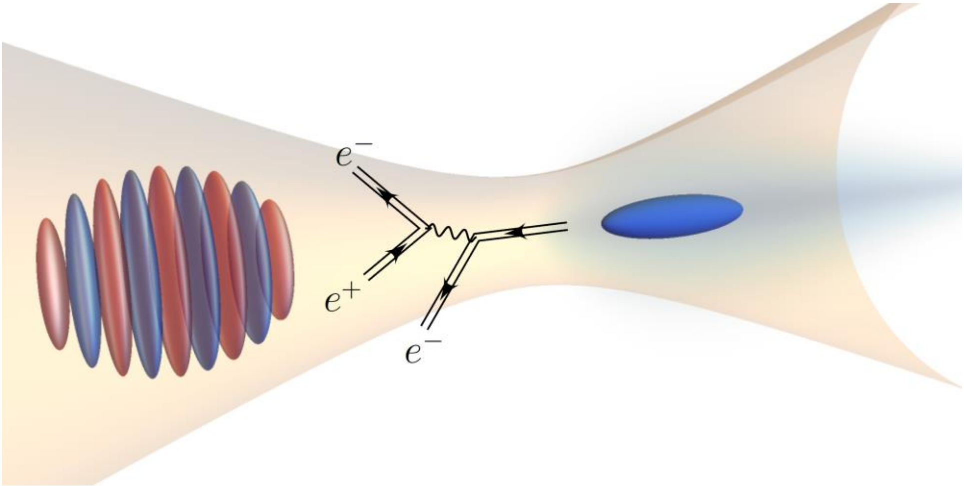
Strong-field QED overview



Tom Blackburn
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www.gu.se/en/research/plasma-physics

15 April 2024

LUXE & LUPE Workshop

Summary

- What is a strong electromagnetic field?
  - Nonlinearity parameters
  - Where are strong EM fields found?
- Strong-field QED:
  - Basic processes
  - Parameter regimes, quasistatic fields
  - Questions we want to answer
- Uncertainties and unknowns

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What is a strong electromagnetic field?

Quantum nonlinearity parameter $\chi_{e,\gamma}$

force exerted by electric field

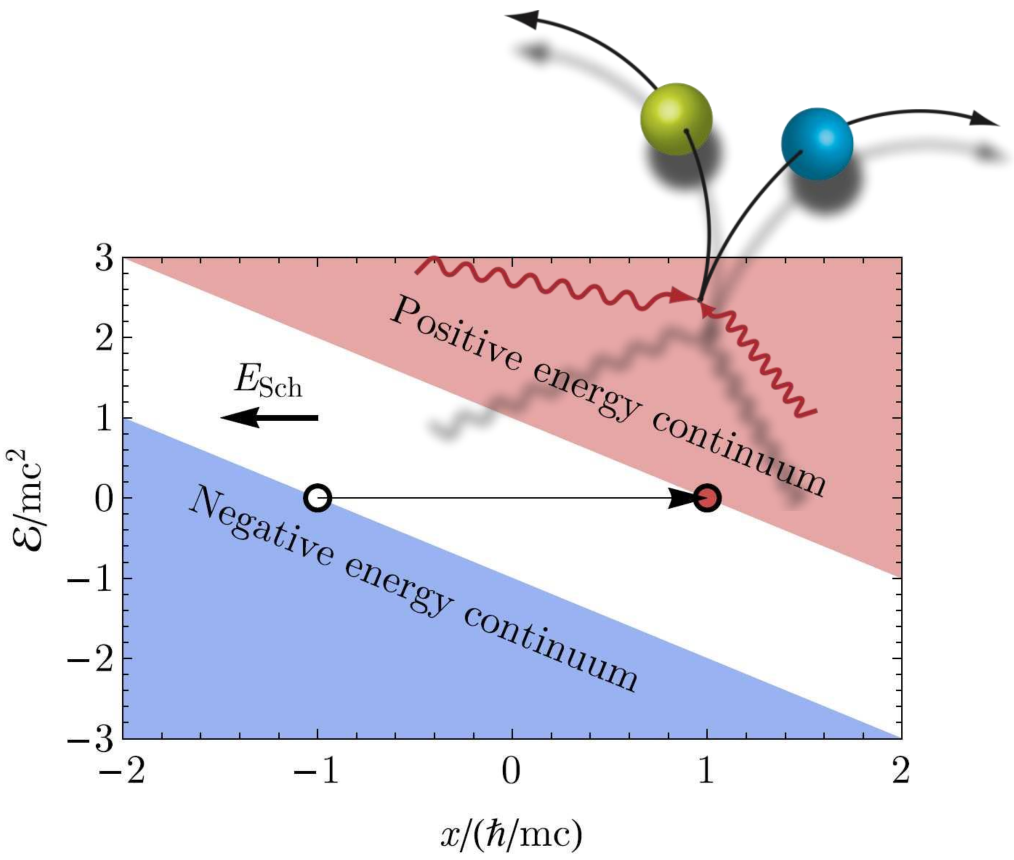
Compton length

$$\chi = \frac{eE\,\frac{\hbar}{mc}}{mc^2}$$

electron rest energy

- Does the field do enough work over a Compton length to create an electron?
- Equal to the field strength in the particle rest frame, in units of the critical (Schwinger) field.

Critical field / Schwinger field



- Critical field of QED = Schwinger field = an electric field strong enough to pull apart the virtual electron-positron pairs that fill the vacuum.
- Tilts the Dirac sea so that we get tunnelling from the negative to the positive energy continuum.
- Rate is non-analytic in the coupling (more about that later).

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What is a strong electromagnetic field?

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Lorentz factor

electric field

$$\chi = \frac{\gamma E}{E_{cr}}$$

$$E_{cr} = 1.3 \times 10^{18}\ \mathrm{V/m}$$
$$B_{cr} = 4.4 \times 10^{9}\ \mathrm{T}$$

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- Controls the importance of nonlinear quantum effects...

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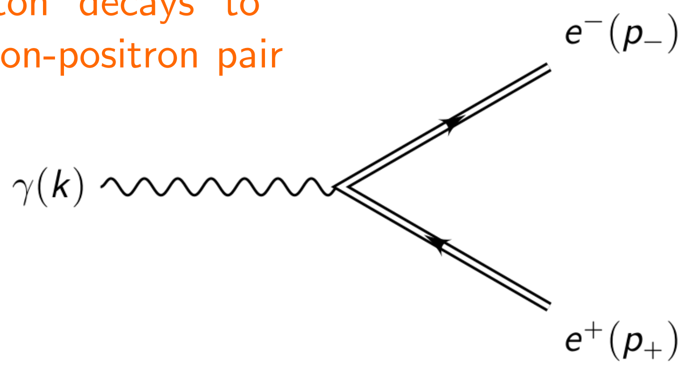
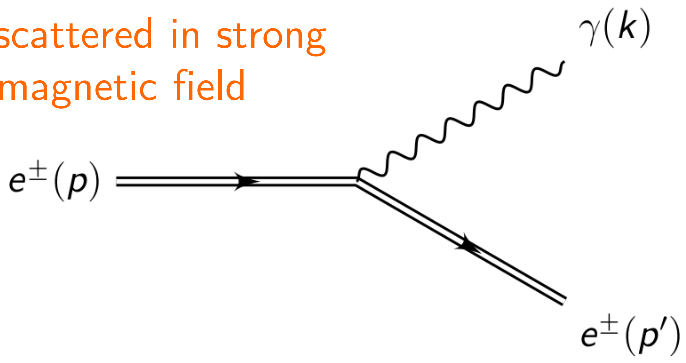
Quantum nonlinearity parameter $\chi_{e,\gamma}$





- A photon is likely to create an electron-positron pair creation if $\chi = 1$.

$$\chi_\gamma = \frac{e\sqrt{-(F_{\mu\nu}k^\nu)^2}}{m^3} = \frac{\omega|\vec{E}_\perp + \vec{n} \times \vec{B}|}{mE_{\text{crit}}}$$

- An electron will emit all its energy in a single photon if $\chi = 1$.

$$\chi_e = \frac{e\sqrt{-(F_{\mu\nu}p^\nu)^2}}{m^3} \simeq \frac{\gamma|\vec{E}_\perp + \vec{v} \times \vec{B}|}{E_{\text{crit}}}$$

Classical nonlinearity parameter, a_0

force exerted by electric field

laser wavelength

$$a_0 = \frac{eE\,\frac{c}{\omega}}{mc^2}$$

electron energy

- Does the field do enough work over one wavelength to accelerate the electron to relativistic energy?

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force exerted by electric field

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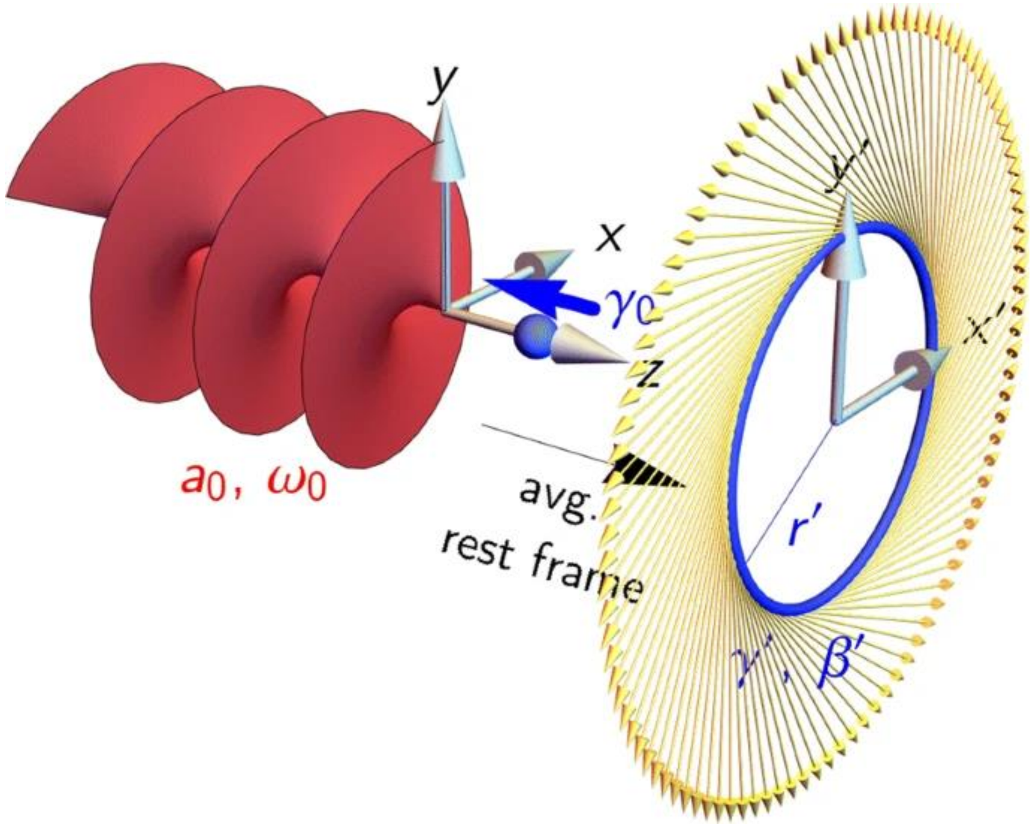


Blackburn, RMPP 2020

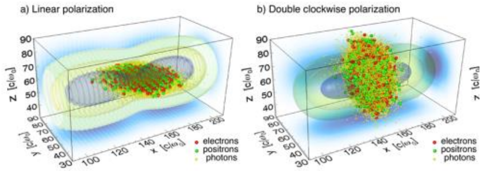
- Electron moves relativistically with transverse momentum mca_0.
- The characteristic frequency of the emitted radiation to the orbital (cyclotron) frequency:

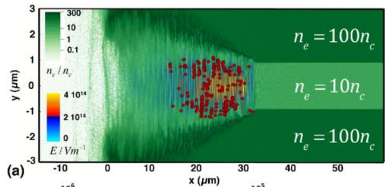
$$\frac{\omega'}{\omega_c} \simeq a_0^3$$

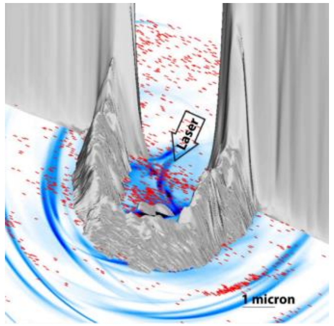
- Harmonic order of the emitted radiation, or number of participating photons.

Where are these fields?

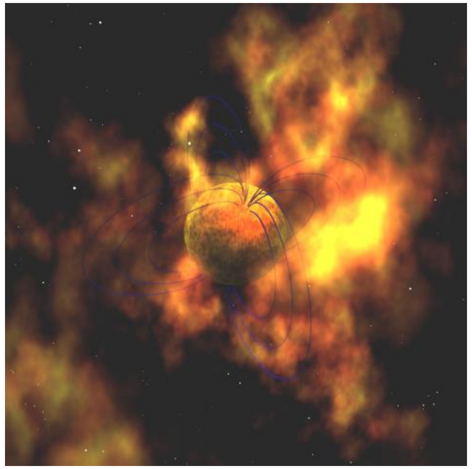
- High-intensity lasers: strong fields because a_0 is large, but also large χ because of accelerated electrons. Field is also spatially macroscopically large (even if characteristic scales are 10s micron/10s fs)







- Compact objects: magnetic fields around pulsars/magnetars >10^8 T (10% of $B_{\rm crit}$), with TeV accelerated particles. (χ depends on pitch angle.)



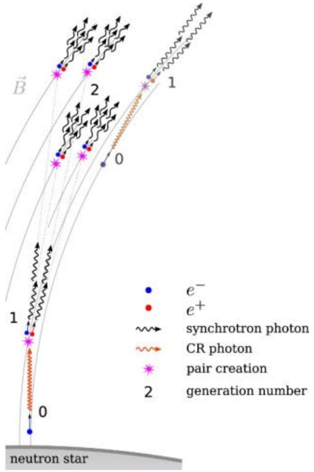
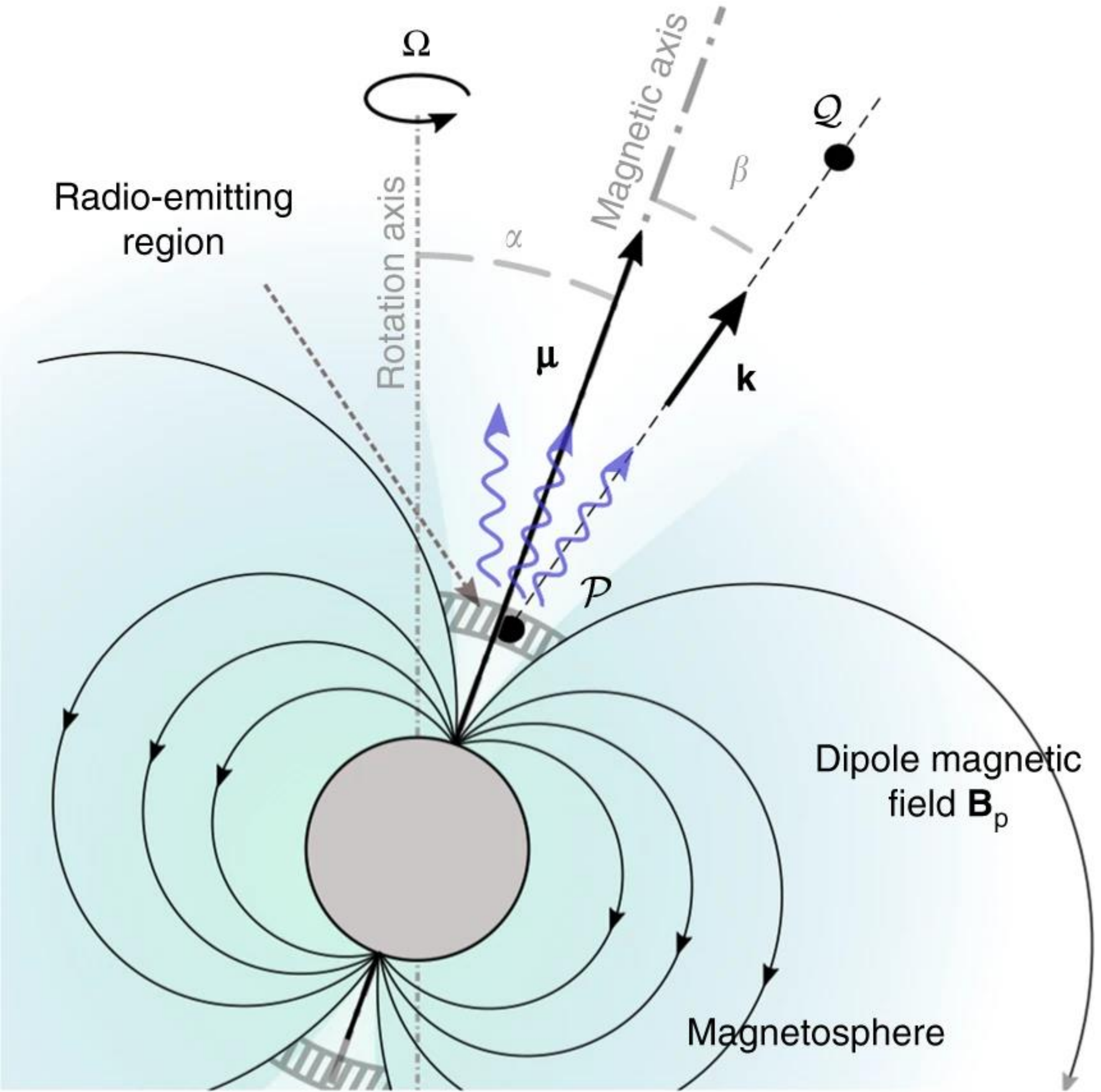


Image credits: Grismayer et al, Stark et al, Ridgers et al, Timokhin et al.

Neutron stars

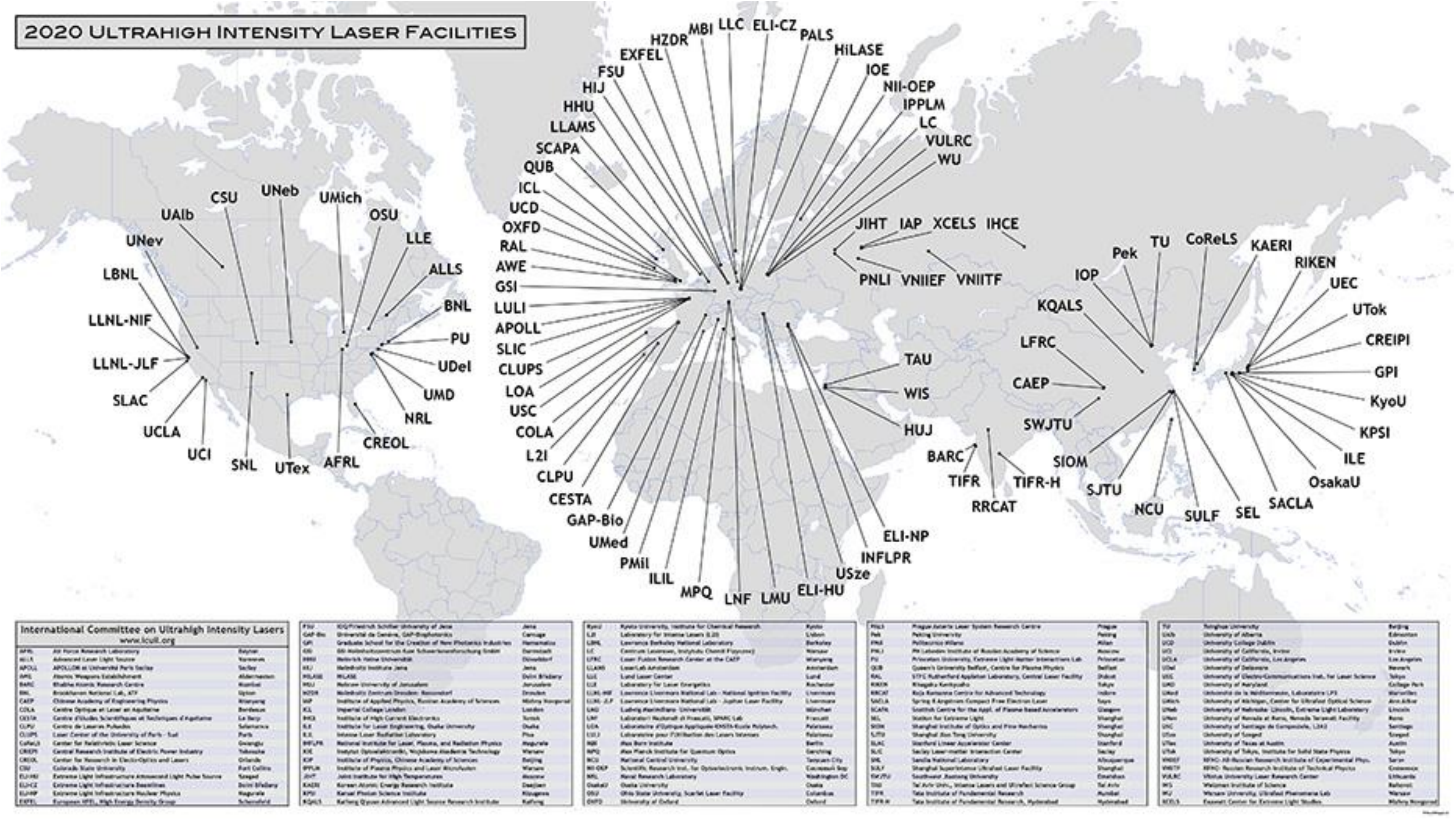


- Magnetic field strength 10^8 to 10^{11} T (the strongest around magnetars)
- Magnetosphere filled with electron-positron plasma
- Source is photon decay in the polar cap or gamma-X collisions in the outer gap.
- Pair plasma that is relativistic, radiative and quantum-electrodynamical.

Guerolt et al, Nat Commun, 2019

Where do we find strong EM fields?

High-power lasers



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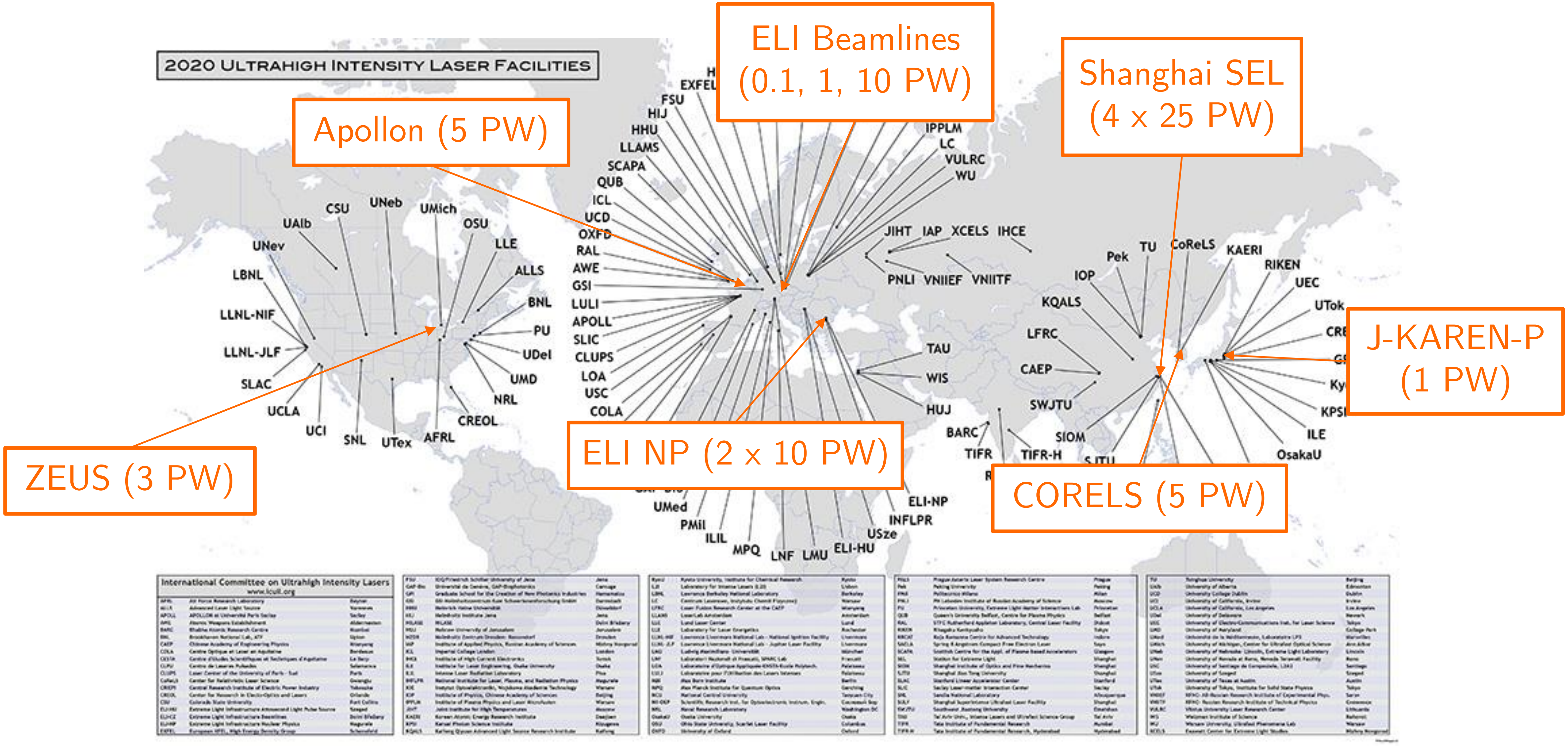
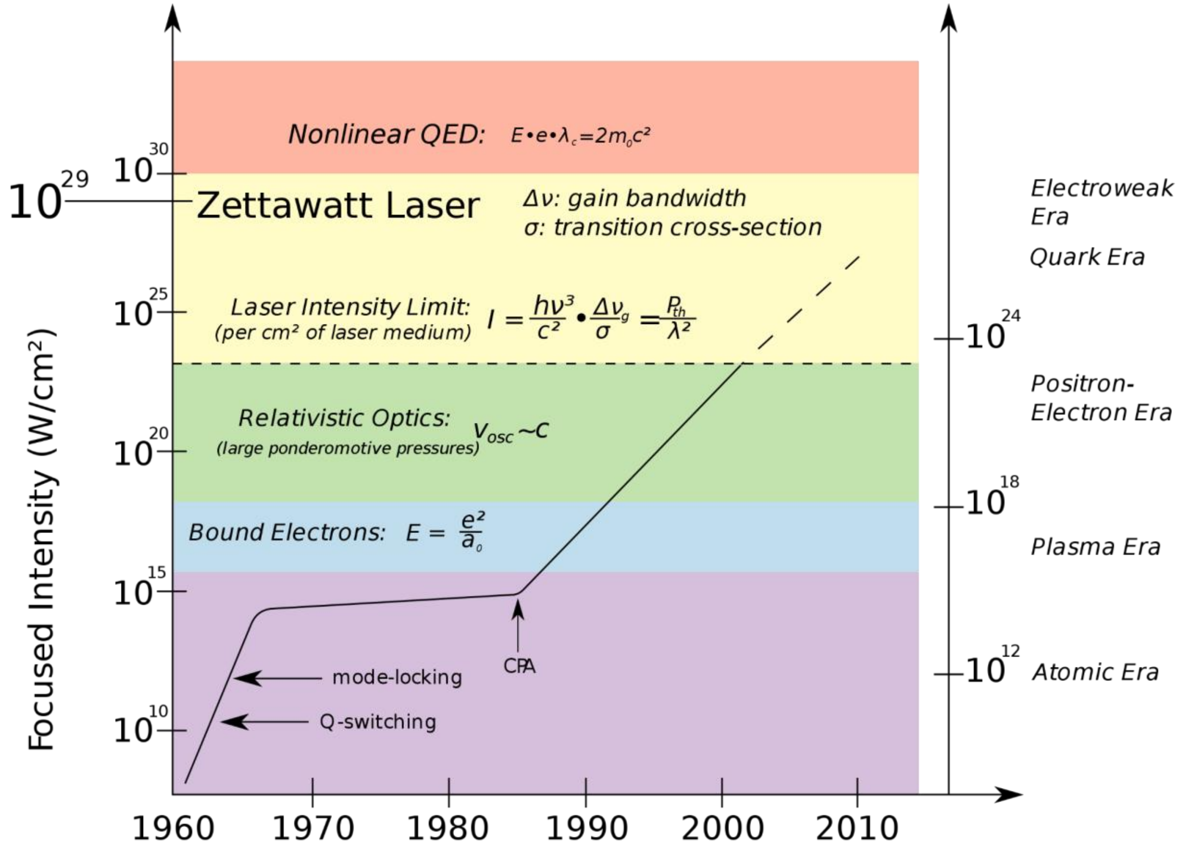


High-intensity lasers



"Moore's law" for laser intensity

- Intensity = power / area
- Characteristic power = TW to PW
- Area = wavelength^2 = micron^2
- Record intensity = 10^{23} W/cm^2 (odd choice of units, for historical reasons)
- Equivalent to focusing all the solar power that falls on Earth to a spot the size of a human hair.

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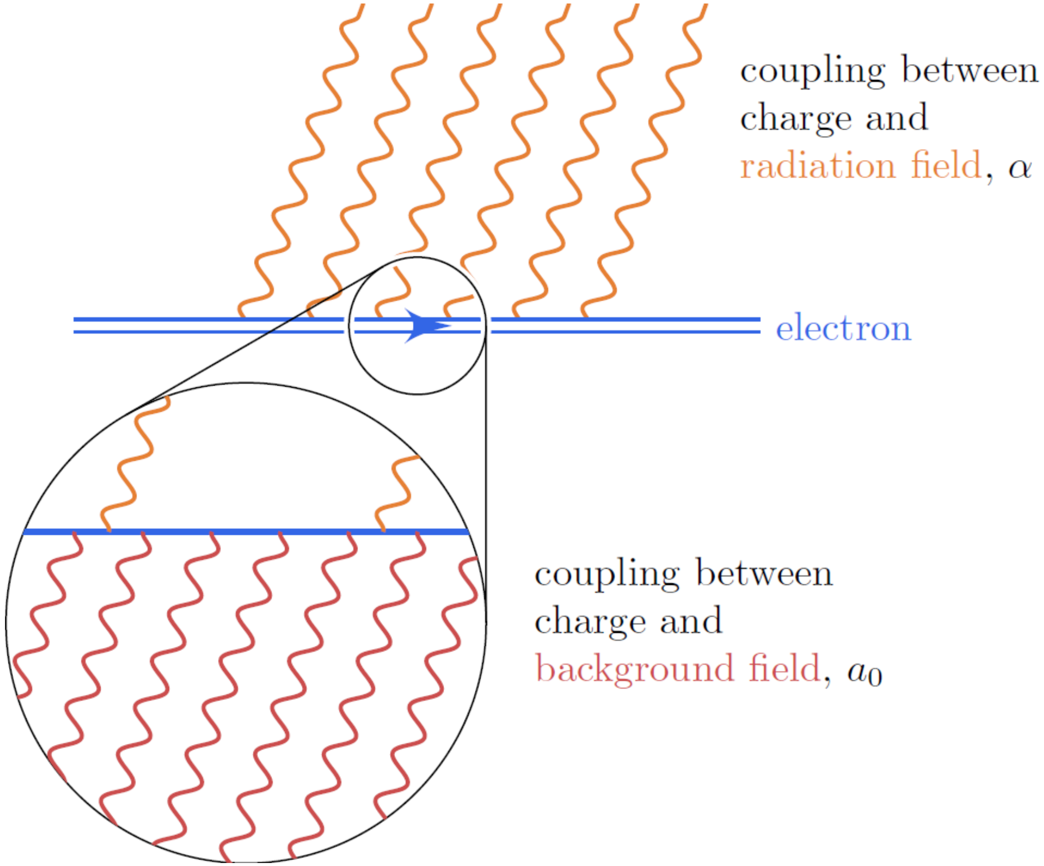
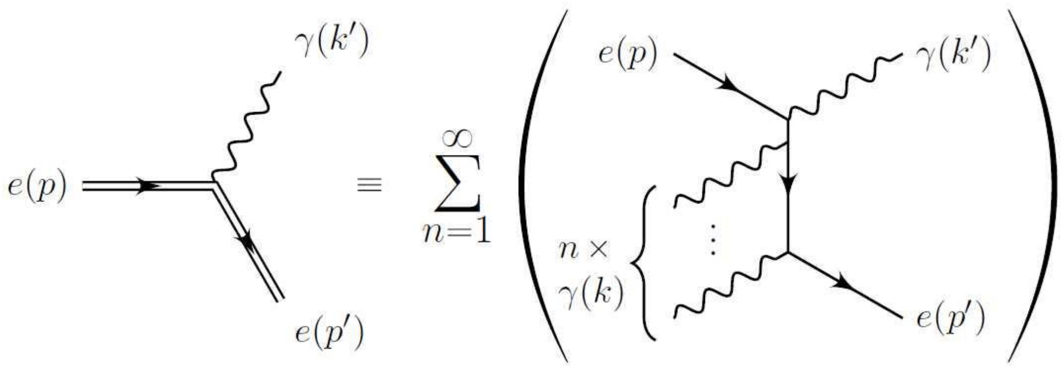
Background and radiation fields



Gonoskov et al, RMP 94, 045001 (2022)

- Splits the EM field into a fixed, classical background and a fluctuating, quantized radiation field.
- Two kinds of nonperturbativity: absorbing many photons from the background (scaling as $a_0{}^3$) – need ‘all order’ solutions.
- Emitting many photons: depends on strength and size/duration of the field.

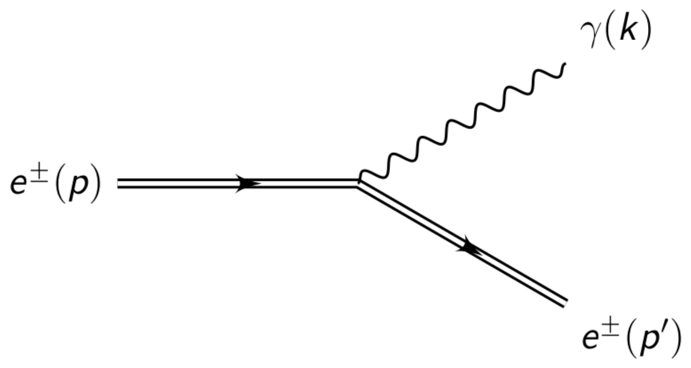
Nonperturbativity in the background field

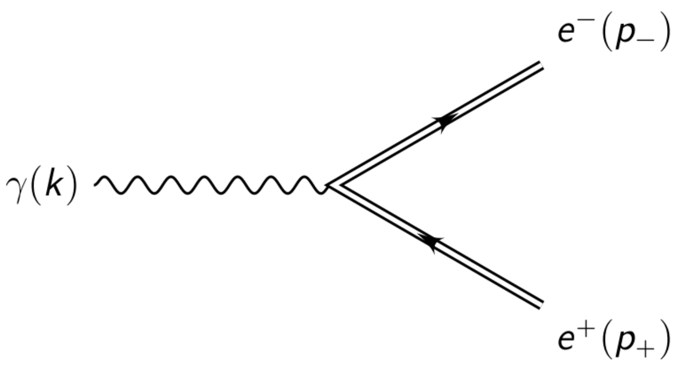


$$j^\mu = \frac{\bar{\Psi}\gamma^\mu\Psi}{\bar{\Psi}\Psi} = \frac{p^\mu(\phi)}{m} = \frac{p_0^\mu + eA^\mu}{m} - \left(\frac{eA.p_0}{k.p_0} + \frac{e^2A^2}{2k.p_0}\right)$$

- This is what the double lines in strong-field QED diagrams means – the interaction with the background field is accounted for exactly.
- In a plane-wave background, the wavefunctions (Volkov states) have a phase-dependent momentum.
- The probability current coincides with classical solution of the Lorentz force equation.

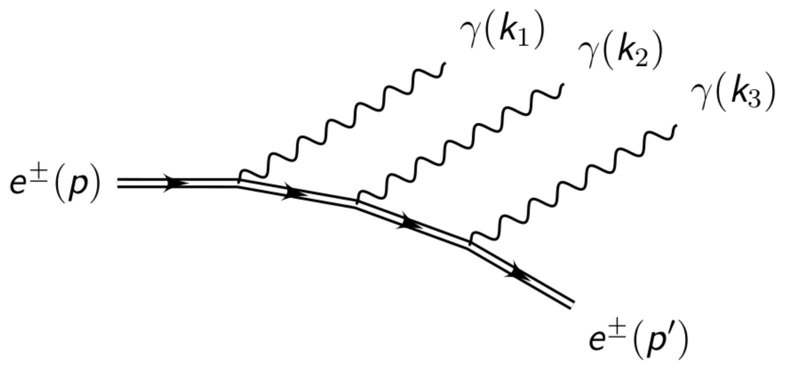
Building blocks

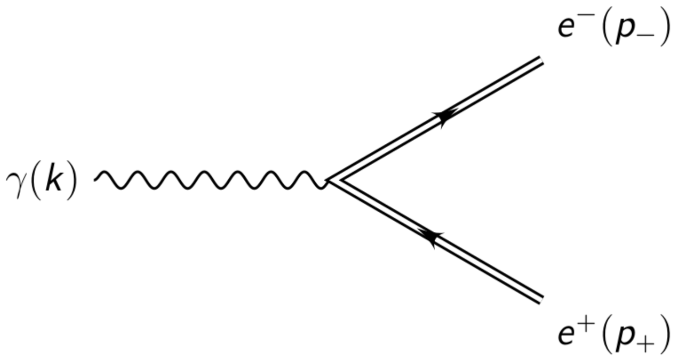




- Simplest two: photon emission and pair creation. Each first order in the fine-structure constant α.
- Expect that first order processes are more probable than second order, which are more probable than third order, etc.
- However, in strong (or long-duration) electromagnetic fields, the probability for only one event is suppressed.

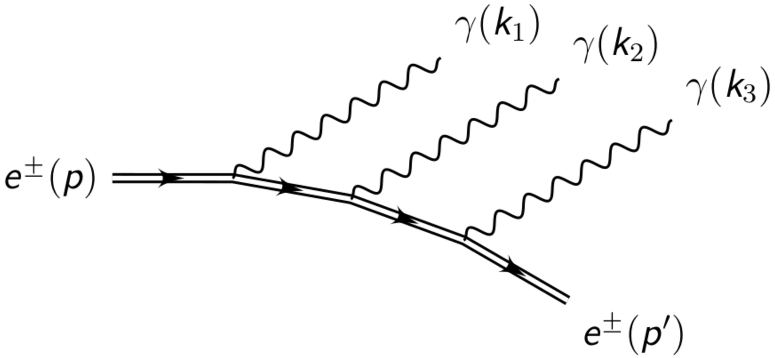
Strong-field QED processes
… at higher order

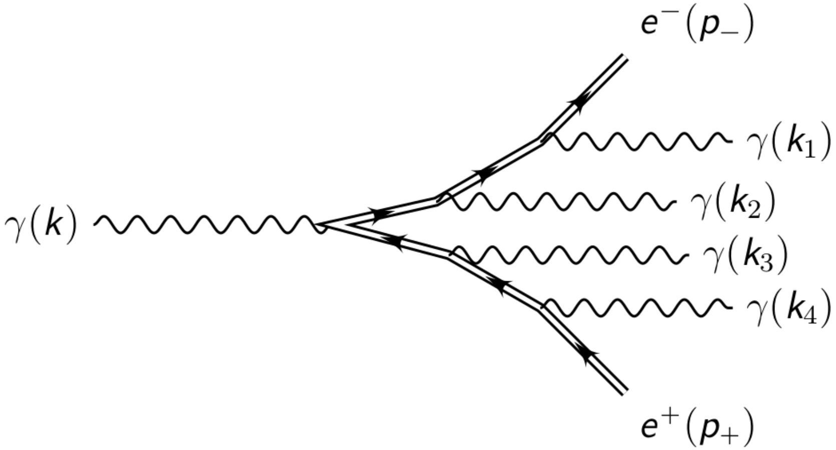




- A single high-energy electron emits many photons (radiation reaction).

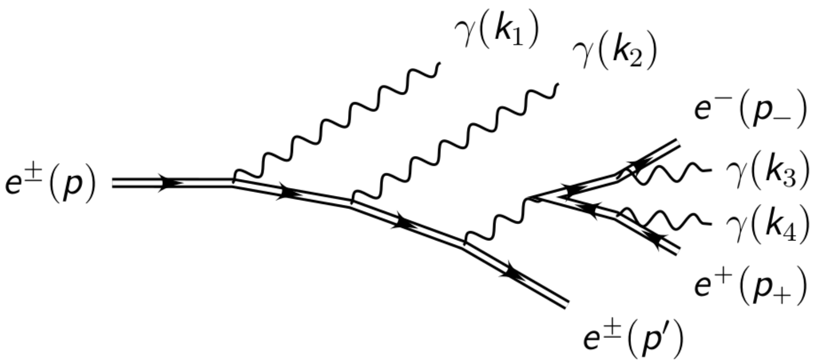
… at higher order

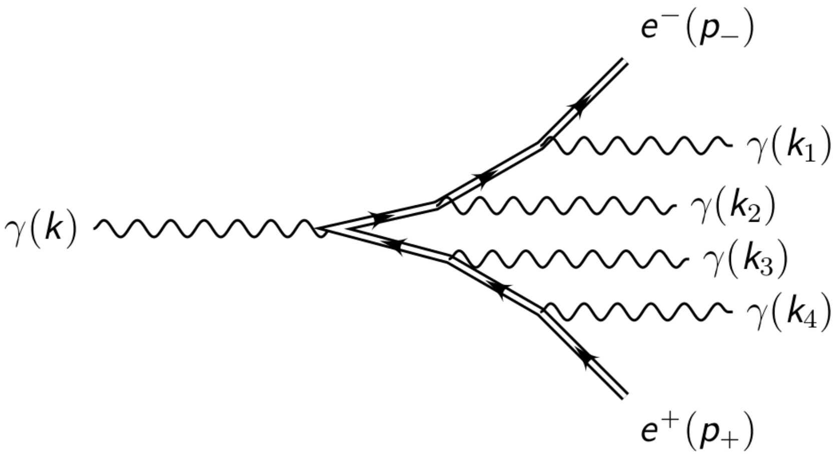




- A single high-energy electron emits many photons (radiation reaction).
- A single photon creates an electron and positron that radiate additional photons.

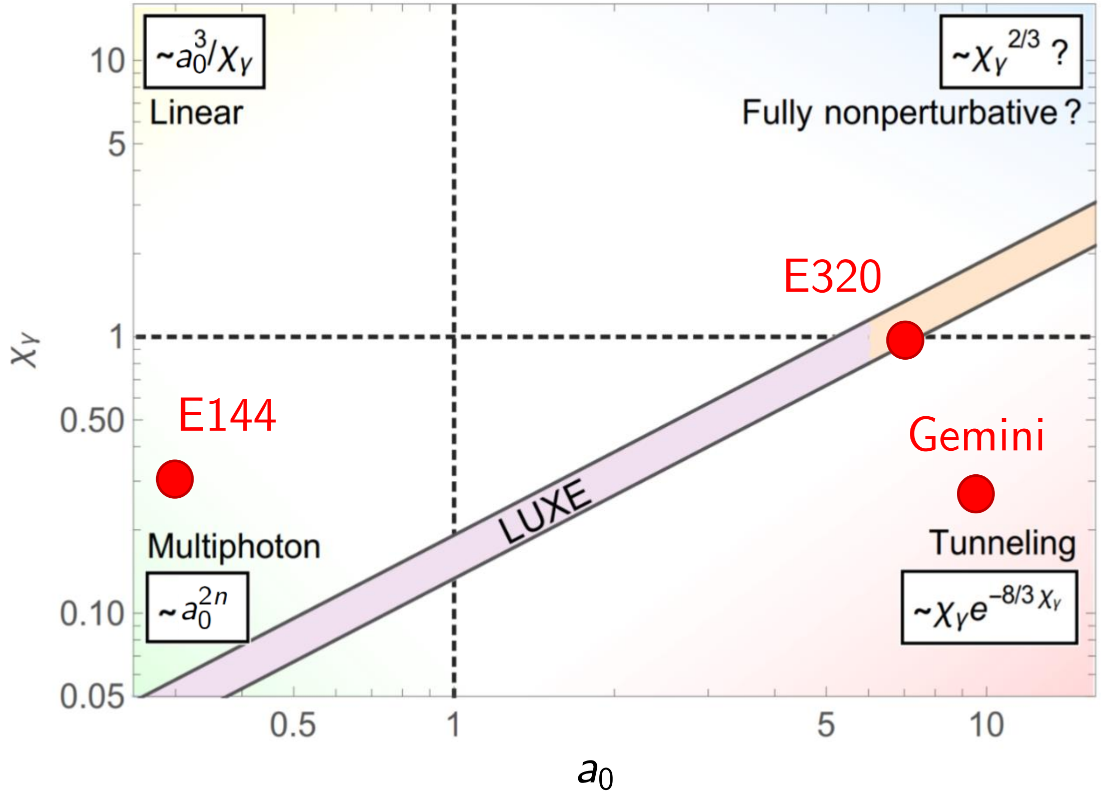
... at higher order





- A single high-energy electron emits many photons (radiation reaction).
- A single photon creates an electron and positron that radiate additional photons.
- ... and so on (e.g. trident pair creation).

Parameter regimes



Abramowicz et al, EPJST 230, 2445 (2021); arXiv:2102.02032

- Classical nonlinearity
  How multiphoton is the interaction?

$$a_0 = \frac{eE}{m\omega_0} = 8.5\left(\frac{I\lambda^2}{10^{20}\ \mathrm{Wcm^{-2}}\mu\mathrm{m}^2}\right)^{1/2}$$

- Quantum nonlinearity
  Recoil parameter; electric field in rest frame / critical (Schwinger) field

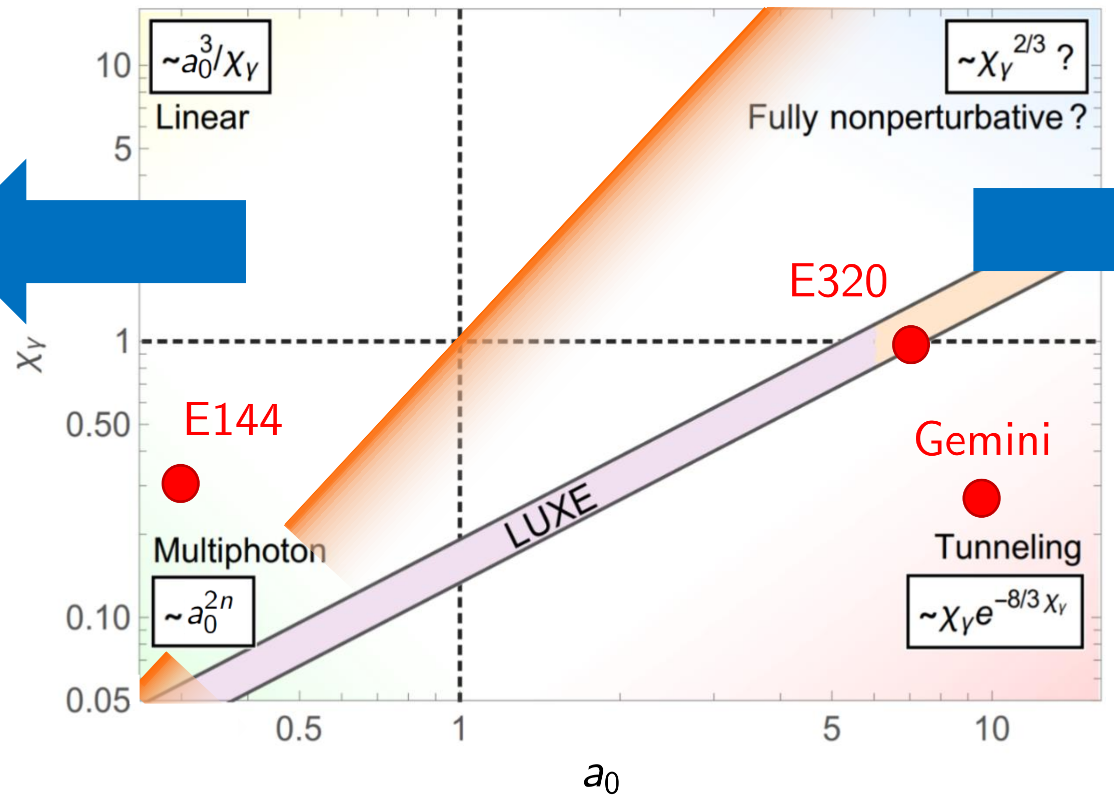
$$\chi = \frac{\gamma E}{E_{\mathrm{crit}}}$$
$$= 0.4\left(\frac{\mathcal{E}}{10\ \mathrm{GeV}}\right)\left(\frac{I}{10^{20}\ \mathrm{Wcm^{-2}}}\right)^{1/2}$$

Parameter regimes

$a_0^3 = \chi$

low intensity,
weakly multiphoton,
use perturbation
theory

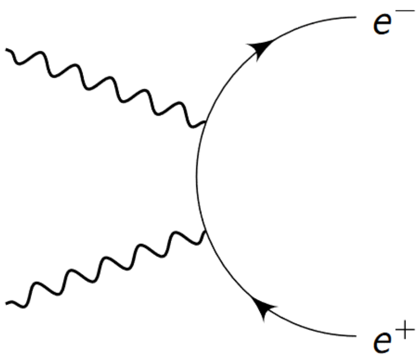
$a_0^3 \ll \chi$



high intensity,
quasistatic,
tunnelling,
field can be treated as
being locally constant

$a_0^3 \gg \chi$

Quasistatic fields



Linear Breit-Wheeler

- Particle-driven
- Perturbative, cross section $\sigma \sim \alpha \lambda_c^2$
- Not yet observed with real photons

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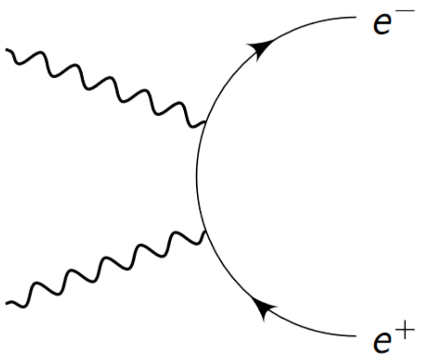

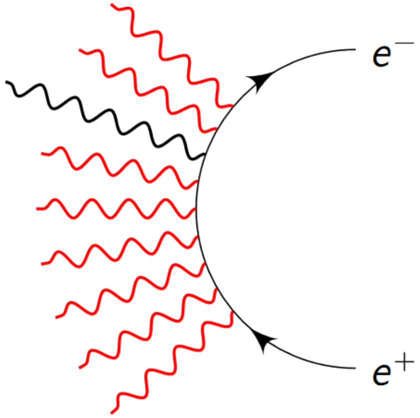

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- Non-analytic dependence on charge e through χ, $P \sim \exp(-8/3\chi)$ at large a_0

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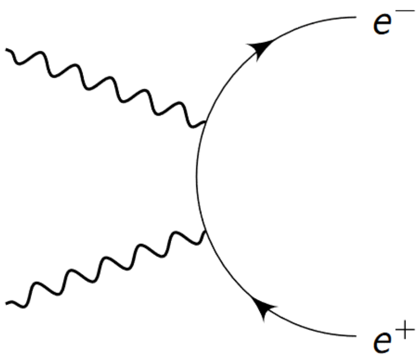

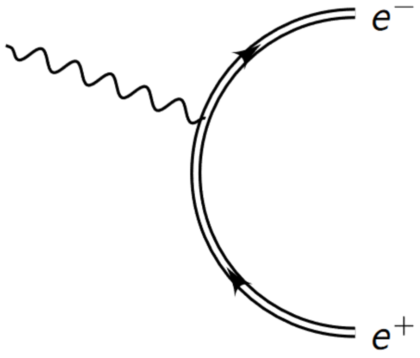

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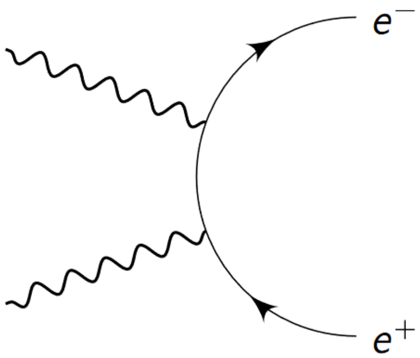
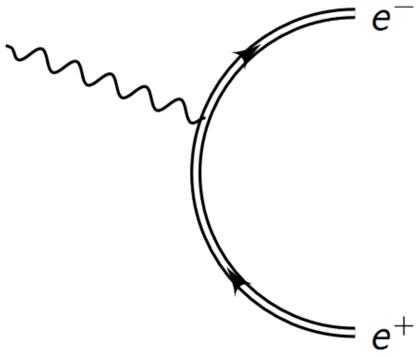
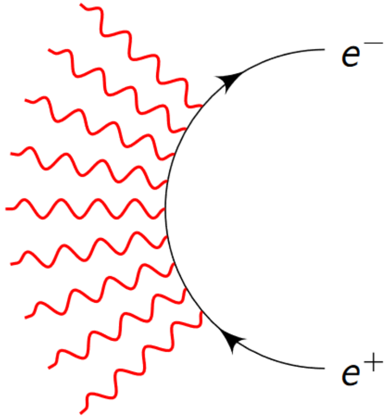
Strong-field QED processes

Quasistatic fields







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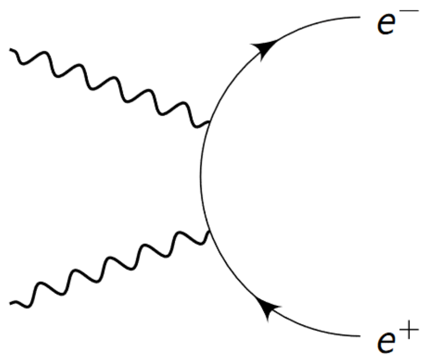
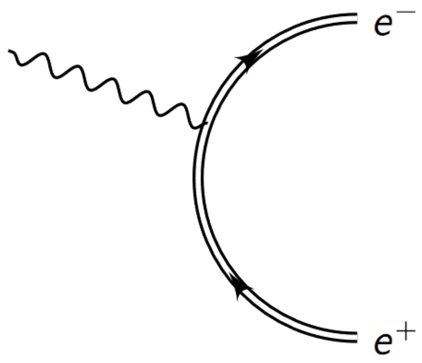
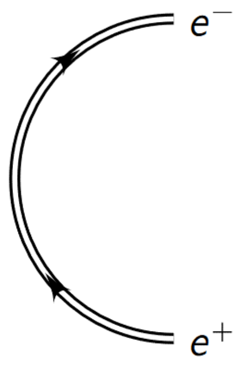
Schwinger

- Field-driven
- Non-analytic dependence on charge e through f, g, $P \sim \exp(-\pi/f)$ for static electric field

Quasistatic fields







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What do we want to do?

- Investigate the transition from perturbative to nonperturbative QED.
  - Scan a_0 from 0.5 to 5 at $\chi > 0.1$.
  - Yield is very low in the perturbative regime even if $\chi > 1$.
- Measure nonperturbative pair creation from light alone ("sparking the vacuum")
  - "Tunnelling" pair creation requires $\chi > 1$ for real photons and large a_0.
- Investigate the onset of higher order processes: from trident pair creation to EM showers, from single to multiple photon emission.
  - Sustain large a_0 and χ for sufficient duration.

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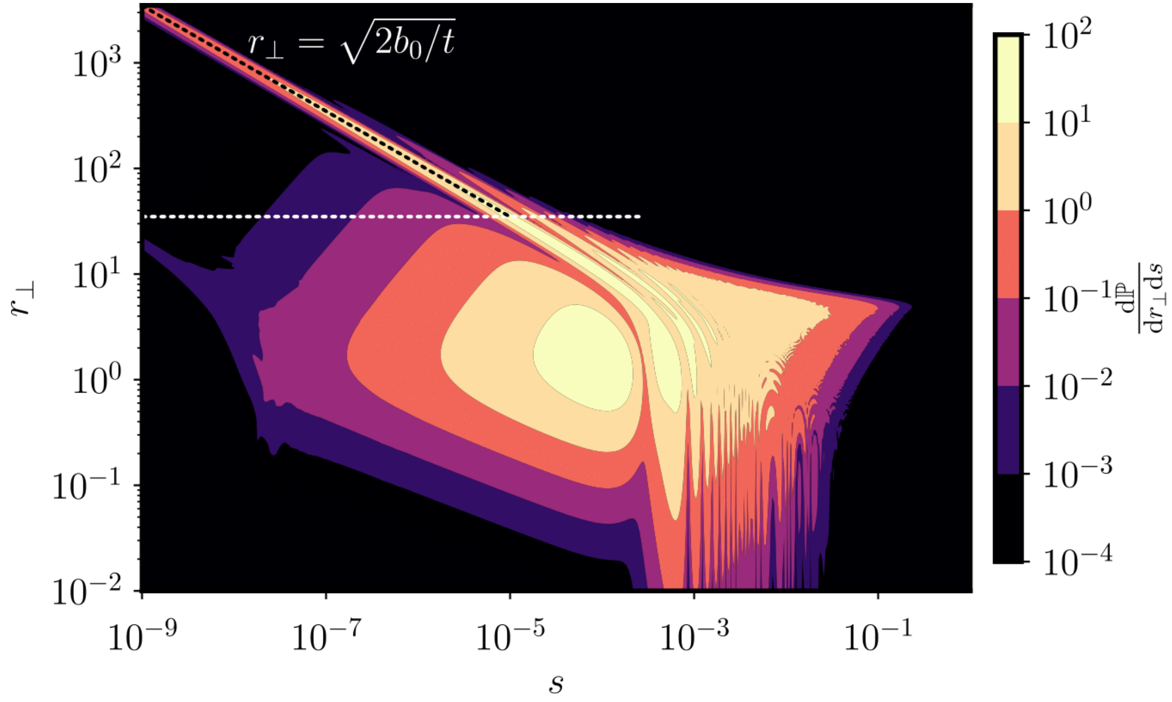
Scattering calculations

$$\frac{\mathrm{d}^3\mathbb{P}}{\mathrm{d}f\,\mathrm{d}^2\mathbf{r}_\perp} = \frac{\alpha m^2}{(4\pi\omega_0 p^+)^2}\frac{f}{1-f}\frac{1}{2}\sum_{\text{spin,pol}}\left|\sum_j \mathscr{T}_j\mathscr{C}_j\right|^2$$

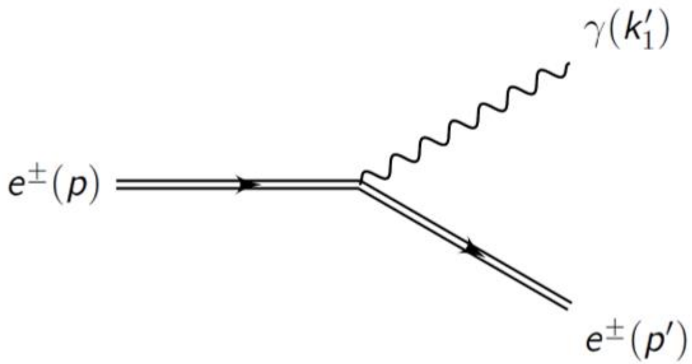


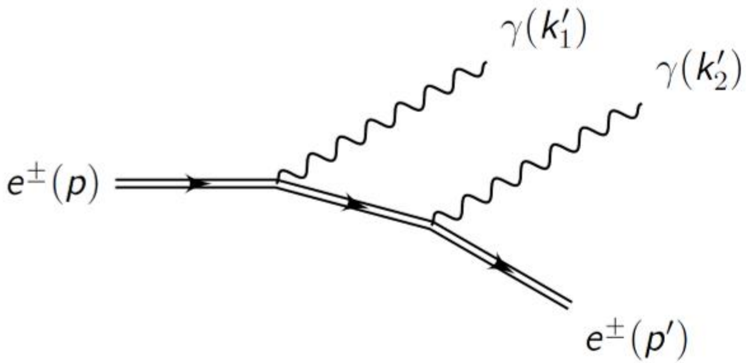
Ilderton et al, PRA 99, 042121 (2019)

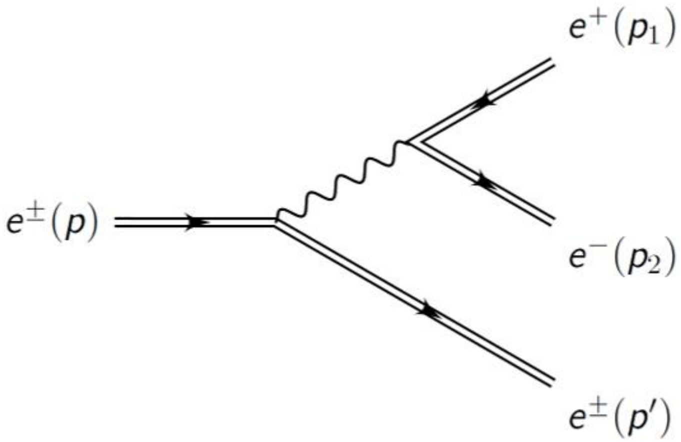
- Fundamental approach: treat interaction with laser field exactly (i.e. nonperturbatively) and expand perturbatively in the dynamical EM field (i.e. the high-energy photons).
- Limitations: transition between asymptotic states → complete knowledge of background field required, can't do arbitrary field configurations, backreaction neglected, multiplicity (# particles in final state).

Scattering calculations

electron-seeded + pulsed plane wave:







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Boca and Florescu, PRA 80, 053403 (2009)
Harvey, Heinzl and Ilderton, PRA 79, 063407 (2009)
Mackenroth, Di Piazza and Keitel, PRL 105, 063903 (2010)
Heinzl, Ilderton and Marklund, PLB 692, 250 (2010)
Krajewska and Kaminski, PRA 85, 062102 (2012)
... and many more

Lötstedt and Jentschura, PRL 103, 110404 (2009)
Seipt and Kämpfer, PRD 85, 101701 (2012)
Mackenroth and Di Piazza, PRL 110, 070402 (2013)
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Dinu and Torgrimsson, PRD 97, 036021 (2018)
King and Fedotov, PRD 98, 16005 (2018)
Mackenroth and Di Piazza, PRD 98, 116002 (2018)
Dinu and Torgrimsson, PRD 102, 16018 (2020)

Also: resummation techniques for very high-order processes

Probability rates

$$\frac{dP}{dk_-} = -i\frac{\alpha}{2\pi}\frac{1}{p_-}\frac{\xi_0}{\chi_0}\int \frac{d\varphi d\varphi'}{\varphi - \varphi' + i0}\left\{1 + \frac{p_-^2 + p_-'^2}{4p_- p_-'}[\boldsymbol{\xi}_\perp(\varphi) - \boldsymbol{\xi}_\perp(\varphi')]^2\right\}$$
$$\times \exp\left\langle i\frac{1}{2}\frac{k_-}{p_-'}\frac{\xi_0}{\chi_0}\left\{\varphi - \varphi' + \int_{\varphi'}^{\varphi} d\tilde{\varphi}\,\boldsymbol{\xi}_\perp^2(\tilde{\varphi}) - \frac{1}{\varphi - \varphi'}\left[\int_{\varphi'}^{\varphi} d\tilde{\varphi}\,\boldsymbol{\xi}_\perp(\tilde{\varphi})\right]^2\right\}\right\rangle$$

$$\downarrow$$

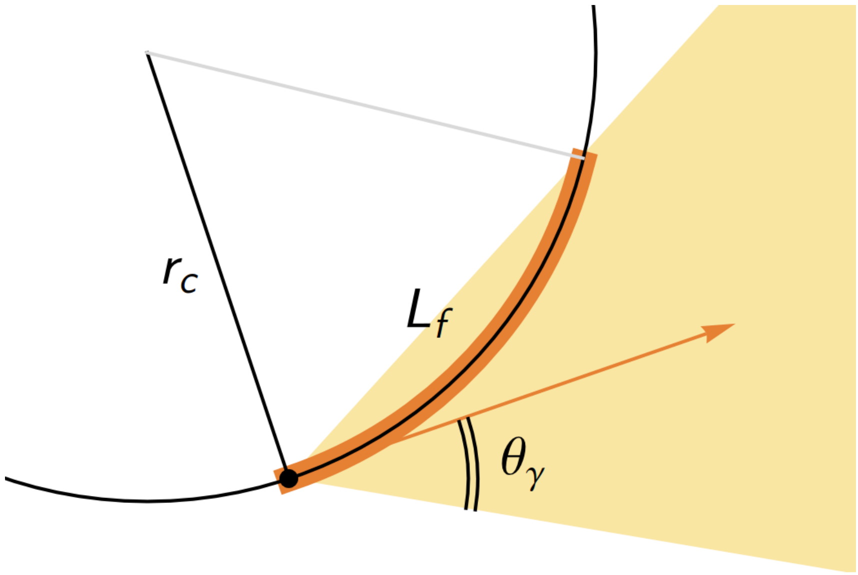
$$\frac{dP}{dk_- d\varphi_+} = \frac{\alpha}{2\pi}\frac{1}{p_-}\frac{\xi_0}{\chi_0}\mathrm{Im}\int \frac{d\varphi_-}{\varphi_- + i0}\left\{1 + \frac{p_-^2 + (p_- - k_-)^2}{4p_-(p_- - k_-)}\left[\boldsymbol{\xi}_\perp\left(\varphi_+ - \frac{\varphi_-}{2}\right) - \boldsymbol{\xi}_\perp\left(\varphi_+ + \frac{\varphi_-}{2}\right)\right]^2\right\} e^{i\Phi(k_-,\varphi_-,\varphi_+)},$$

$$\Phi(k_-, \varphi_-, \varphi_+) = \frac{1}{2}\frac{k_-}{p_- - k_-}\frac{\xi_0}{\chi_0}\left\{\varphi_- + \int_{-\varphi_-/2}^{\varphi_-/2} d\tilde{\varphi}\,\boldsymbol{\xi}_\perp^2(\varphi_+ + \tilde{\varphi}) - \frac{1}{\varphi_-}\left[\int_{-\varphi_-/2}^{\varphi_-/2} d\tilde{\varphi}\,\boldsymbol{\xi}_\perp(\varphi_+ + \tilde{\varphi})\right]^2\right\},$$

from Di Piazza et al, PRA 98, 012134 (2018)

- Probability for a single-vertex process is given by a double integral over phase variables φ_1 and φ_2.
- Exchange for average phase $\varphi_{av} = (\varphi_1 + \varphi_2)/2$ and interference phase $\varphi = (\varphi_1 - \varphi_2)/2$.
- In the limit that the interference phase is small, the probability is a single integral over a probability rate.

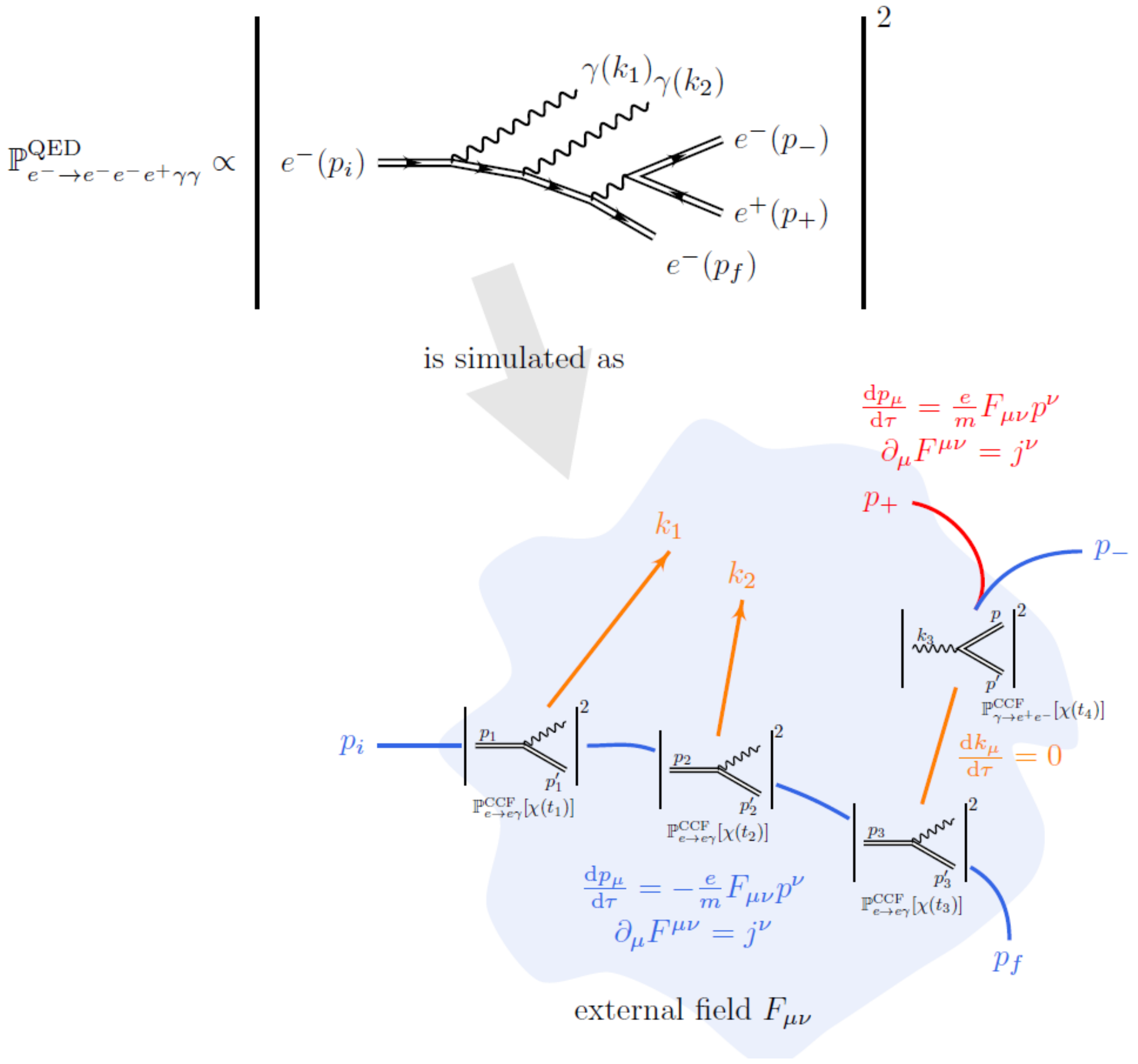
Quasistatic fields



- If a_0 is large, rates depend only on instantaneous quantum parameter χ.
- Can be understood classically as χ controlling the radius of curvature of the electron trajectory.
- Characteristic distance over which the photon is emitted:

$$\frac{L_f}{C} = \frac{1}{2\pi a_0}$$

Factorising high-order processes

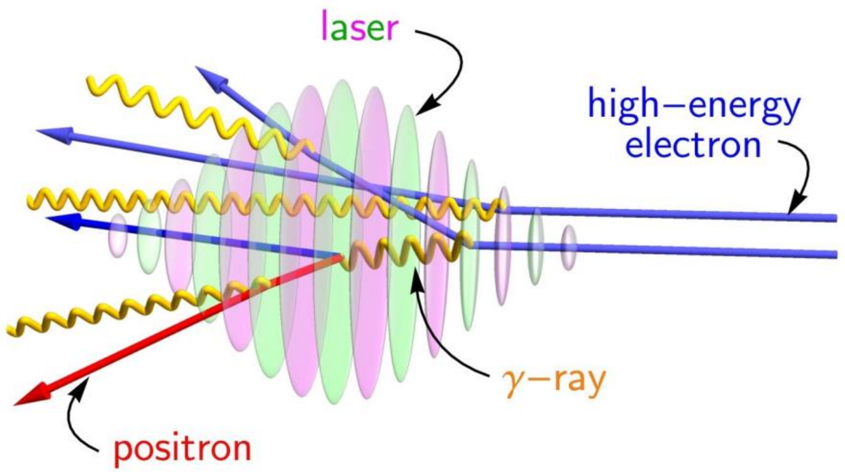


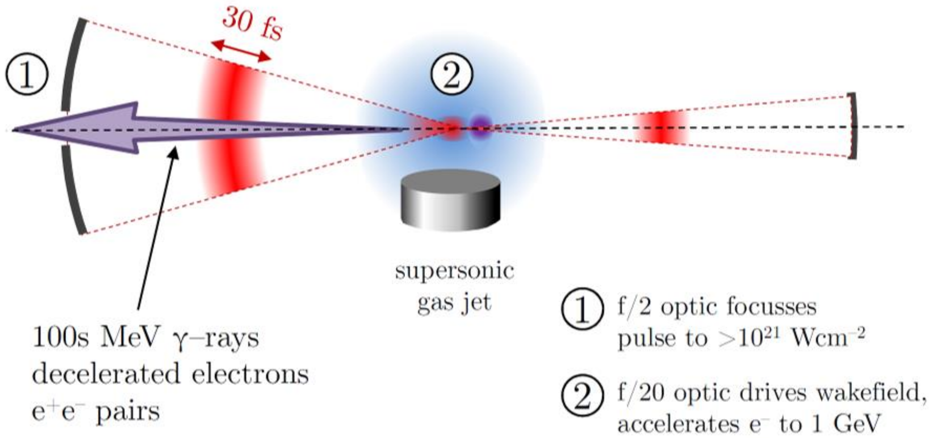
- QED rates in the LCFA / LMA + point-like emission events linked by classical trajectories that are determined by Lorentz force / ponderomotive force equation.
- Higher-order processes are broken down into a chain of first-order processes.
- Requires $a_0 \gg 1$ (strictly, $a_0^3/\chi \gg 1$) or sufficiently long pulses.

On the theory side...

- If first-order processes dominate (e.g. electron emits only one photon), possible to do everything exactly, with perturbation theory.
  - Small a_0 only.
  - Requires the full spatiotemporal structure of the background field.
- In the transition regime, interference at the scale of the laser wavelength can be accounted for using LMA-based simulations + factorisation.
  - Requires "long" duration, estd. accuracy for energy spectrum is few %.
  - Intermediate particles assumed to be on shell...
- Error less well characterised for higher order processes.
  - Loop corrections scale as $\alpha\chi^{2/3}$ (large a0!)

Current experimental status



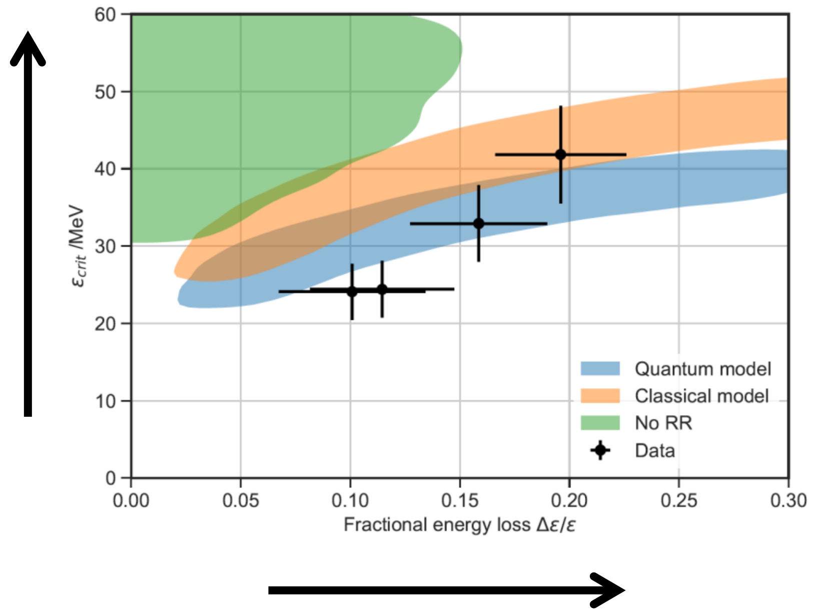


T G Blackburn et al, PRL 112, 015001 (2014)

- With higher laser intensities available, we could reach a similar χ with much lower electron energies, as well as the radiation-reaction regime $R_c > 1$.
- In the "all-optical" configuration, one laser is used to drive a wakefield, accelerating the electron beam; the other acts as the target. This exploits the small size of the electron beam and inherent synchronization of the lasers.

Current experimental status

harder gamma spectrum

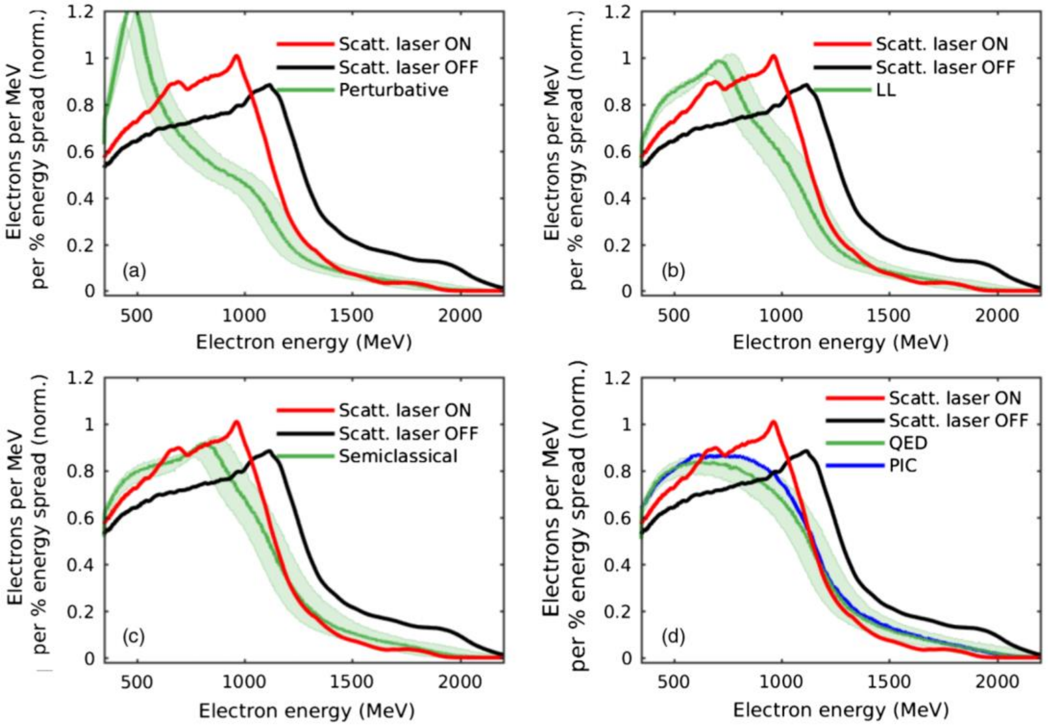


decreasing electron energy

J M Cole et al, PRX 8, 011020 (2018)

- 4 shots with CsI signal significantly above background.
- Hardest gamma rays associated with lowest energy in electron beam: indicative of a radiation reaction process.
- Data inconsistent with neglect of RR. Classical RR overpredicts critical energies. Quantum RR slightly better, but not distinguishable beyond 1 sigma.

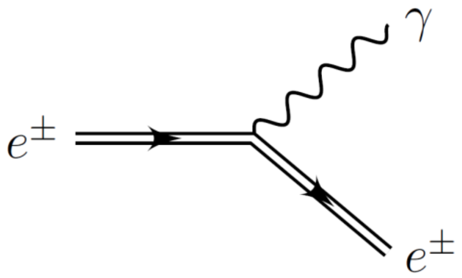
Current experimental status



K Poder et al, PRX 8, 031004 (2018)

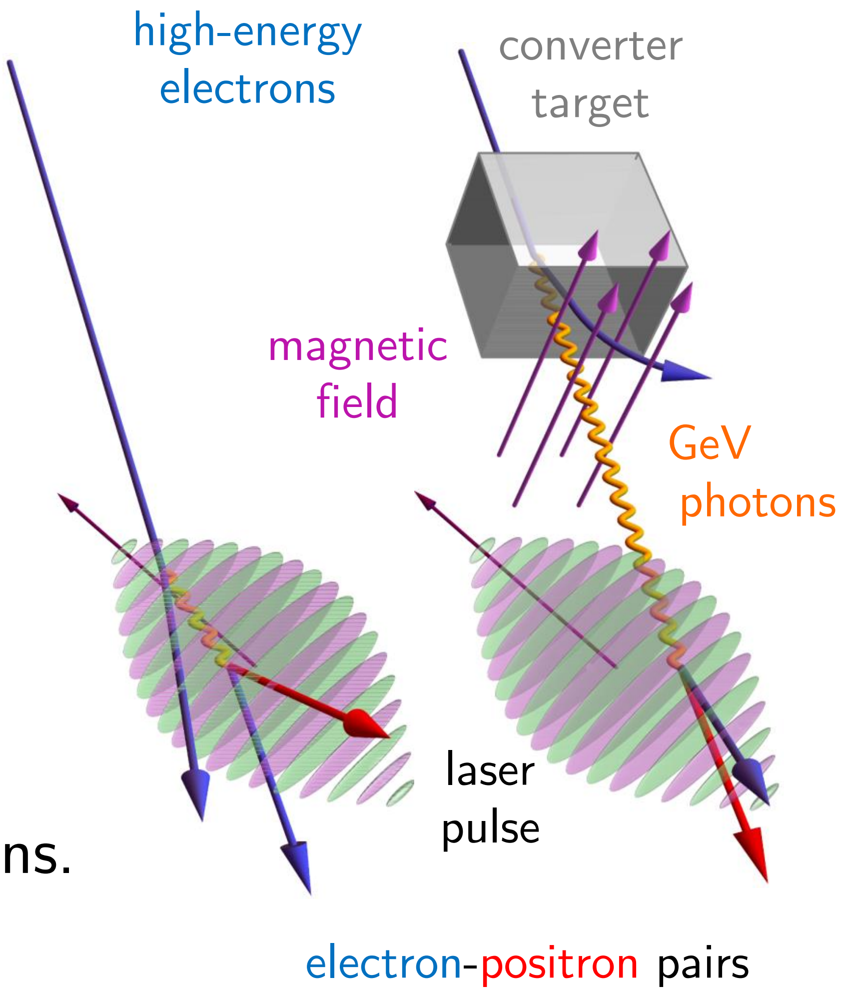
- Comparison of predicted and measured electron energy spectra for various models.
- $R^2 = 87\%$ for classical (Landau-Lifshitz) vs 92% (96%) for stochastic (deterministic) quantum RR.
- Quantum corrections present, but agreement lacking. Failure of the approximations in simulations? Characterization of initial conditions?

LUXE modes of operation



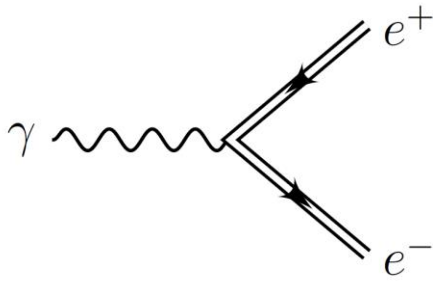
Electron-laser collisions:

- Nonlinear Compton scattering of multi-GeV photons
- “Mass shift” of the electrons.
- Trident electron-positron pair creation



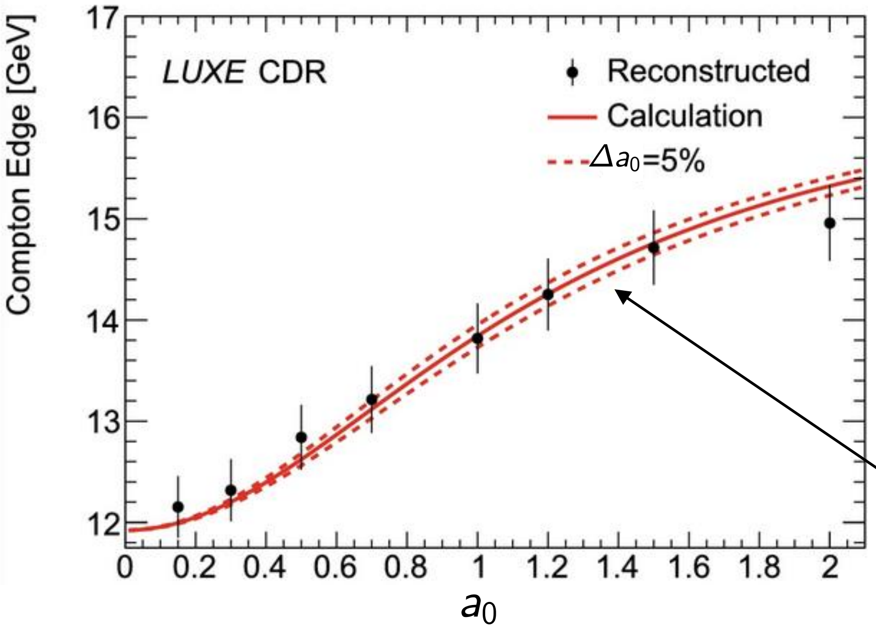
Photon-laser collisions:

- Electron bunch directed onto foil, bremsstrahlung photons collide with the laser downstream
- Nonlinear Breit-Wheeler pair creation



Uncertainties and unknowns

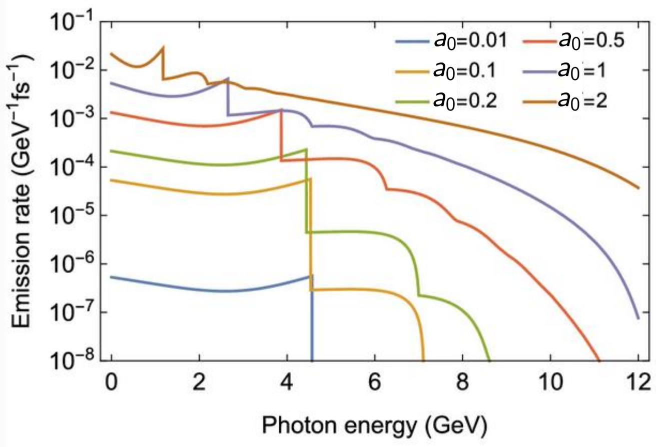
Nonlinear Compton scattering



Reconstructed from simulated data, precision (2.5%) dominated by energy scale uncertainty assuming 1 hour of data taking

- Position of the first nonlinear Compton edge is intensity-dependent ("mass shift"):

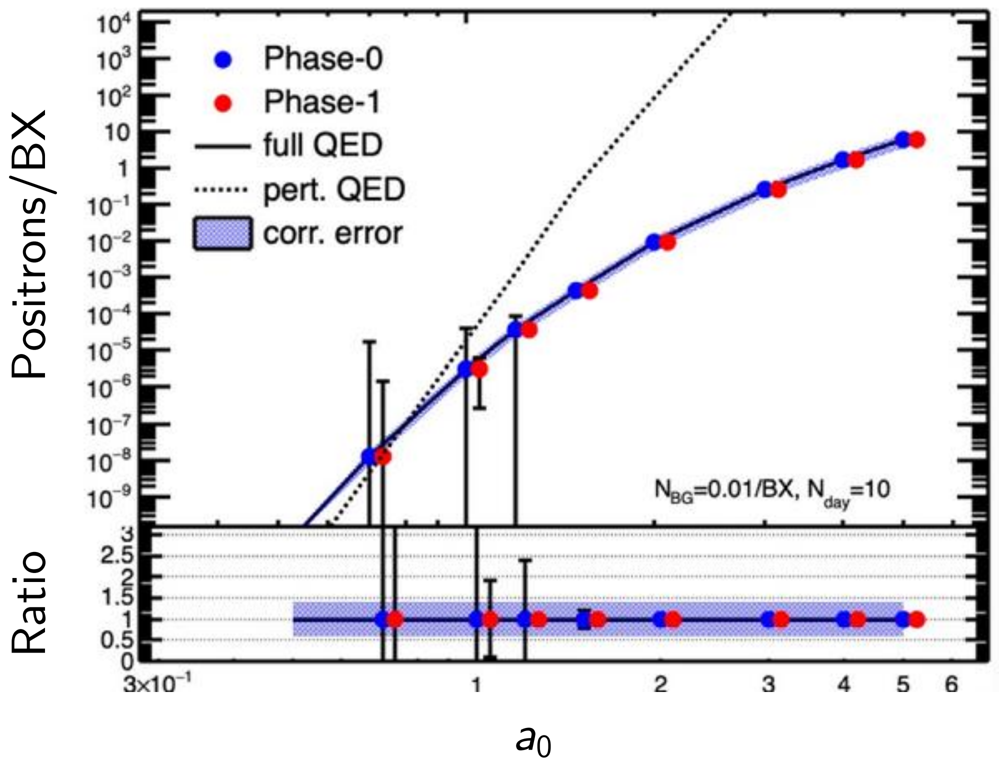
$$\frac{\mathcal{E}_\gamma}{\mathcal{E}_e} = \frac{2\eta}{1 + a_0^2 + 2\eta}$$



energy parameter

$$\eta \simeq \frac{(1+\cos\theta)\mathcal{E}\omega_L}{m^2}$$

Electron-positron pair creation



Positron yield per collision [LUXE Conceptual Design Report, arXiv:2102.02032]

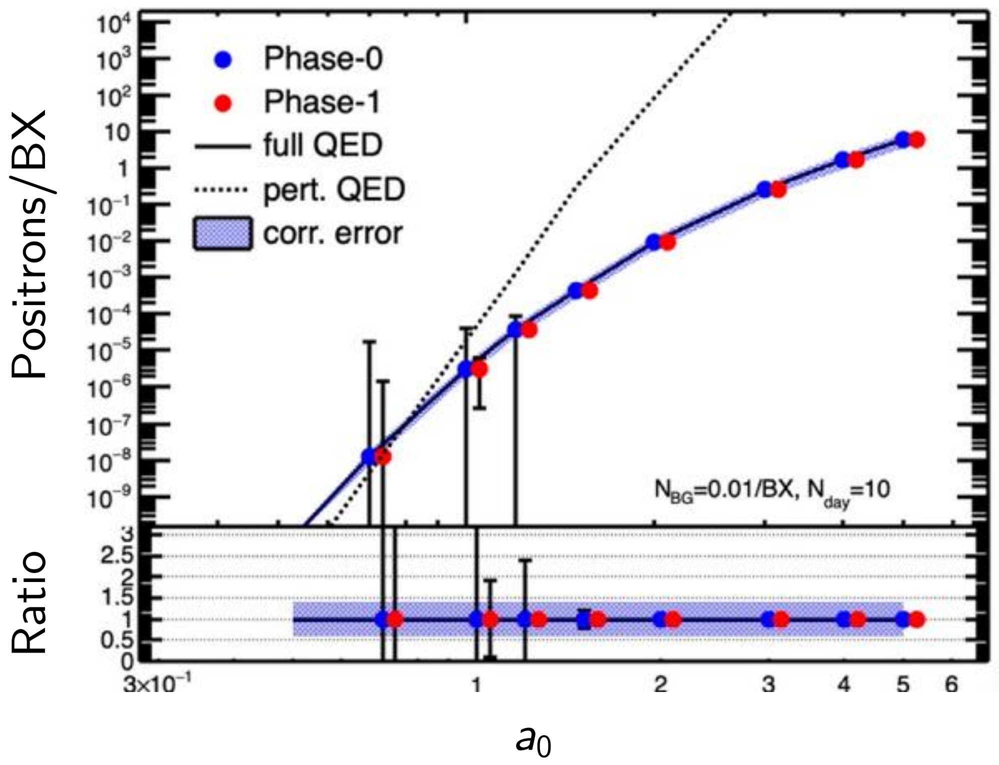
- Measure positron yield as a function of laser intensity.
- "Turning of the curve": dependence of the rate on a_0 moves from power law (multiphoton)

$$N_\pm \sim a_0^{2n} \qquad n = \lceil 2(1 + a_0^2)/\eta \rceil$$

to Schwinger-like (tunnelling) scaling

$$N_\pm \sim a_0 \eta \exp\left(-\frac{8}{3a_0\eta}\right)$$

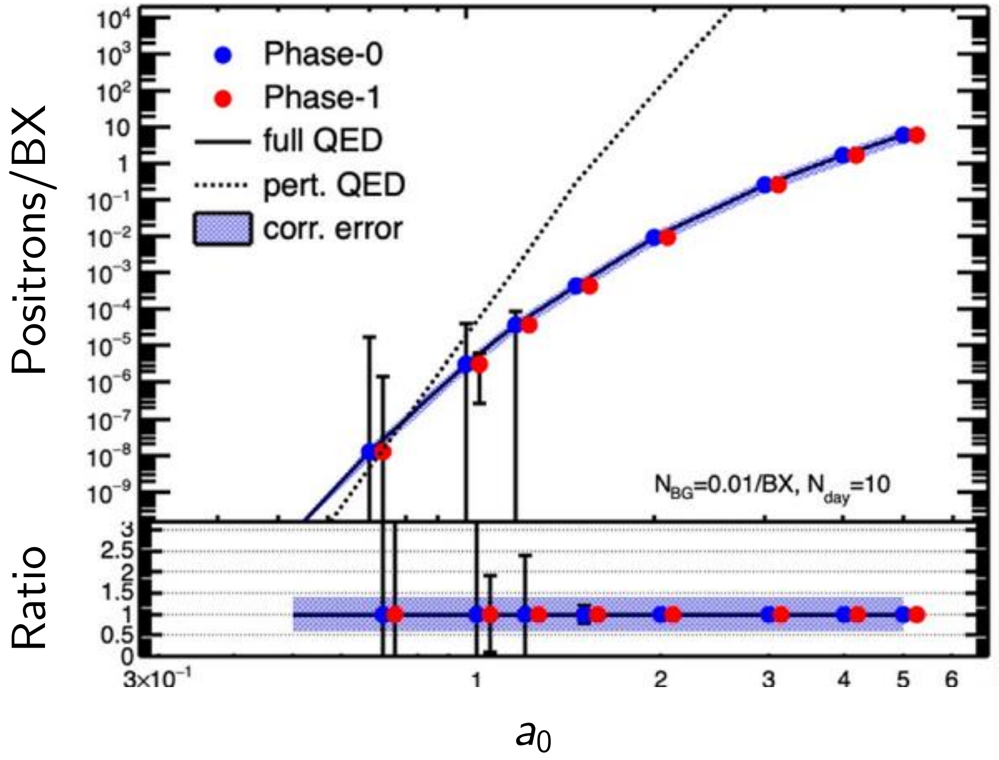
So you want to test some theory...



Positron yield per collision [LUXE Conceptual Design Report, arXiv:2102.02032]

- Precision tests of SFQED require good knowledge of the properties of the background field.
- One important parameter (among many!) is the laser intensity or a_0.
- e.g. 2.5% fluctuation in intensity leads to 40% fluctuation in positron yield
- Photon polarization effects reduce yield by 20%.

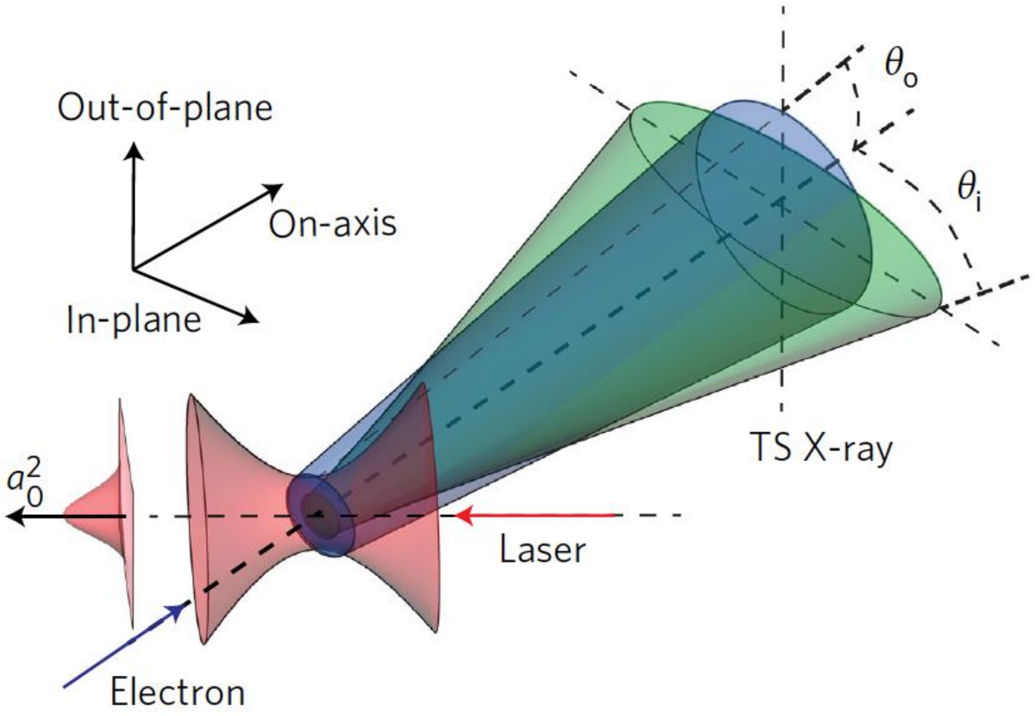
So you want to test some theory...



Positron yield per collision [LUXE Conceptual Design Report, arXiv:2102.02032]

- Precision tests of SFQED require good knowledge of the properties of the background field.
- Infer from focal spot size and energy, or measure via ionisation of heavy atoms [Ciappina et al, PRA 2019], scattering of low-energy electrons [He et al, Opt Express 2019].
- What about intensity at the collision point?

Radiation profile



Har-Shemesh and Di Piazza, Opt Lett 37, 1352 (2012)
Figure from: Yan et al, Nat Photon 11, 514 (2017)
Blackburn et al, PRAB, 23, 064001 (2020)

- Classical explanation for the angular distribution uses the shape of the electron trajectory in a plane EM wave.
- For LP, the only non-zero angle, a_0/γ, is in the plane of polarization.
- At sufficiently high intensity, the photon emission is directed along the instantaneous velocity, so distribution is elliptical: $a_0/\gamma \times 1/\gamma$

Experimental diagnostic

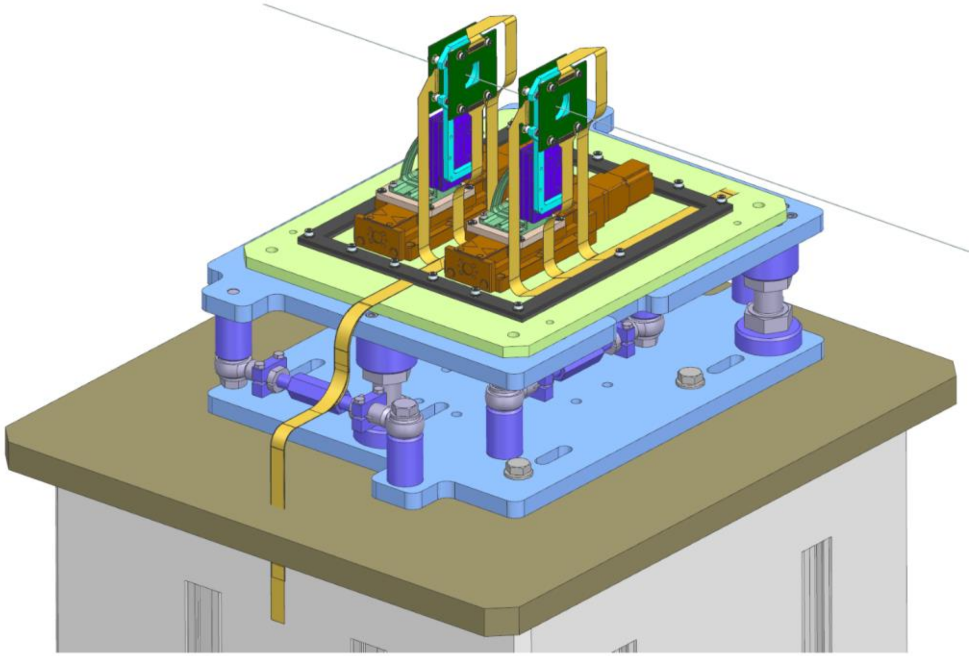
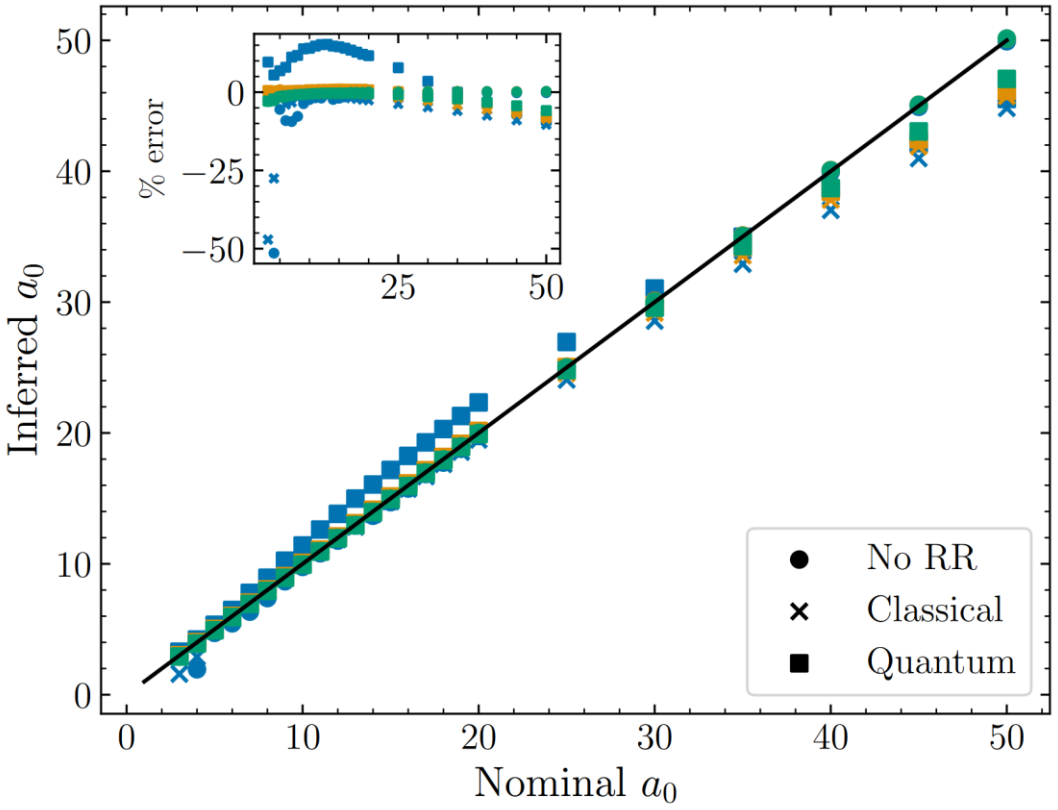


Figure 9.30: GBP station overview (brown: x stages; violet: y stages.)

Gamma Beam Profiler [M. Bruschi et al, from the LUXE Technical Design Report]

- Spatial profile of the gamma rays emitted in a laser-electron beam collision can be measured downstream with two sapphire strip detectors.
- Response is proportional to the number of photons per unit area (assuming low-energy gammas are shielded).
- How to extract information from the spatial profile?

Extraction from simulated data



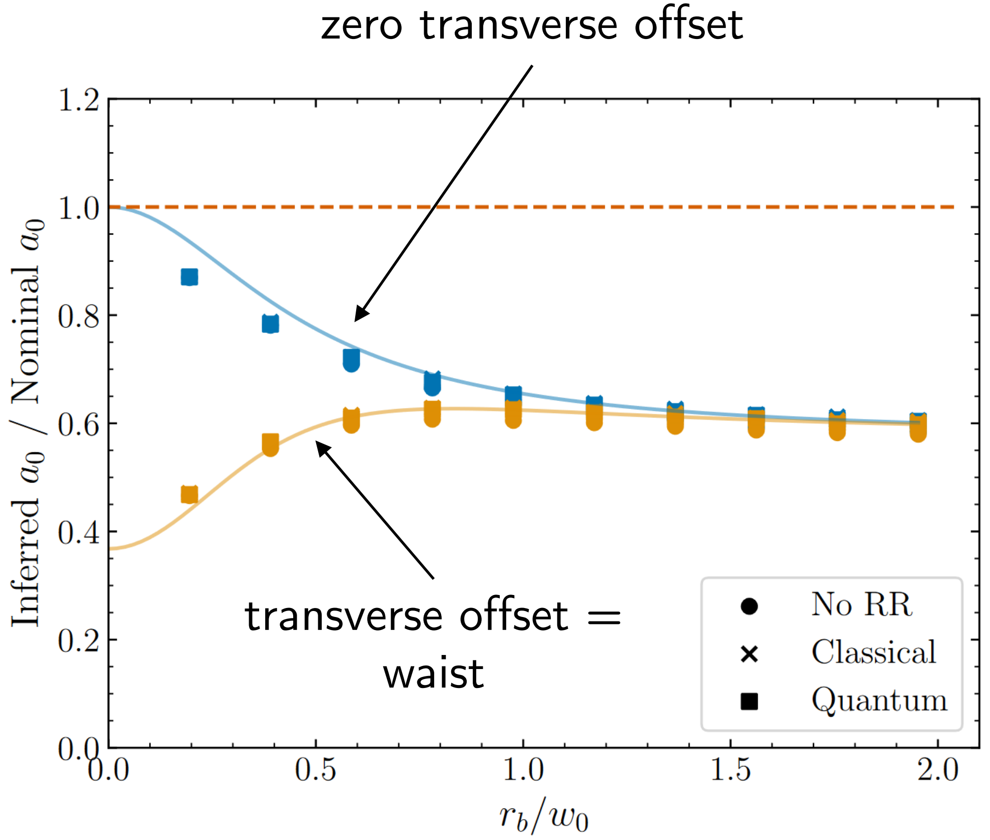
Electron beam energy 250 MeV, 1 GeV and 15 GeV (1% energy spread, 1 mrad div) [K Fleck et al, to appear]

- Assuming classical radiation reaction (and plane wave), profile size is given by

$$\sigma_{\|}^2 - \sigma_{\perp}^2 = \frac{a_0^2}{3\sqrt{3}} \left[\frac{1}{\gamma_i \gamma_f} + 0.315 \left(\frac{1}{\gamma_f} - \frac{1}{\gamma_i} \right)^2 \right]$$

- σs are the angular variances parallel and perpendicular to laser polarization.
- Ellipticity depends on a_0 as well as electron initial and final energies (averages in the QRR case).

Extraction from simulated data



Electron beam energy 250 MeV, 1% energy spread, laser $a_0 = 20$, waist = 1.02 micron [K Fleck et al, to appear]

- Assuming classical radiation reaction (and plane wave), profile size is given by

$$\sigma_{\parallel}^2 - \sigma_{\perp}^2 = \frac{a_0^2}{3\sqrt{3}} \left[\frac{1}{\gamma_i \gamma_f} + 0.315 \left(\frac{1}{\gamma_f} - \frac{1}{\gamma_i} \right)^2 \right]$$

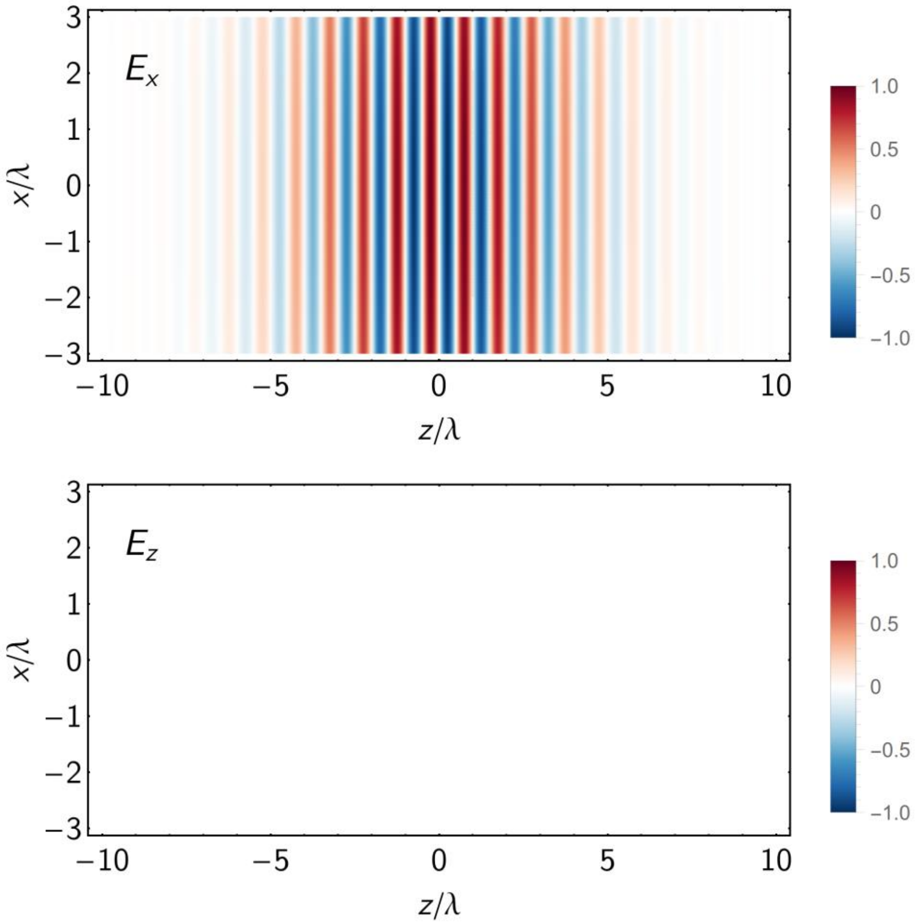
- Finite size effects / transverse offsets lead to decrease in the inferred a_0, but characteristic of collision as a whole.
- Combine with measurements of the global peak intensity.

Summary

- What is a strong electromagnetic field?
  - Nonlinearity parameters. a_0 = multiphoton effects, χ = quantum effects.
  - Where are strong EM fields found? Pulsar magnetospheres, lasers.
- Strong-field QED:
  - Basic processes. Compton scattering, Breit-Wheeler pair creation.
  - Parameter regimes, quasistatic fields. Nonperturbative if ${a_0}^3/\chi$ large, rates non-analytic in the coupling (tunnelling).
  - Questions we want to answer. Transition regime, pair creation from light alone, higher order processes.
- Uncertainties and unknowns. Approximations / knowledge of the EM field.

Motivation

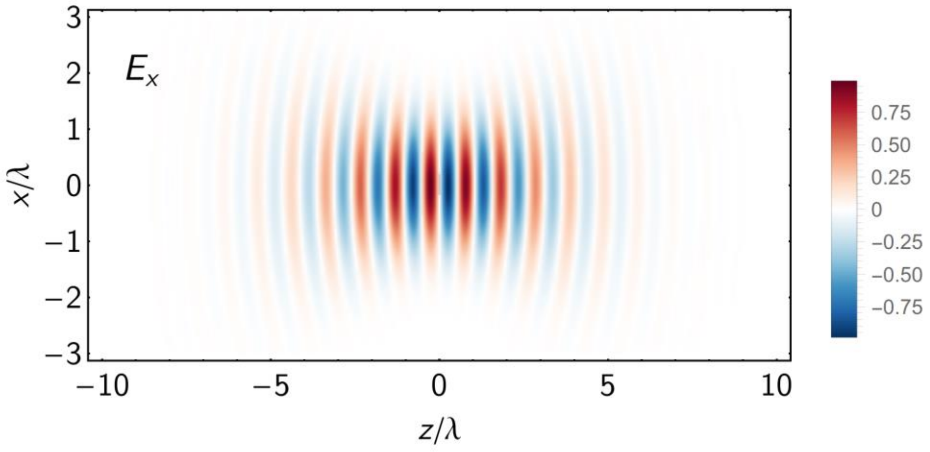
Why simulate at all?

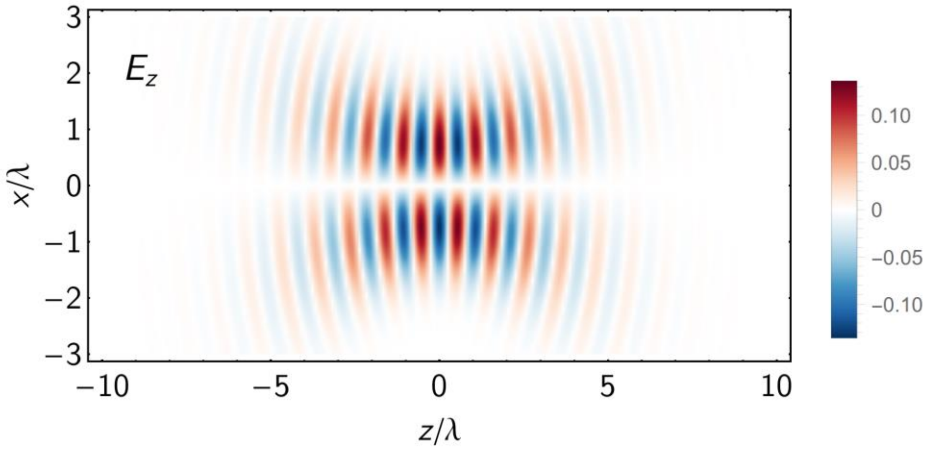


- The plane wave is the paradigmatic choice of background for calculations of nonlinear classical and quantum processes in strong electromagnetic fields.

- Classical and quantum dynamics of an electron in a plane-wave background are exactly solvable [see, for example, Heinzl and Ilderton, PRL 118, 113202 (2017)]

Why simulate at all?





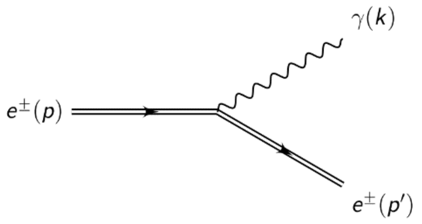
- Lasers reach high intensity by focusing – getting close to the diffraction limit
- A focusing electromagnetic pulse has to be described numerically (usually with a certain degree of approximation).
- No complete theory for QED interactions exists in this background. High-energy approximations possible [Di Piazza, PRL 113, 040402 (2014)]

LUXE experiment
Theory/simulation requirements

Electron + laser	Bremsstrahlung γ + laser	Electron + laser

Electron + laser

Nonlinear Compton scattering

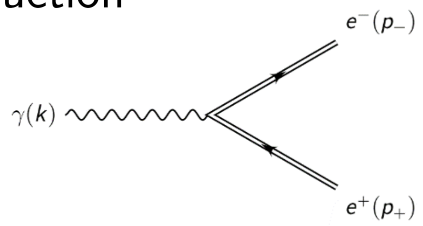


Signals:
- Intensity dependence of Compton edges
- γ-photon angular profile

Needed:
- Photon emission rate

Bremsstrahlung γ + laser

Nonlinear Breit-Wheeler pair production

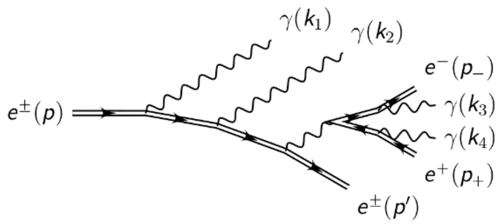


Signals:
- Intensity dependence of positron yield

Needed:
- Pair creation rate, unpolarized γ photons

Electron + laser

Nonlinear trident pair creation



Signals:
- Intensity dependence of positron yield

Needed:
- Photon emission rate, γ-polarization resolved
- Pair creation rate, γ-polarization resolved

Overview

A male ptarmigan in winter plumage

- Ptarmigan is a Monte-Carlo particle-tracking code that simulates the interaction between high-energy electron/photon beams and laser pulses.
- Designed to be accurate (and fast) across the full range of a_0.
- Single-particle, so collective interactions neglected, as well as feedback on the laser fields.

Physics coverage

Process	Polarization			Available modes		
	e^+/e^-	γ	laser	QED	classical	modified classical
Photon emission	averaged (initial), summed (final)	arbitrary	LP / CP	LMA / LCFA	LMA / LCFA	LCFA
Pair creation	summed	arbitrary	LP / CP	LMA / LCFA	n/a	n/a

- Fundamental processes included are: photon emission (NLC) and electron-positron pair creation (NLBW).
- All processes fully angularly resolved.
- Building blocks for higher-order processes, like EM showers.

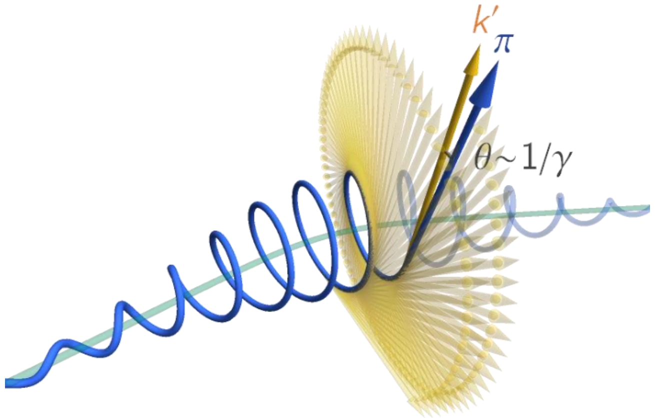
Physics coverage

Process	**Polarization**			**Available modes**		
	e^+/e^-	γ	laser	QED	classical	modified classical
Photon emission	averaged (initial), summed (final)	arbitrary	LP / CP	LMA / LCFA	LMA / LCFA	LCFA
Pair creation	summed	arbitrary	LP / CP	LMA / LCFA	n/a	n/a

- LMA available for $a_0 \leq 20$ and $\eta = \chi/a_0 \leq 2$ [170 GeV @ λ = 800 nm]
- LCFA available for arbitrary χ.
- Classical radiation reaction also available (Landau-Lifshitz, including Gaunt factor if so desired)

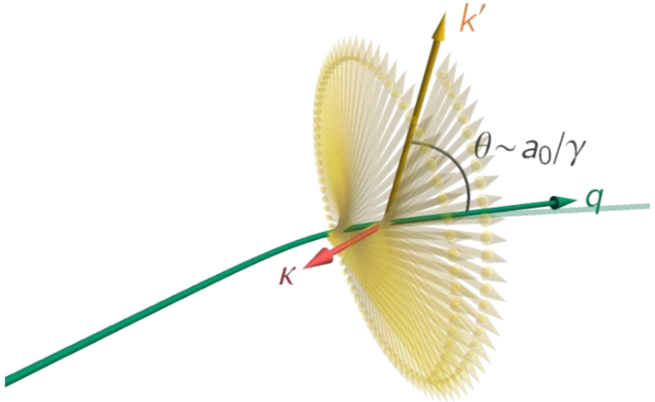
Approximations compared

LCFA:



- Locally constant field approximation
- Advantage: build arbitrary fields from slices of constant, crossed field.
- Disadvantage: no interference effects, does not work in transition regime.

LMA:

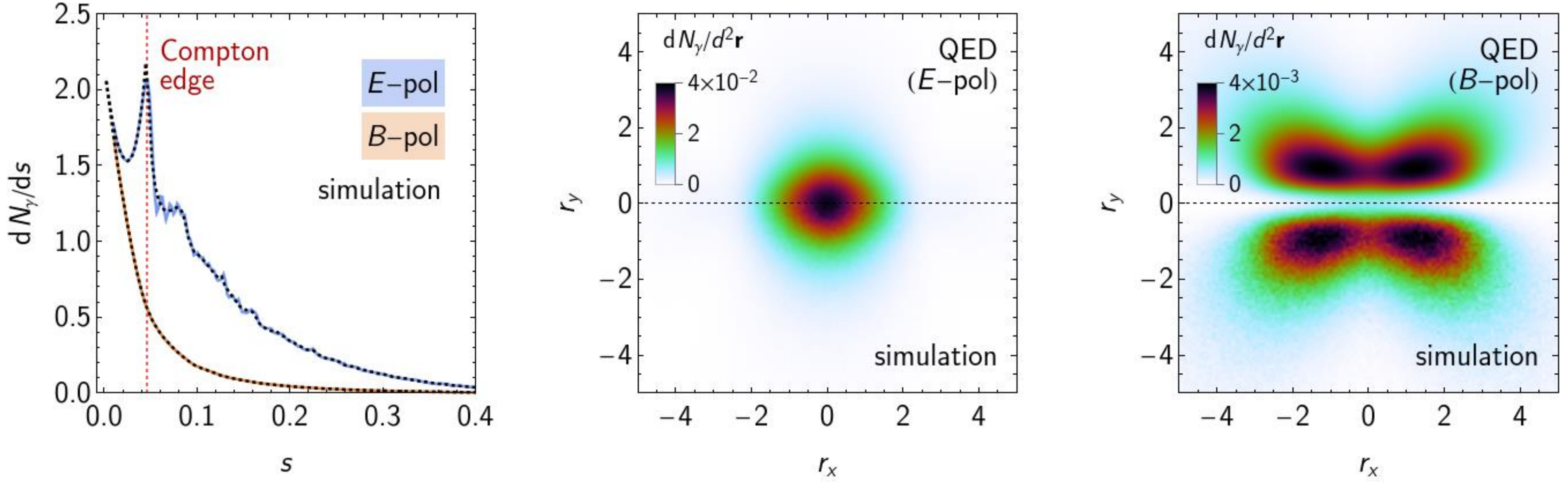


- Locally monochromatic approximation
- Advantage: includes wavelength-scale interference effects, works at all a_0.
- Disadvantage: background must be sufficiently “plane-wave-like”, i.e. amplitude and frequency required.

Simulations with Ptarmigan

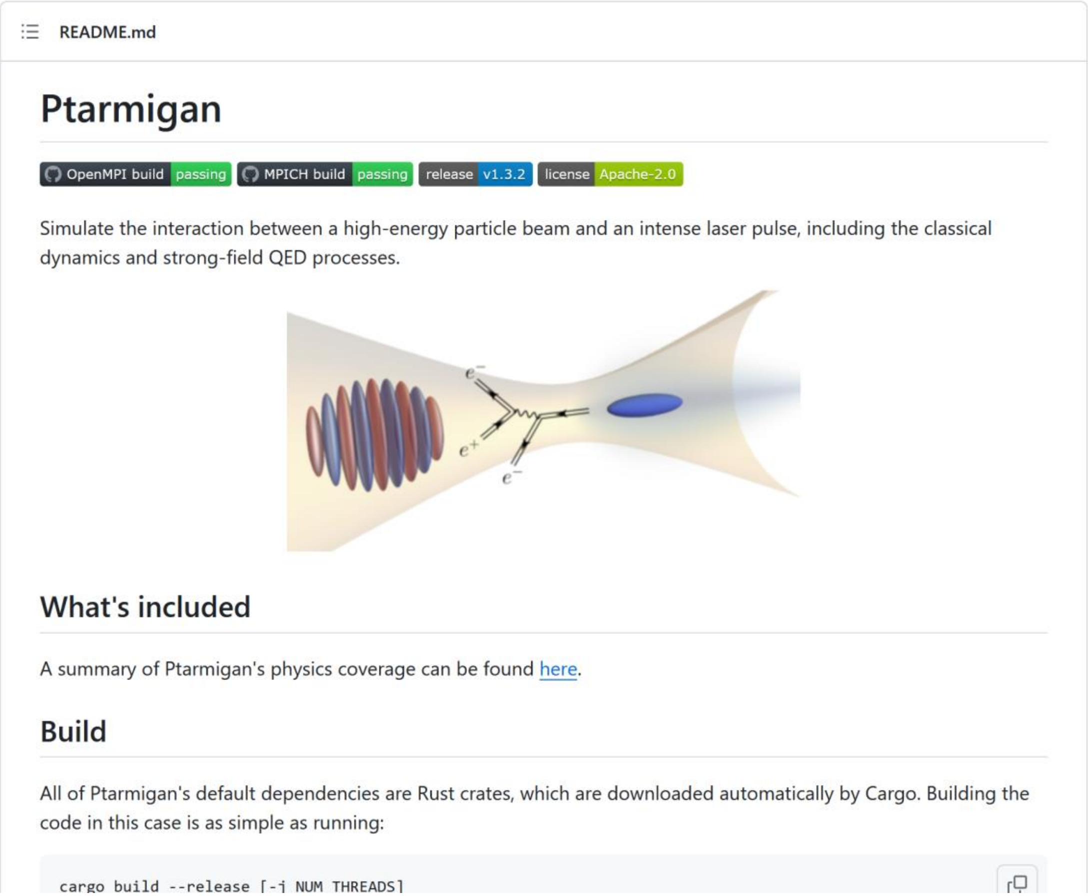
Benchmarking example

- $a_0 = 2.5$, under LMA:



- Photon spectra at fixed electron energy parameter $\eta = 0.1$ (8 GeV @ 800 nm laser wavelength). *E*-pol: photons polarized parallel to laser *E*; *B*-pol, perpendicular to *E*.

Access



README.md

Ptarmigan

OpenMPI build passing | MPICH build passing | release v1.3.2 | license Apache-2.0

Simulate the interaction between a high-energy particle beam and an intense laser pulse, including the classical dynamics and strong-field QED processes.

What's included

A summary of Ptarmigan's physics coverage can be found here.

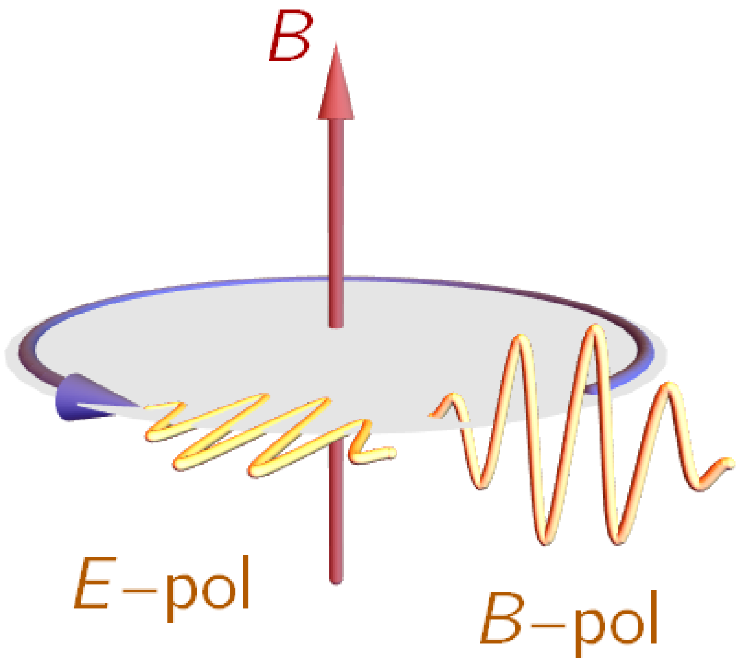
Build

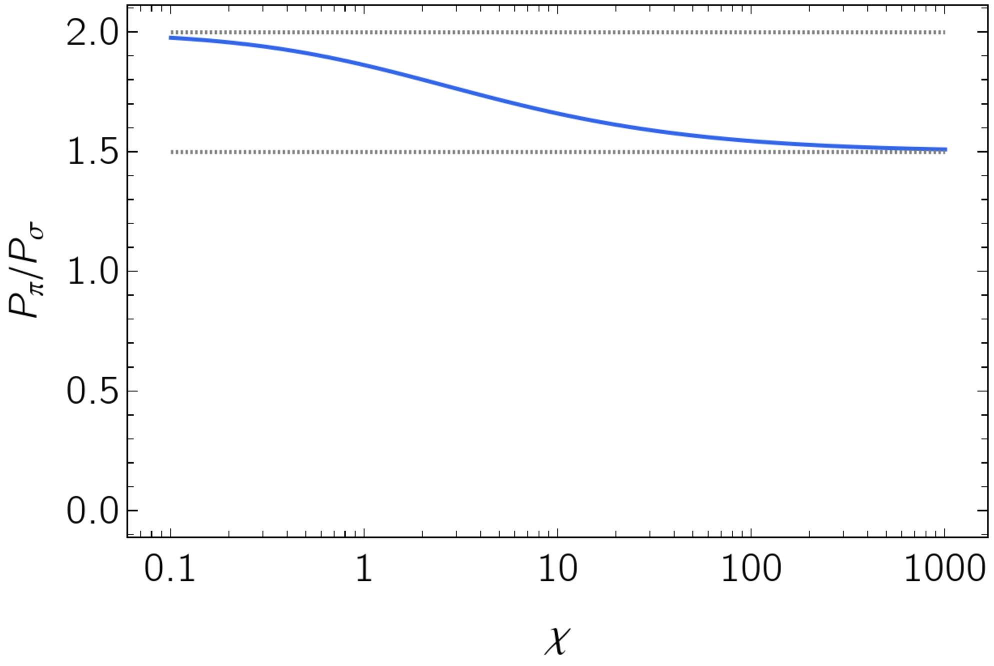
All of Ptarmigan's default dependencies are Rust crates, which are downloaded automatically by Cargo. Building the code in this case is as simple as running:

```
cargo build --release [-j NUM_THREADS]
```

- Open source and permissively licensed, available on Github (github.com/tgblackburn/ptarmigan).
- Documentation and example input files included, and more being added.
- MPI and HDF5 support available as opt-in features.
- Pull requests (bug fixed, additional features) always welcome!

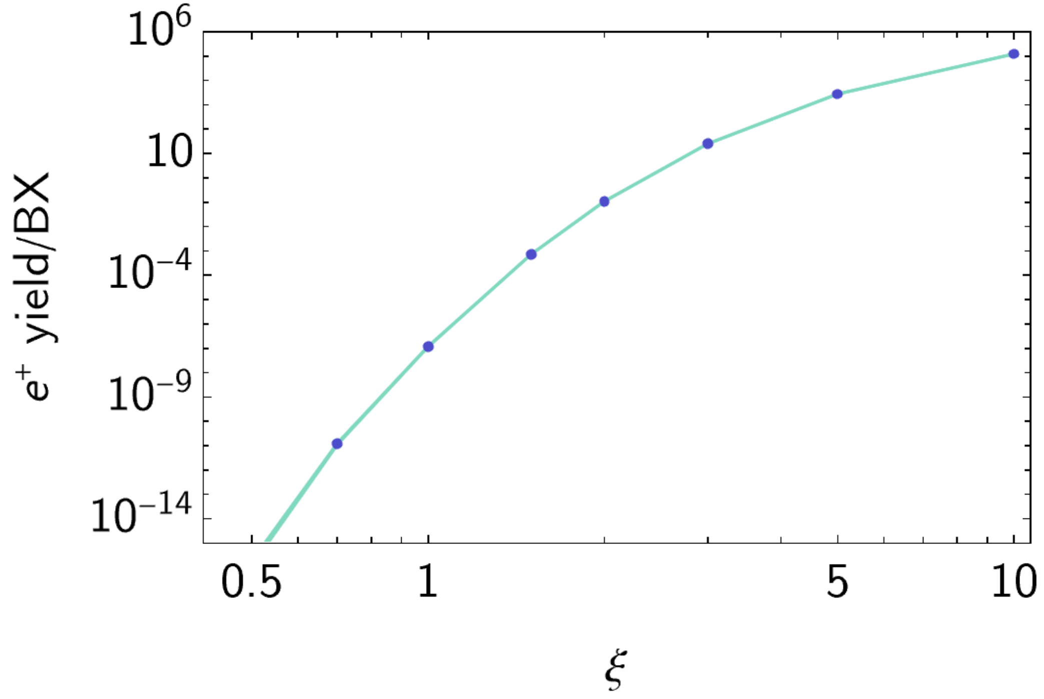
Motivation

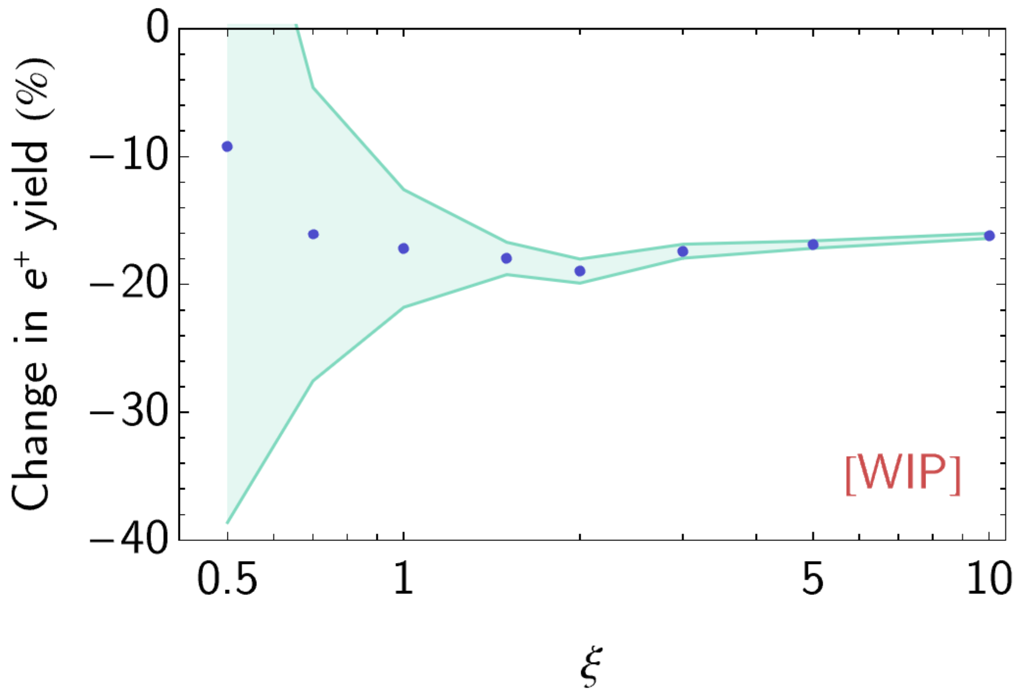




- Synchrotron radiation is predominantly *E*-polarized (i.e. in the plane of the orbit).. [measure directly]
- … but *B*-polarized photons are more likely to create electron-positron pairs [measure indirectly]

Positron yield is overestimated





- Standard electron beam parameters
- Phase-0 laser (40 TW), linearly polarized

- Positron yield reduced by 20%.
- Expected to be almost independent of ξ, according to theory.

PIC codes that include SFQED processes

EPOCH

CALDER

Smilei

PICADOR

PIConGPU

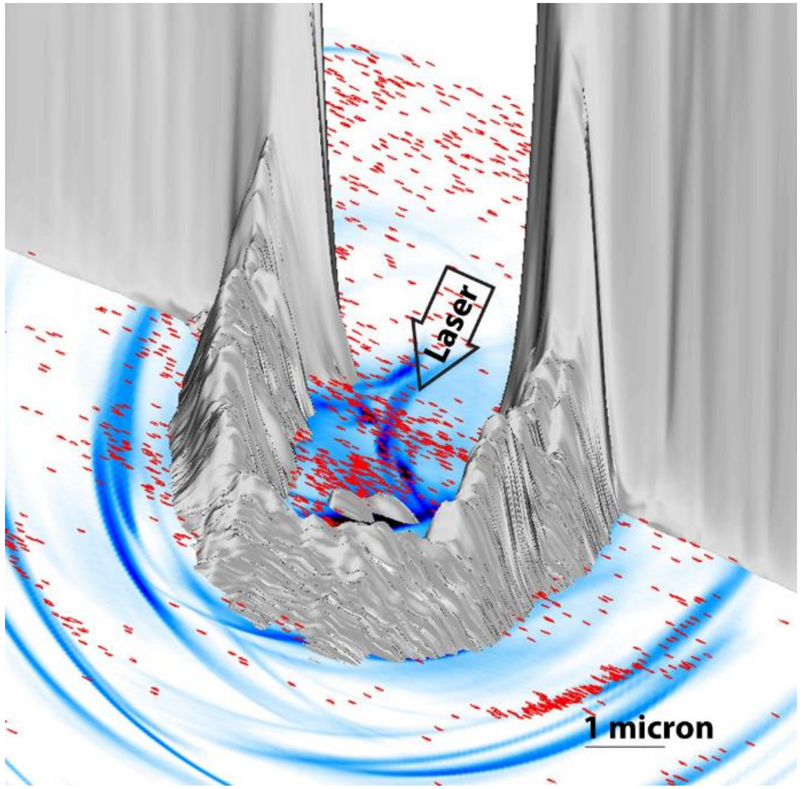
WarpX

Osiris 4.0

VLPL

QUILL

Laser-driven plasmas



C P Ridgers et al, PRL 108, 165006 (2012)

- Next-generation laser facilities producing intensities 10^{23} W/cm^2 (ELI, Apollon etc).
- Critical density pair plasmas formed in laser-foil, laser-laser, laser-gas interactions.
- Coupling between classical plasma dynamics and nonlinear QED in fields with complex structure.

How do we study strong EM fields? (Simulations)

Laser-driven plasmas

Classical plasma dynamics

Quantum processes

- Next-generation laser facilities producing intensities 10^{23} W/cm^2 (ELI, Apollon etc).
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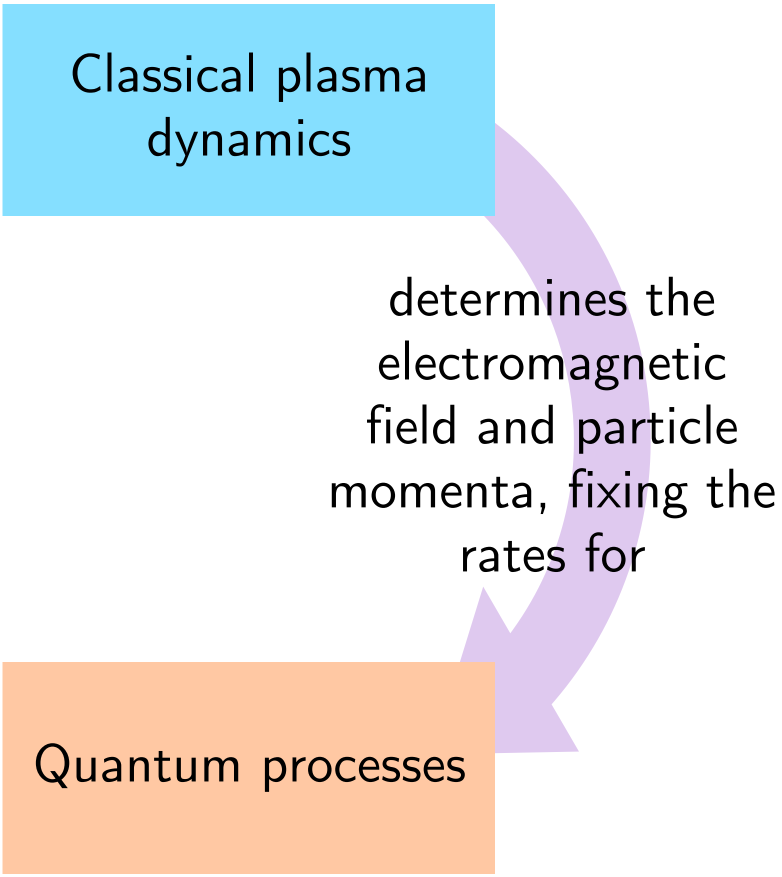
Laser-driven plasmas



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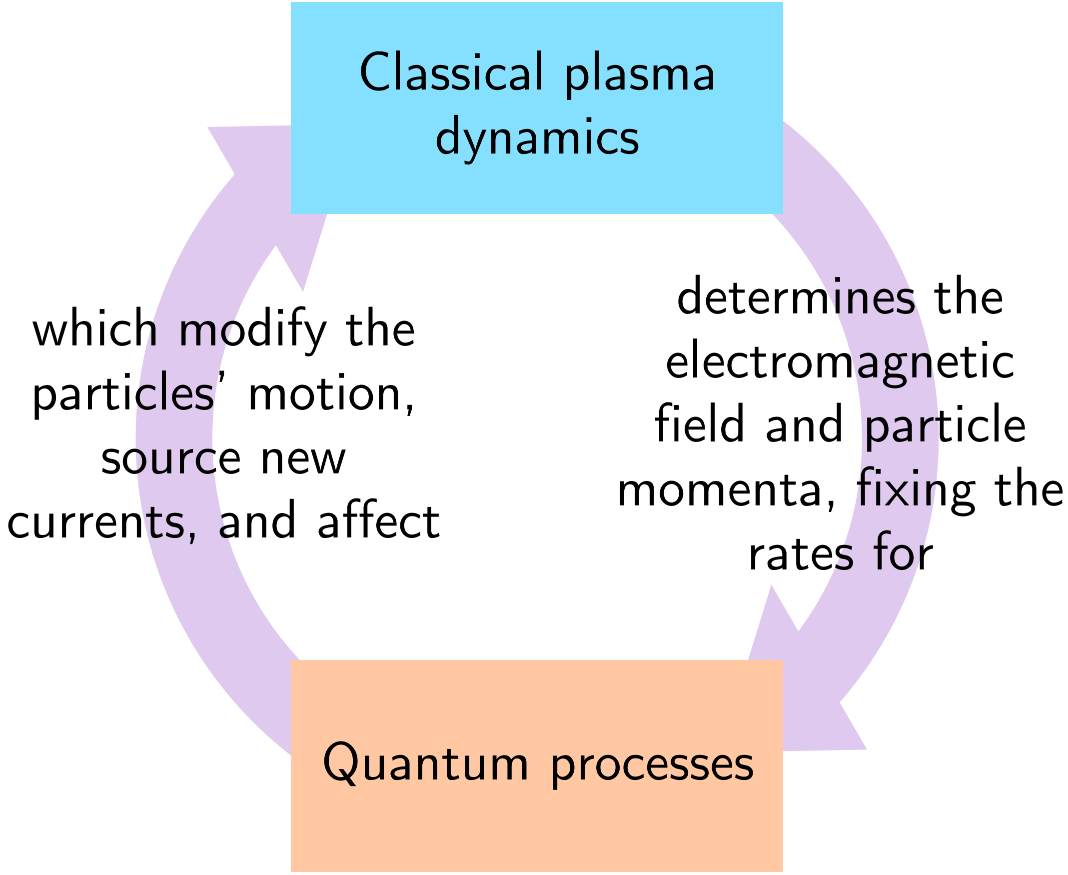
How do we study strong EM fields? (Simulations)

Laser-driven plasmas



- Next-generation laser facilities producing intensities 10^{23} W/cm^2 (ELI, Apollon etc).
- Critical density pair plasmas formed in laser-foil, laser-laser, laser-gas interactions.
- Coupling between classical plasma dynamics and nonlinear QED in fields with complex structure.

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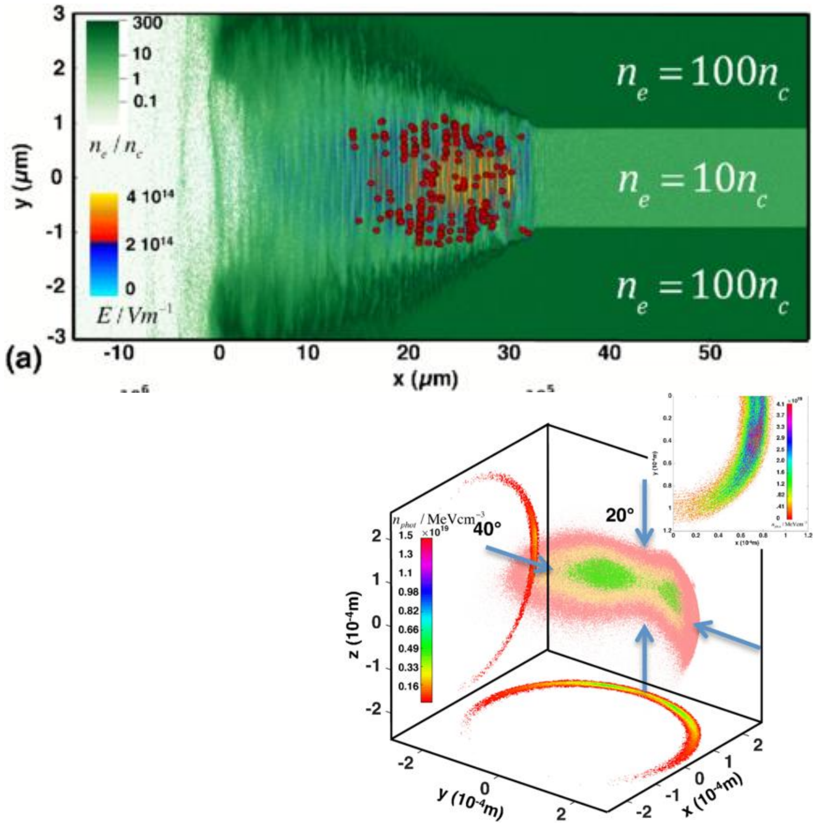
How do we study strong EM fields? (Simulations)

Single laser-driven plasmas



D J Stark et al, PRL 116, 185003 (2016)

- e.g. laser irradiation of a compound target creates a quasistatic magnetic field that guides electron acceleration.
- Combination of the laser and plasma fields gives a quantum parameter $\chi = 0.1$, leading to high-energy photon emission.
- 10s TW emitted in >10 MeV photons, collimated within tens of degrees, at $a_0 = 200$.

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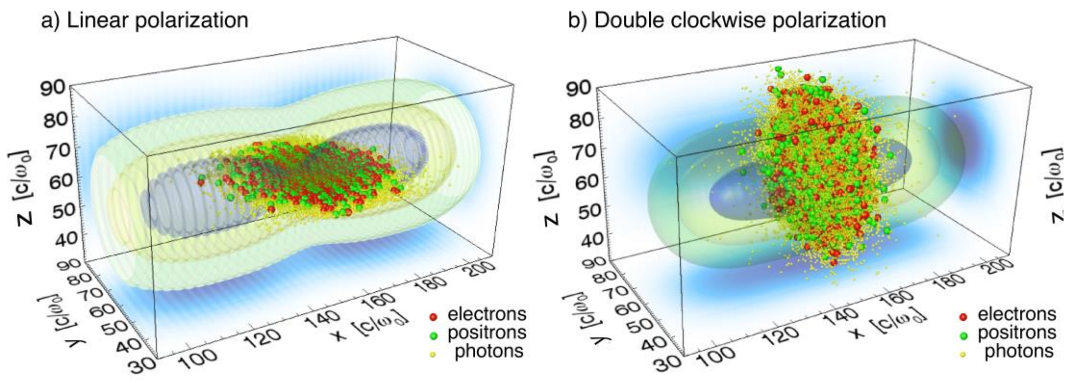
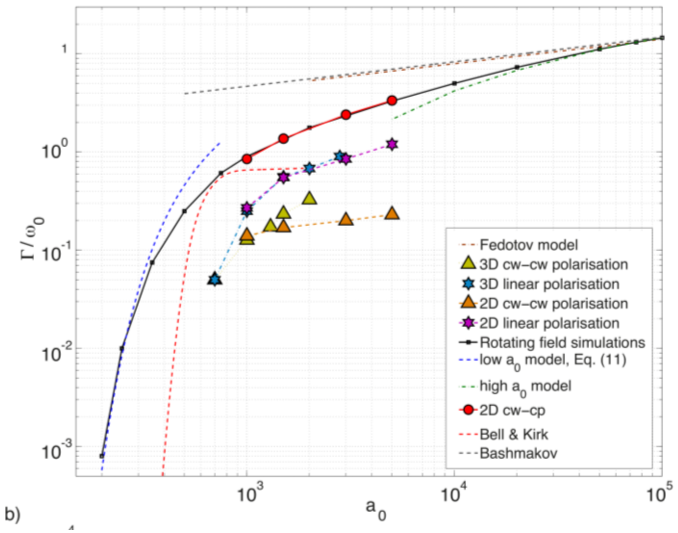
Dual laser-driven cascades



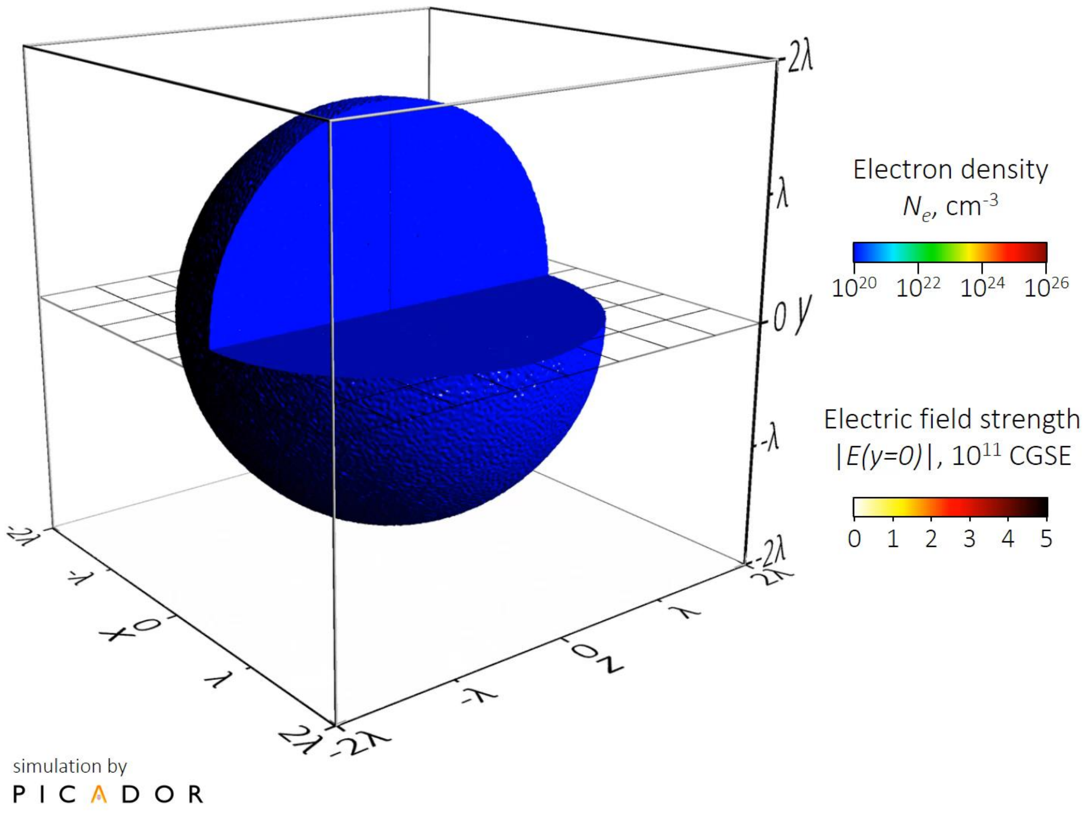


T Grismayer et al, PRE 95, 023210 (2017)

- e.g. exponential growth of the positron density when two counterpropagating lasers accelerate seed electrons to high energy.
- Formation of critical-density electron-positron plasmas that absorb and convert laser energy to γ rays.
- Threshold intensity for cascade initiation (linear polarization) predicted to be 7×10^{23} W/cm^2.

How do we study strong EM fields? (Simulations)

Multiple laser-driven plasmas



A Gonoskov et al, PRX 7, 041003 (2017)

- Multi-beam configurations mean higher intensity is reached for lower input power.
- 4π irradiation of a plasma target with 40 PW of laser power (divided among 12 pulses) traps electrons on special trajectories.
- These electrons oscillate back and forth along the field axis, leading to collimated emission of GeV photons.