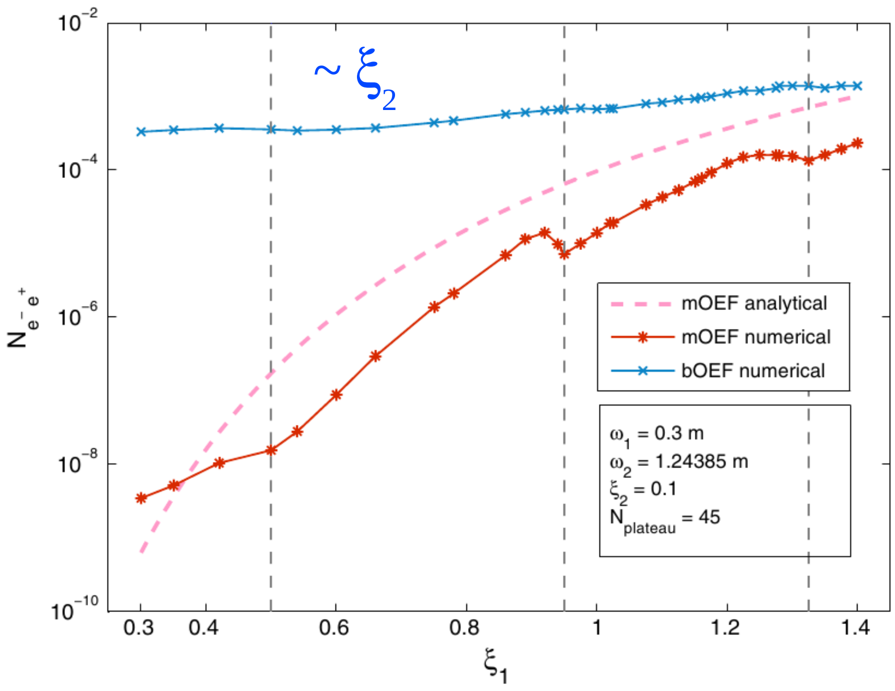


Popov (1973)

Pair creation in bifrequent oscillating *E*-field

$$\vec{A}(t) \sim [\xi_1 \sin(\omega_1 t) + \xi_2 \sin(\omega_2 t)]\, \vec{e}_y$$

Number density of created pairs

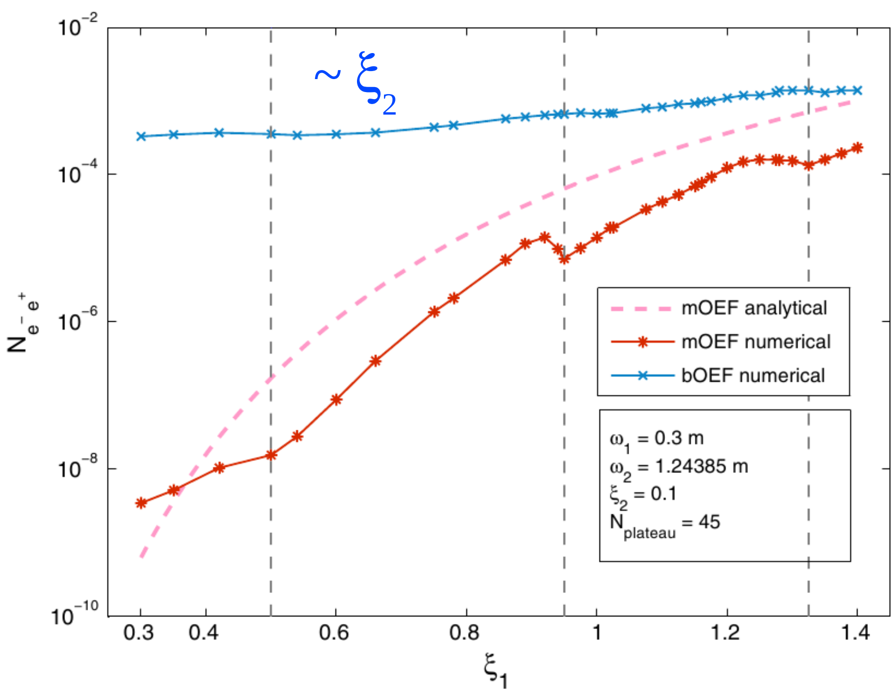


Resonances: $n_1\omega_1 + n_2\omega_2 = 2\varepsilon(\mathrm{p})$

Pair creation in bifrequent oscillating *E*-field

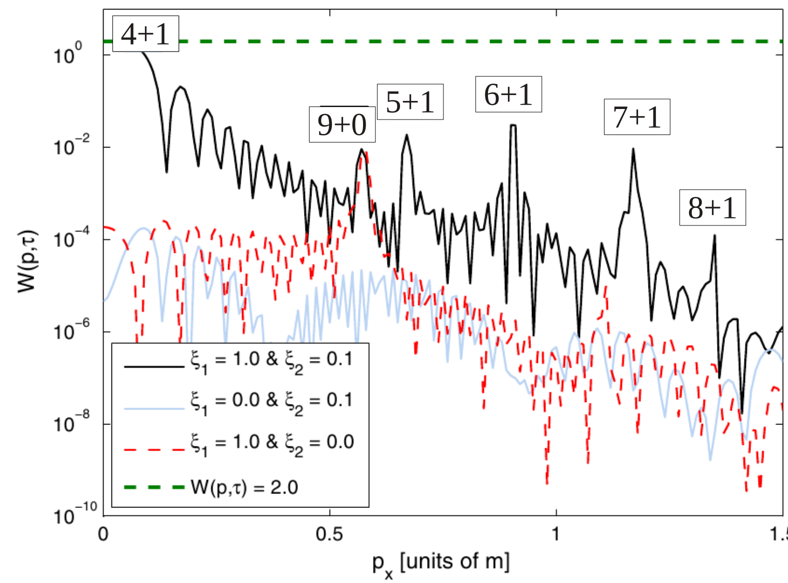
$$\vec{A}(t) \sim [\xi_1 \sin(\omega_1 t) + \xi_2 \sin(\omega_2 t)]\, \vec{e}_y$$

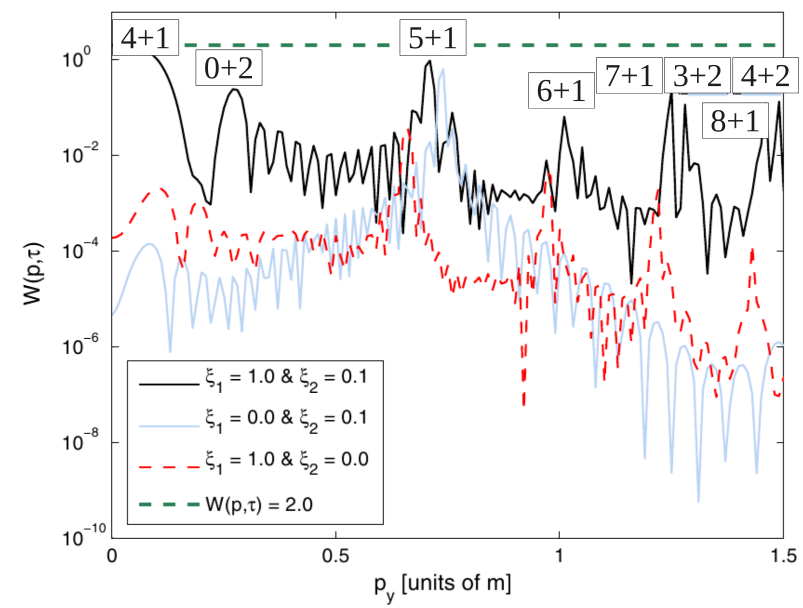
Number density of created pairs



Resonances: $n_1\omega_1 + n_2\omega_2 = 2\varepsilon(\mathrm{p})$

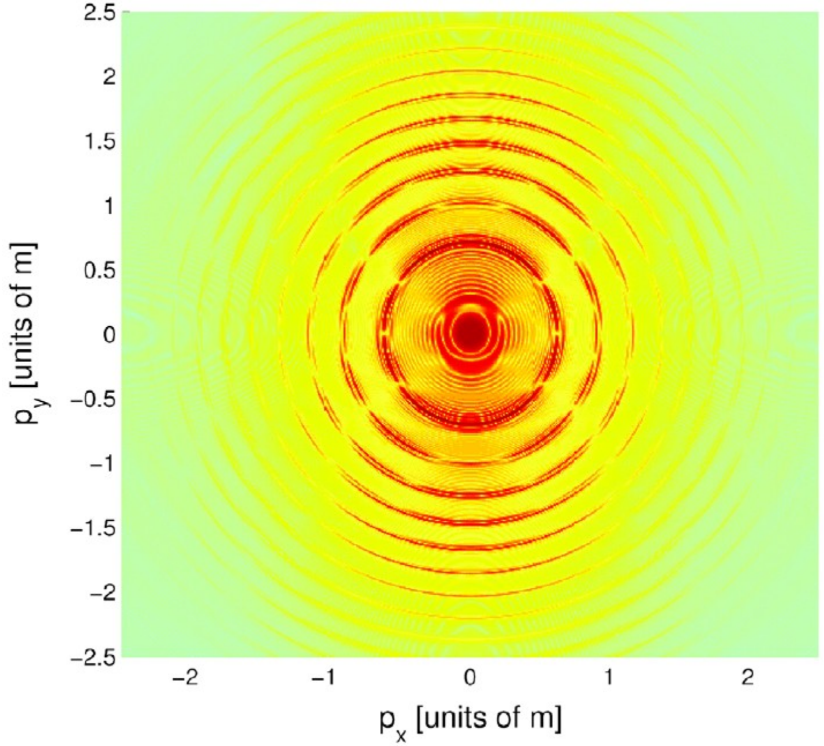
Momentum spectra





Pair creation in bifrequent oscillating *E*-field

[4+1] – resonance

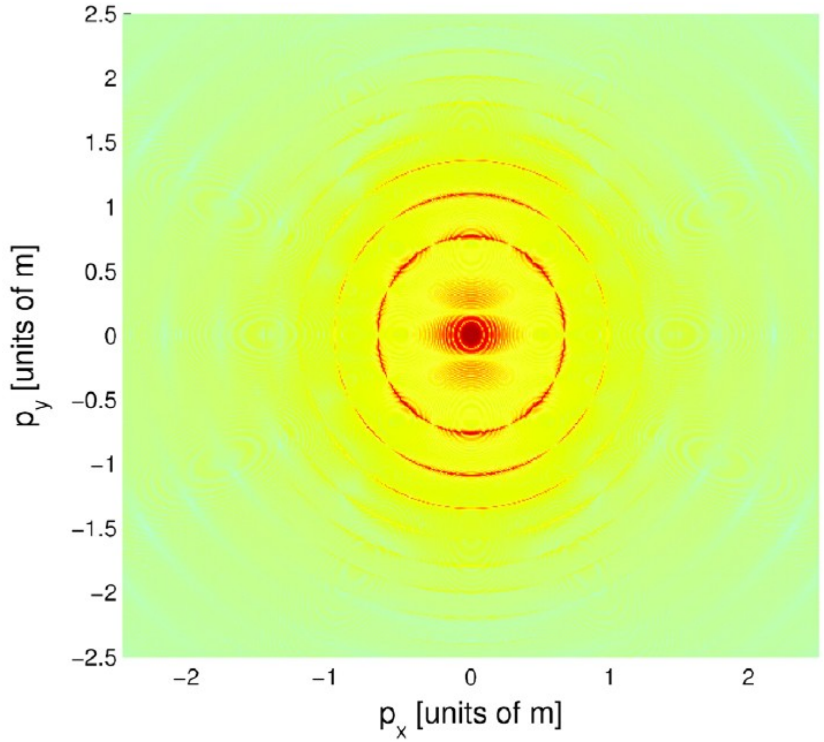


$\omega_1 = 0.3\,m$, $\xi_1 = 1.0$

$\omega_2 = 1.24\,m$, $\xi_2 = 0.1$

$N = 16$

monochrom. [7] – resonance



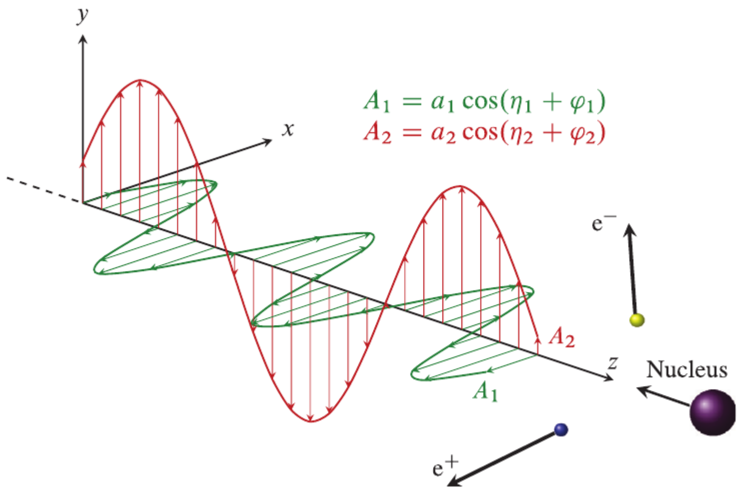
$\omega_1 = 0.35\,m$, $\xi_1 = 1.0$

$N = 45$

Akal, Villalba-Chavez, Müller, PRD 90, 113004 (2014)

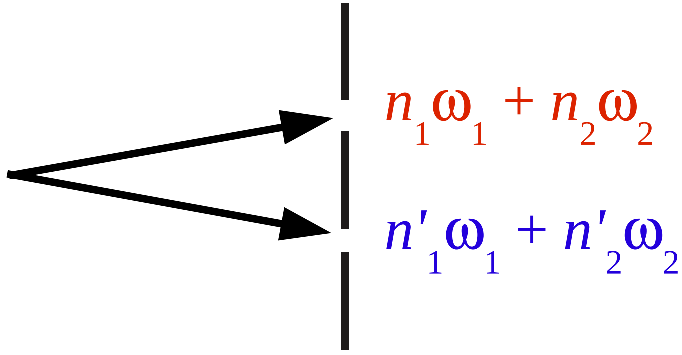
[see also Orthaber, Hebenstreit, Alkofer, PLB (2011)]

Quantum interferences in bichromatic fields



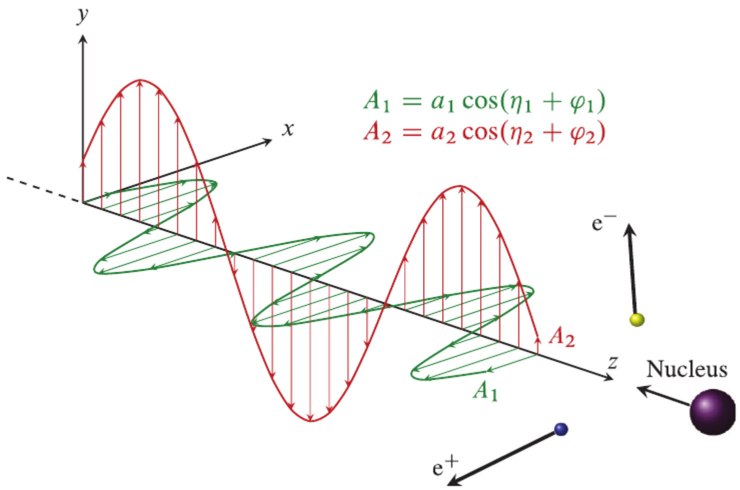
Suppose $\omega_1 = 2\omega_2$ (commensurate)

Two-pathway interference:



see also Krajewska & Kaminski, PRA 86, 021402 (2012)

Quantum interferences in bichromatic fields



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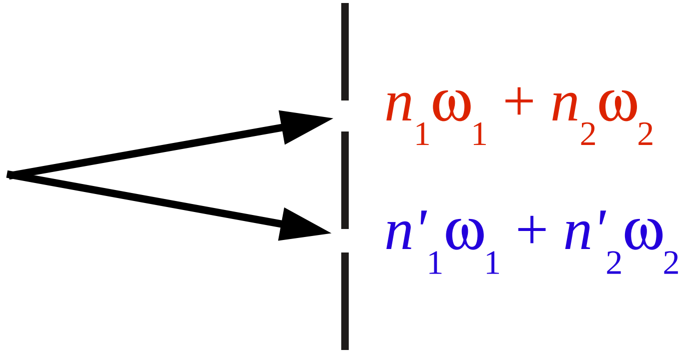
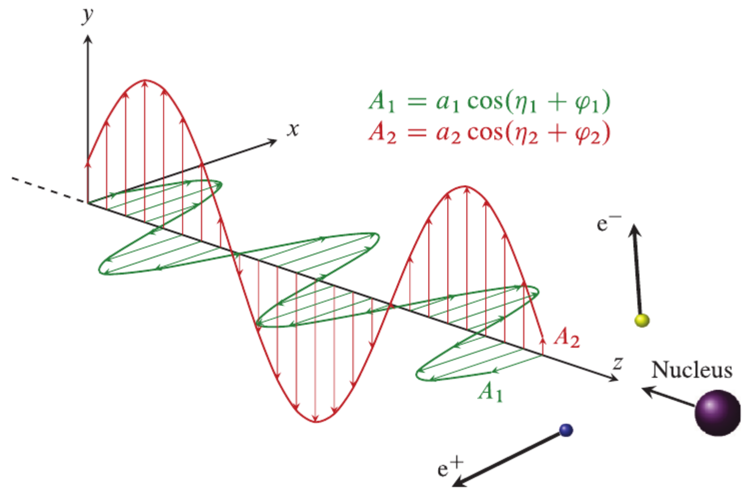


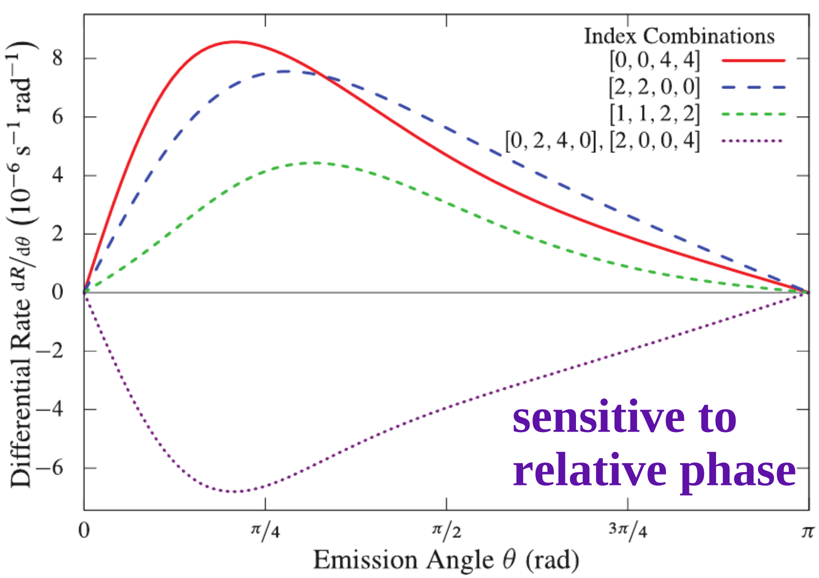
$$|\mathscr{S}|^2 = \sum_{\substack{n'_1,n'_2 \\ n_1,n_2}} \mathscr{P}_{(n_1,n_2,n'_1,n'_2)}$$

Maximize interference: $\xi_1^{\,2} \sim \xi_2^{\,4} \ll 1$

see also Krajewska & Kaminski, PRA 86, 021402 (2012)

Quantum interferences in bichromatic fields

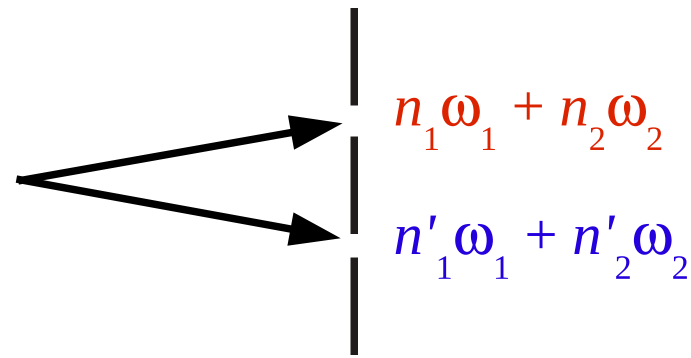




ω_1 = 550 keV (in nuclear frame)

Suppose $\omega_1 = 2\omega_2$ (commensurate)

Two-pathway interference:



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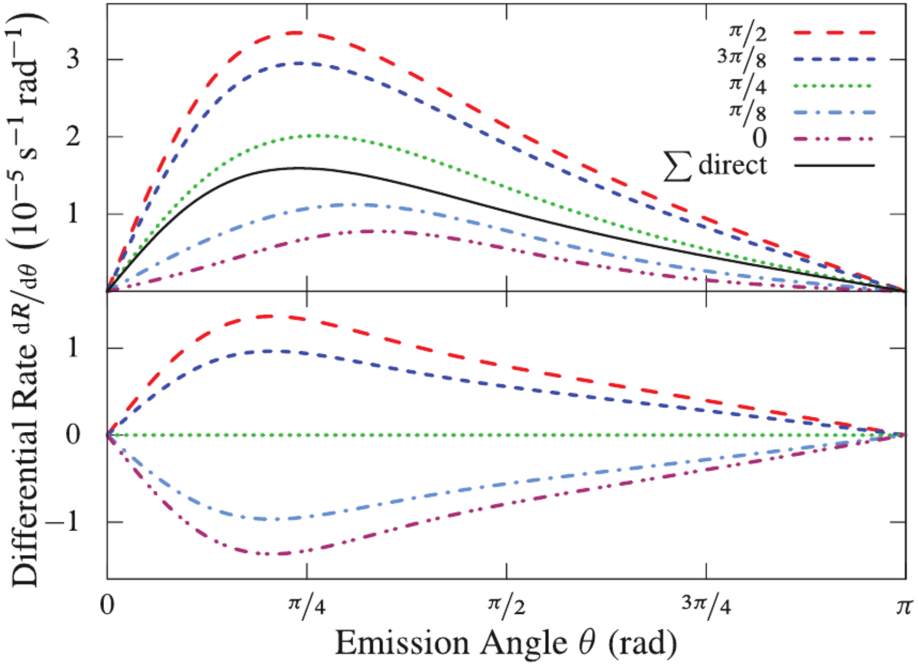
see also Krajewska & Kaminski, PRA 86, 021402 (2012)

Quantum interferences in bichromatic fields

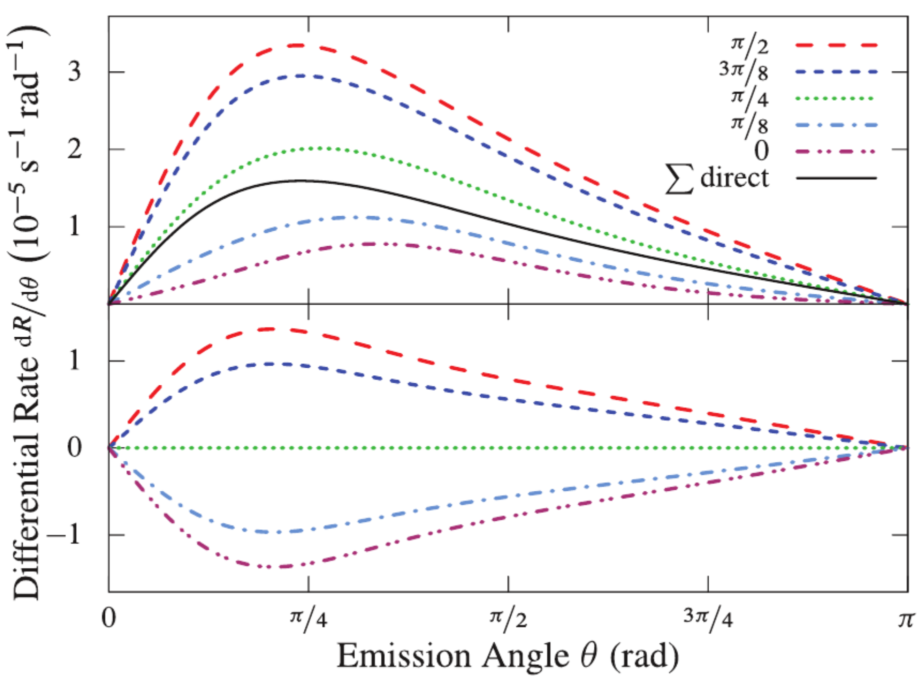
Interference can affect total rate



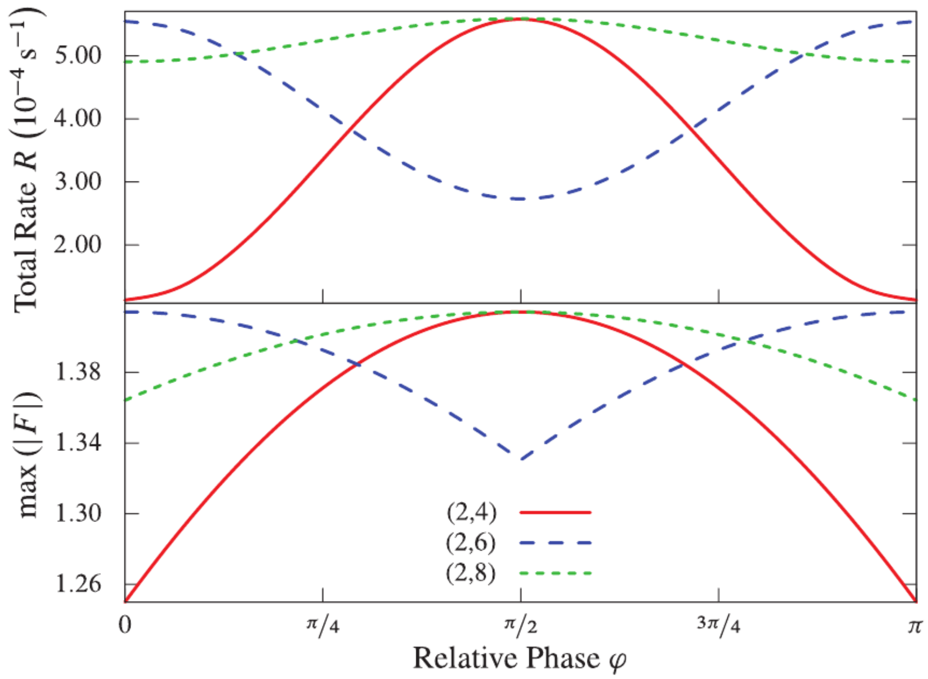
Augustin & Müller, PRA 88, 022109 (2013)

Quantum interferences in bichromatic fields

Interference can affect total rate



Peak field strength relevant



$$F^2(ct-z) = \sum_{i=1}^{2} \frac{c^2}{\mathbf{a}_i^2 \omega_i^2} E_i^2 = \sum_{i=1}^{2} \sin^2(\eta_i + \varphi_i)$$

Augustin & Müller, PRA 88, 022109 (2013)

Summary

- Theory of QED in strong laser fields relies on Furry picture and Volkov states
- Three standard types of laser-induced pair creation:
  with γ-photon, Coulomb field or second laser beam;
  various interaction regimes – tunable by laser parameters
- Recent developments: pair creation in more complex field configurations (e.g. two-colors or finite pulses)
  → enriched creation dynamics, more realistic description
  and enhanced pair yields

Thank you for your attention!