Launching QED cascades in high-intensity laser pulses

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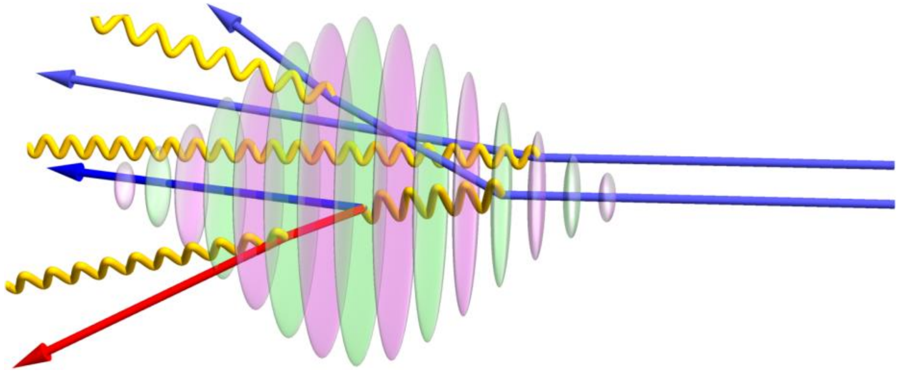
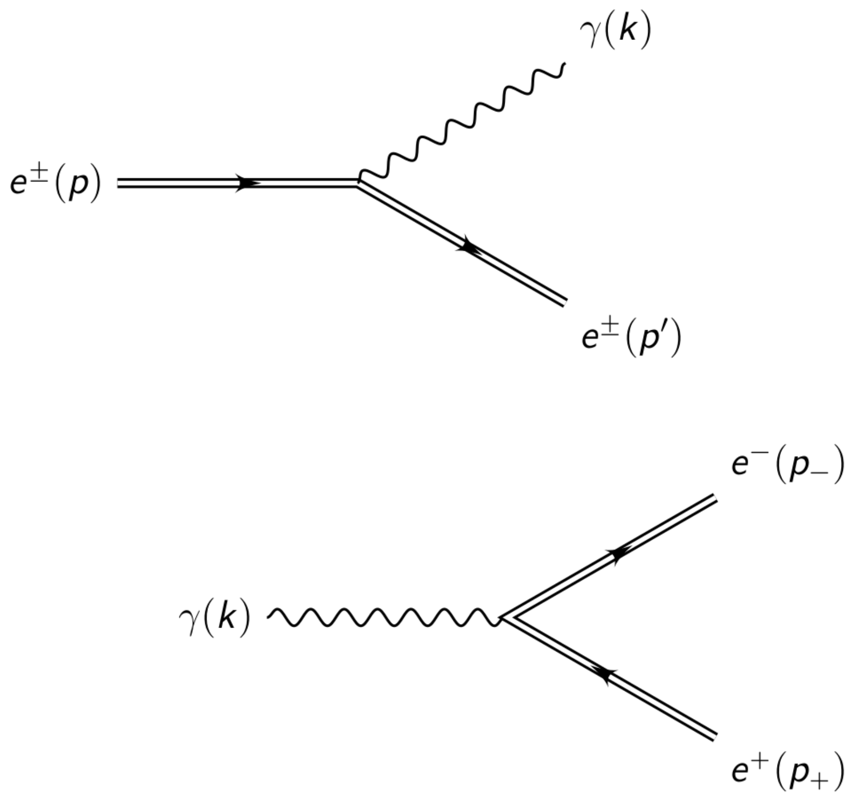


- Nonlinear QED in strong EM fields: radiation reaction, electron-positron pair creation and cascades.
- Exploring the same physics at near-term laser intensities: high-energy electrons and photons as cascade seeds.
- Prospects for experimental observation.

Nonlinear QED

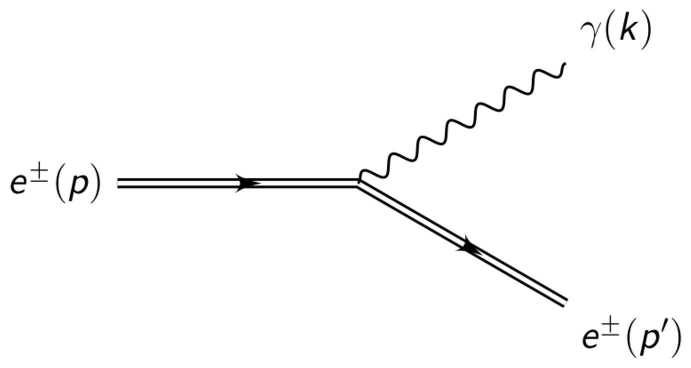
Fundamental processes

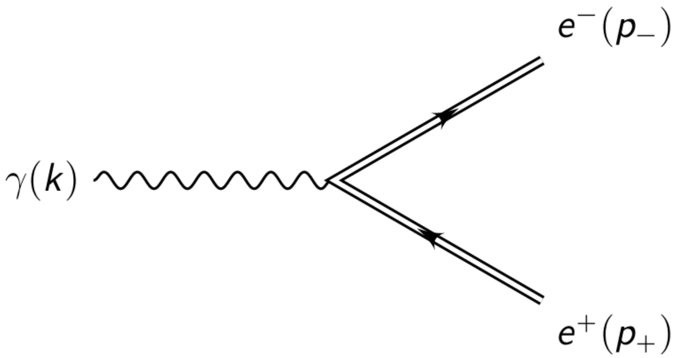


- Simplest two: photon emission and pair creation.
- Each first order in the fine-structure constant α.
- Expect that first order processes are more probable than second order, which are more probable than third order, etc.

Nonlinear QED

Cascades...

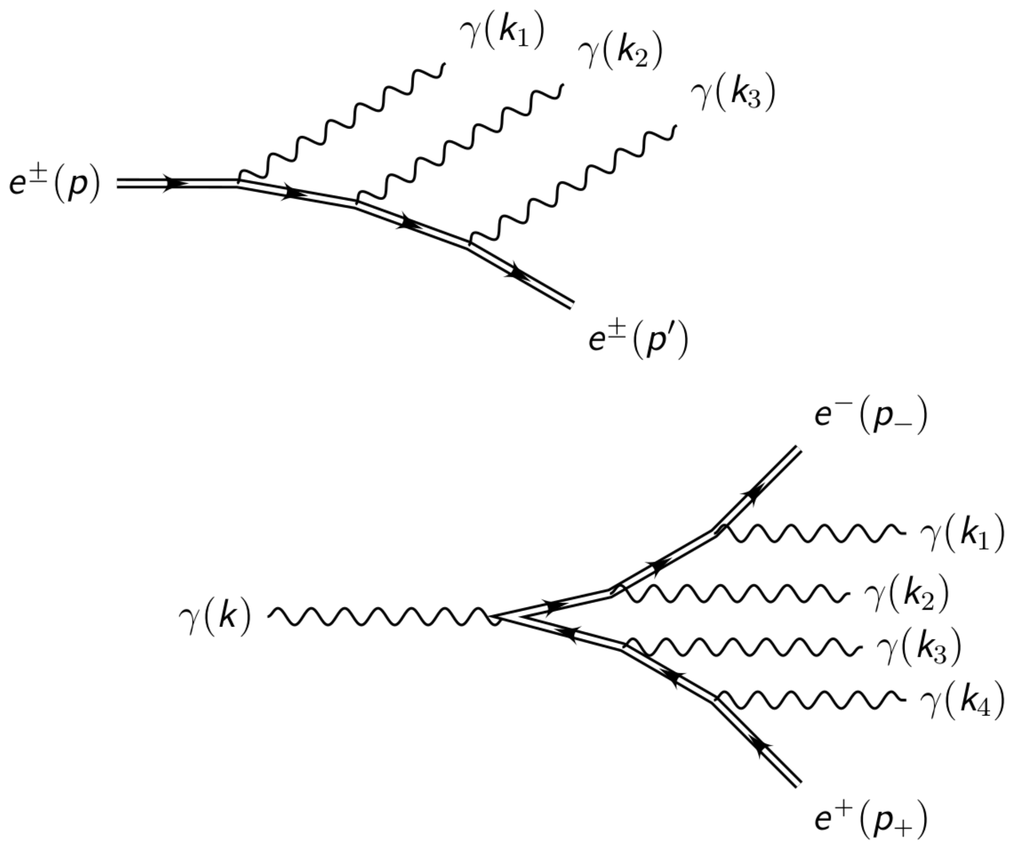




- However, in strong electromagnetic fields, the probability for "only one" process is exponentially suppressed.

Nonlinear QED

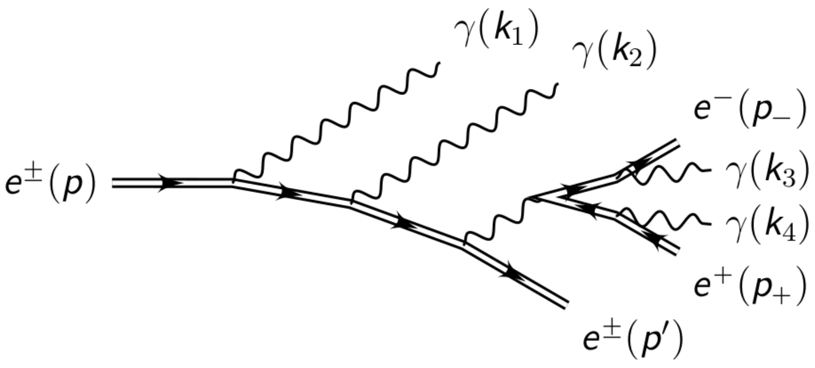
Cascades...

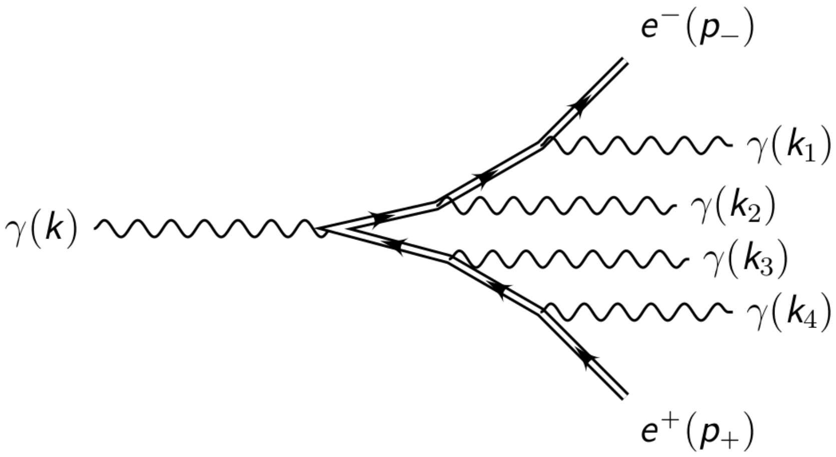


- However, in strong electromagnetic fields, the probability for "only one" process is exponentially suppressed.
- A single high-energy electron emits many photons (radiation reaction).
- A single photon creates an electron and positron that radiate additional photons.

Nonlinear QED

Cascades...





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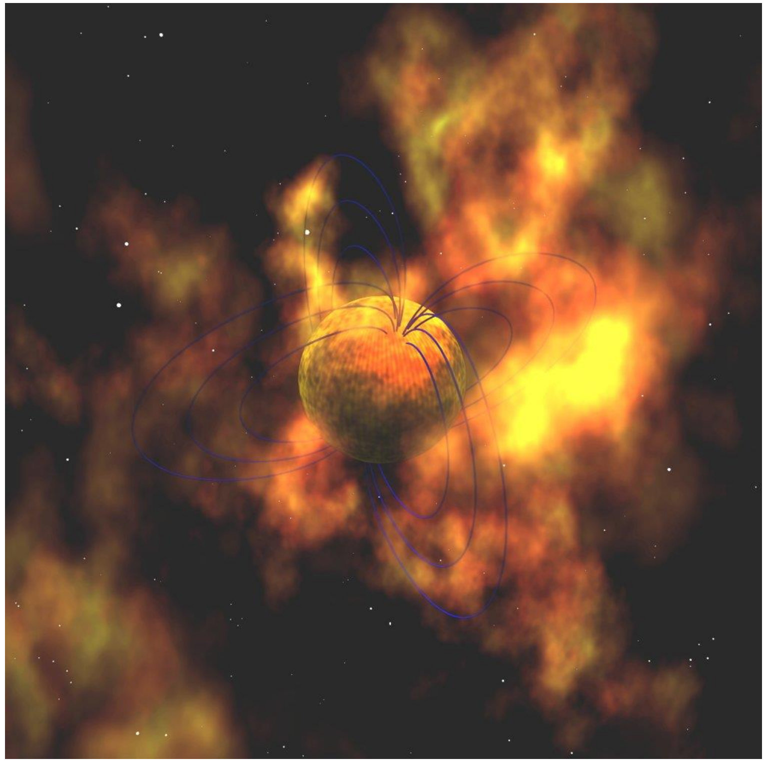
Nonlinear QED

… in strong electromagnetic fields



- Energetic particles in strong magnetic fields feature in astrophysical environments.
- Magnetars are speculated to have magnetic fields $10\times$ the critical field of QED.
- Vacuum birefringence, photon splitting and electromagnetic cascades.

Nonlinear QED

… in strong electromagnetic fields

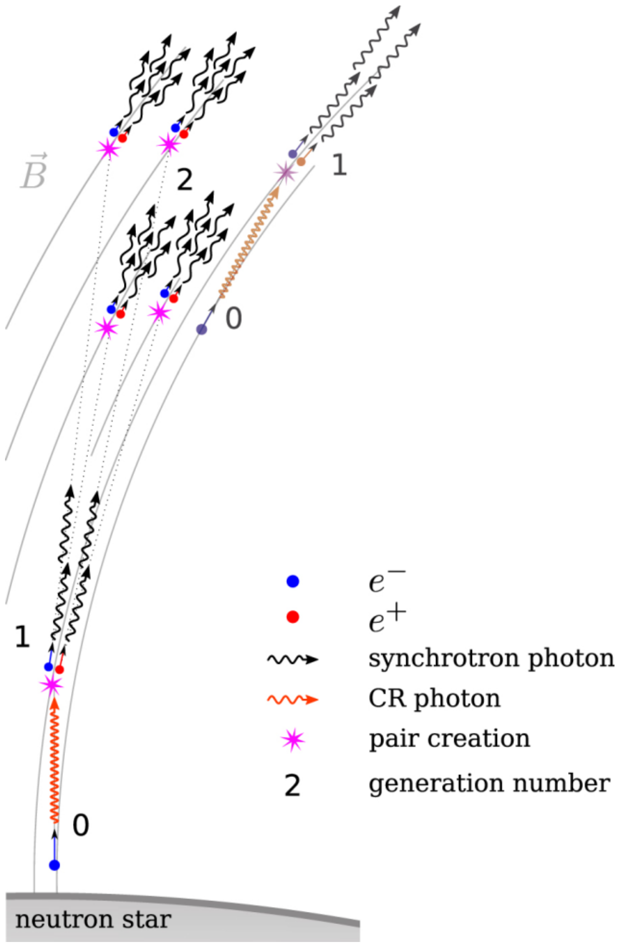


Image from A. N. Timokhin and A. K. Harding, Ap. J. 810, 144 (2015)

- State-of-the-art QED calculations are limited to second-order, i.e. multiplicity = 2, and to field configurations with high symmetry.
- Estimated multiplicity in the polar cap of a pulsar magnetosphere = 10^5.
- Also, back-reaction of cascade development can cause depletion of the strong EM field.

Nonlinear QED
… in future laser experiments

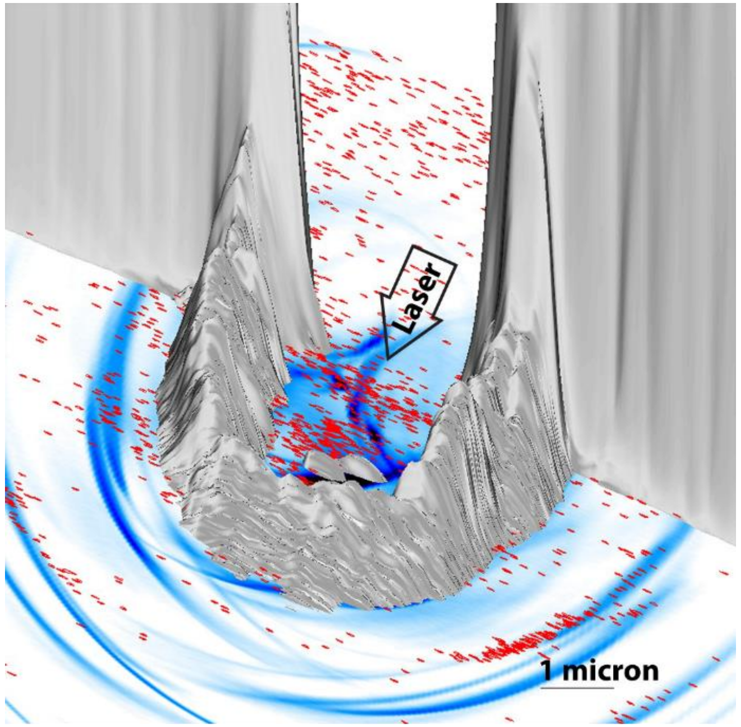
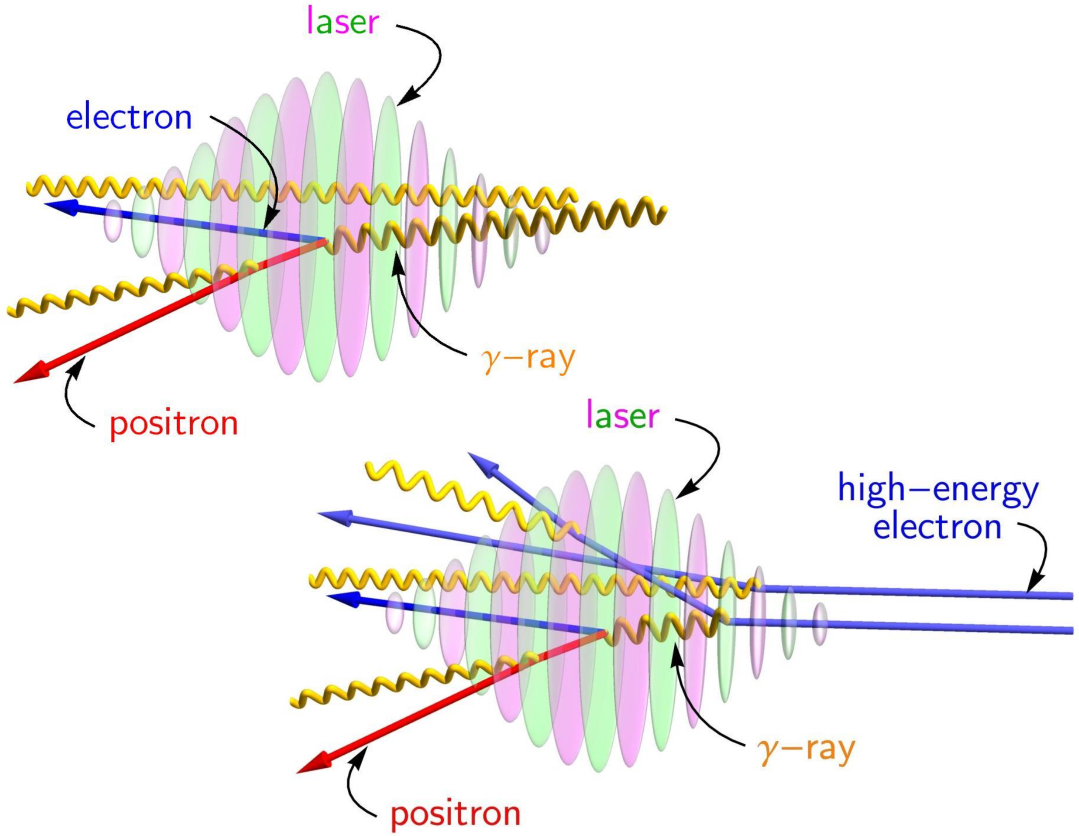


Image from C. P. Ridgers et al, PRL 108, 165006 (2012)

- 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.

Colliding beams

Motivation

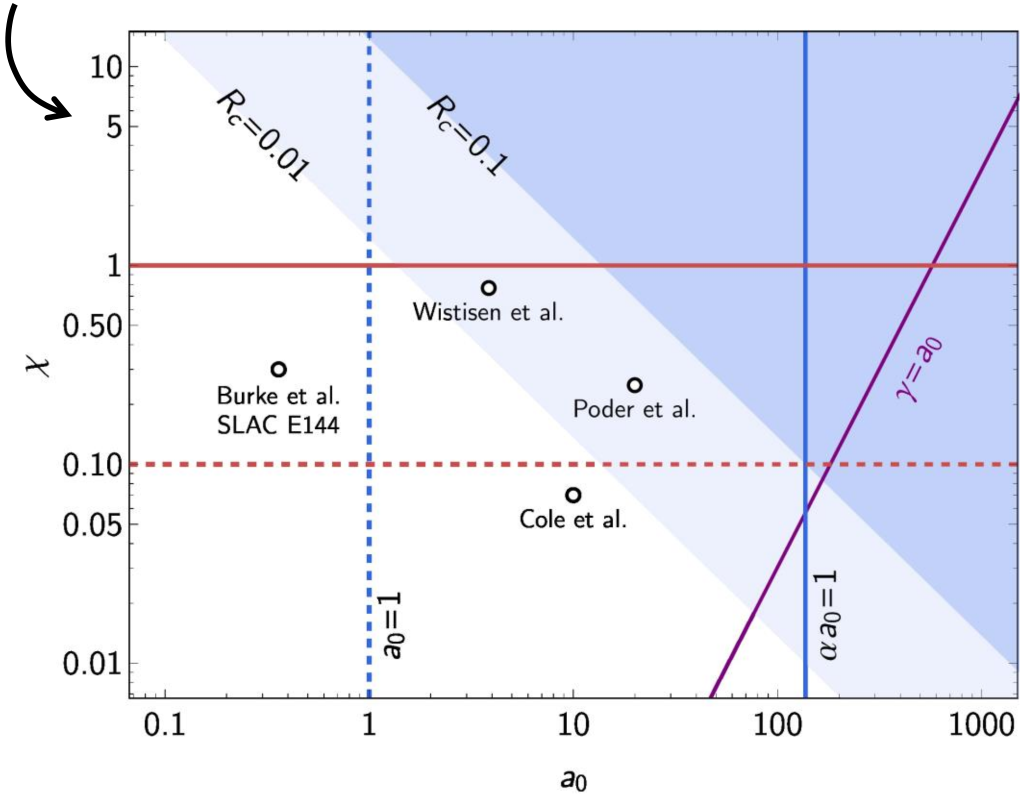


- Explore the same physics at lower laser intensity.
- Probabilities for QED processes depend on parameter $\chi = \gamma E / E_{\text{crit}}$, i.e rest frame electric field.
- Probe laser pulses exceeding 10^{21} W/cm^2 with energetic electrons or photons (γ or $\omega/m > 1000$), e.g. Gemini, CoReLS, Apollon, ELI etc.

Colliding beams

Parameter space

quantum nonlinearity

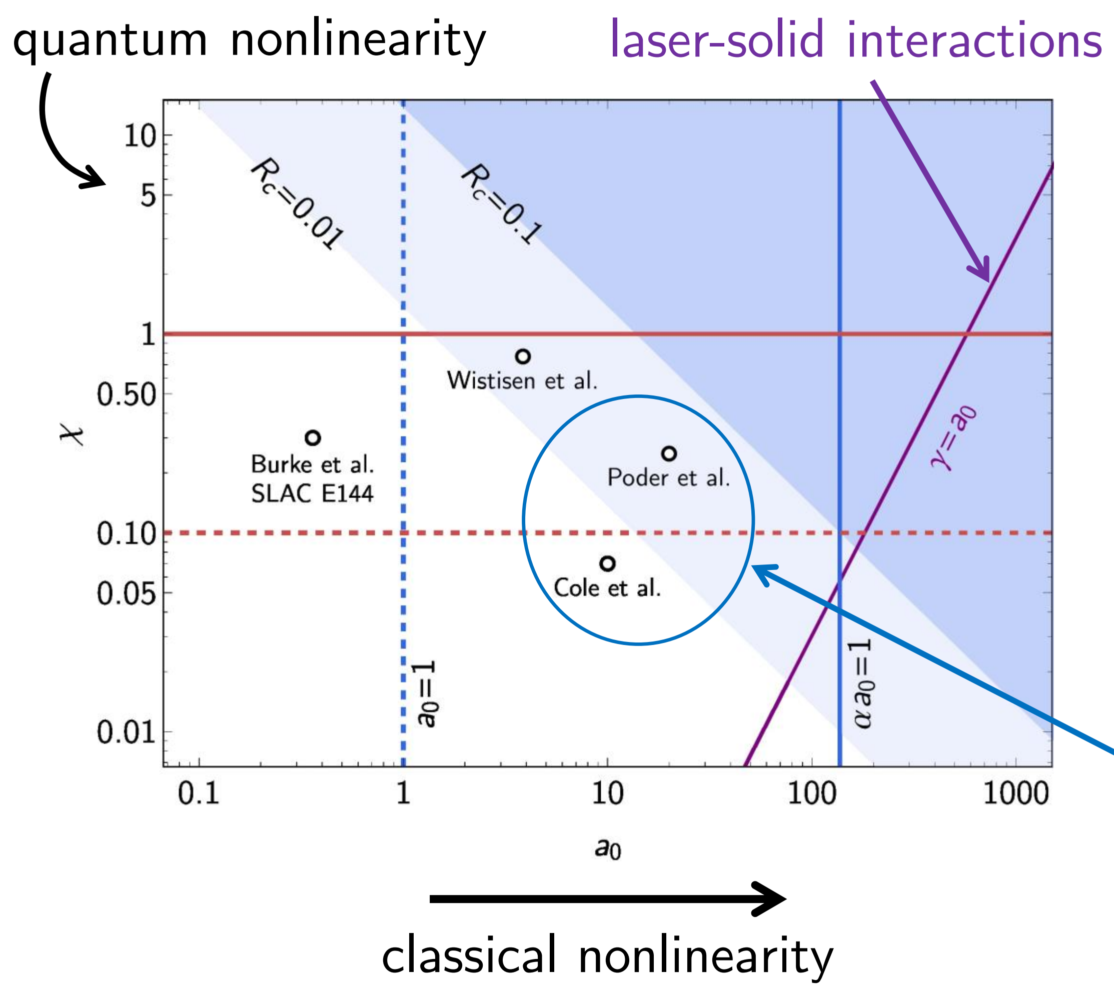


classical nonlinearity

- R_c = radiation reaction parameter, ratio of the RR and Lorentz forces (or the fractional energy loss per laser period)

$$
\begin{aligned}
R_c &= \alpha a_0 \chi_0 \\
&\simeq 0.13 \left(\frac{E_0}{500\ \mathrm{MeV}}\right)\left(\frac{I_0}{10^{22}\ \mathrm{Wcm}^{-2}}\right)\left(\frac{\lambda}{\mu\mathrm{m}}\right)
\end{aligned}
$$

Colliding beams
Parameter space



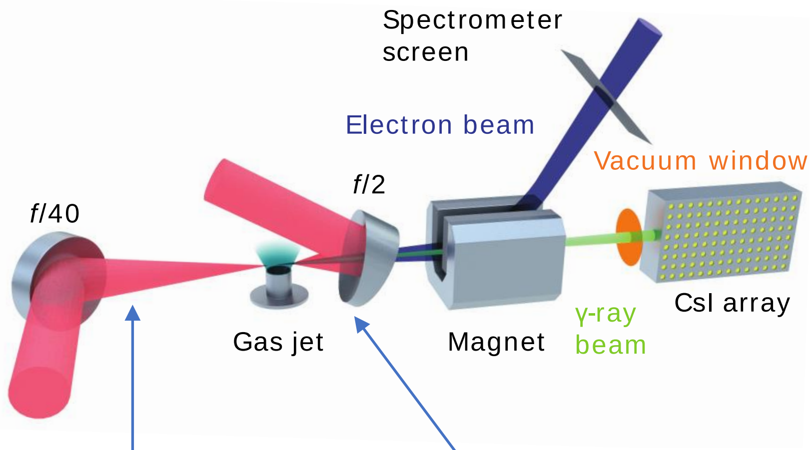
- R_c = radiation reaction parameter, ratio of the RR and Lorentz forces (or the fractional energy loss per laser period)

$$R_c = \alpha a_0 \chi_0 \simeq 0.13 \left(\frac{E_0}{500\ \text{MeV}}\right)\left(\frac{I_0}{10^{22}\ \text{Wcm}^{-2}}\right)\left(\frac{\lambda}{\mu\text{m}}\right)$$

- Recently @ $a_0 = 10$, $\chi = 0.1$: evidence of radiation reaction

Colliding beams

All-optical experiments



10 J / 45 fs, $a_0 = 25$

9 J / 45 fs, $a_0 = 2$

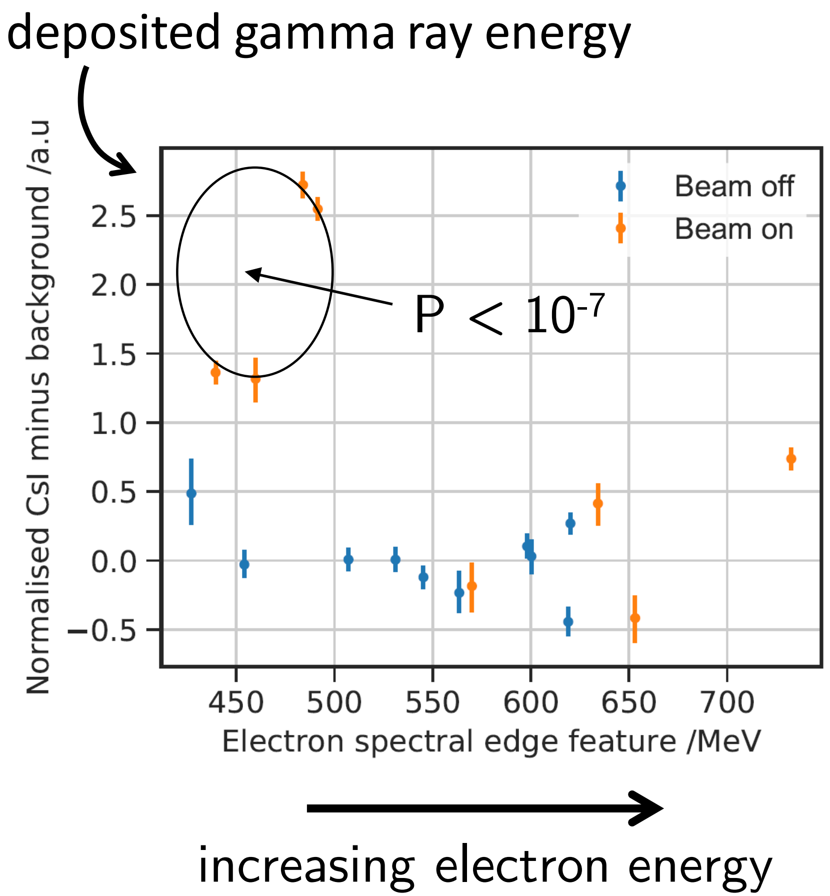
Gemini laser facility,
CLF Rutherford Appleton Laboratory, UK

- Collision between wakefield-accelerated electron beam and intense laser pulse.
- Decelerated electrons and gamma rays pass through hole in f/2 optic.
- Measure electron and gamma spectra on a shot-to-shot basis and look for coincidences.

Cole et al, PRX 8, 011020 (2018)

Colliding beams

All-optical experiments



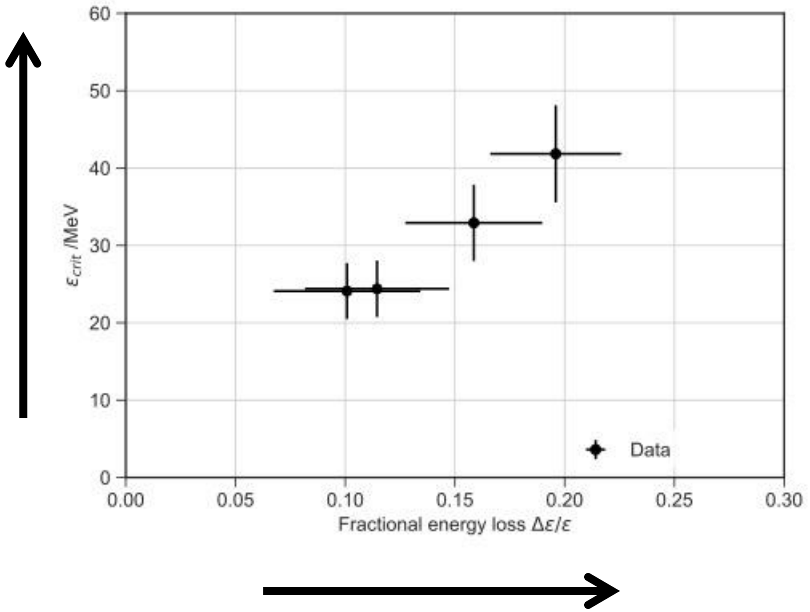
- Beams with lower energy associated with largest gamma ray signal.
- Low probability to get this signal purely from background fluctuations.
- Augment with the critical energy of the gamma spectrum, inferred from Geant simulations of the CsI scintillator response.

Cole et al, PRX 8, 011020 (2018)

Colliding beams

All-optical experiments

harder gamma spectrum



decreasing electron energy

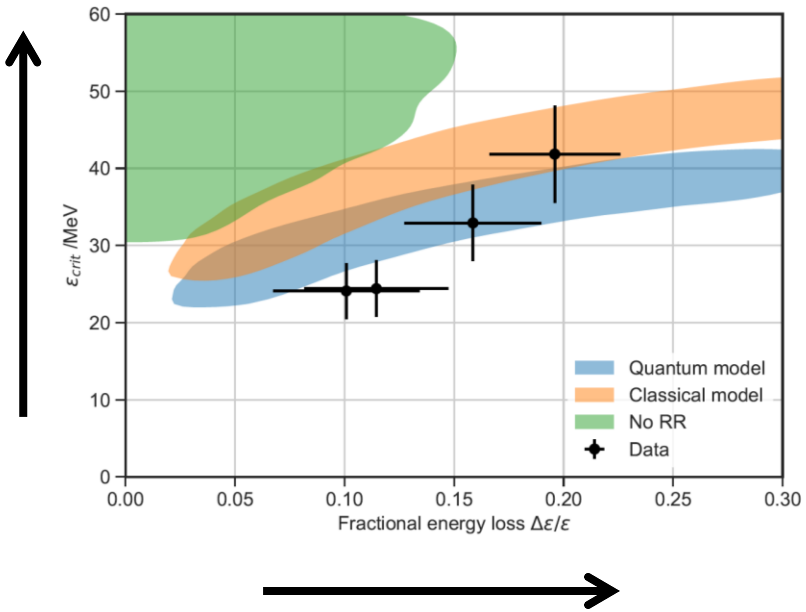
- 4 shots with CsI signal significantly above background.
- Hardest gamma rays associated with lowest energy in electron beam: indicative of a radiation reaction process.

Cole et al, PRX 8, 011020 (2018)

Colliding beams

All-optical experiments

harder gamma spectrum



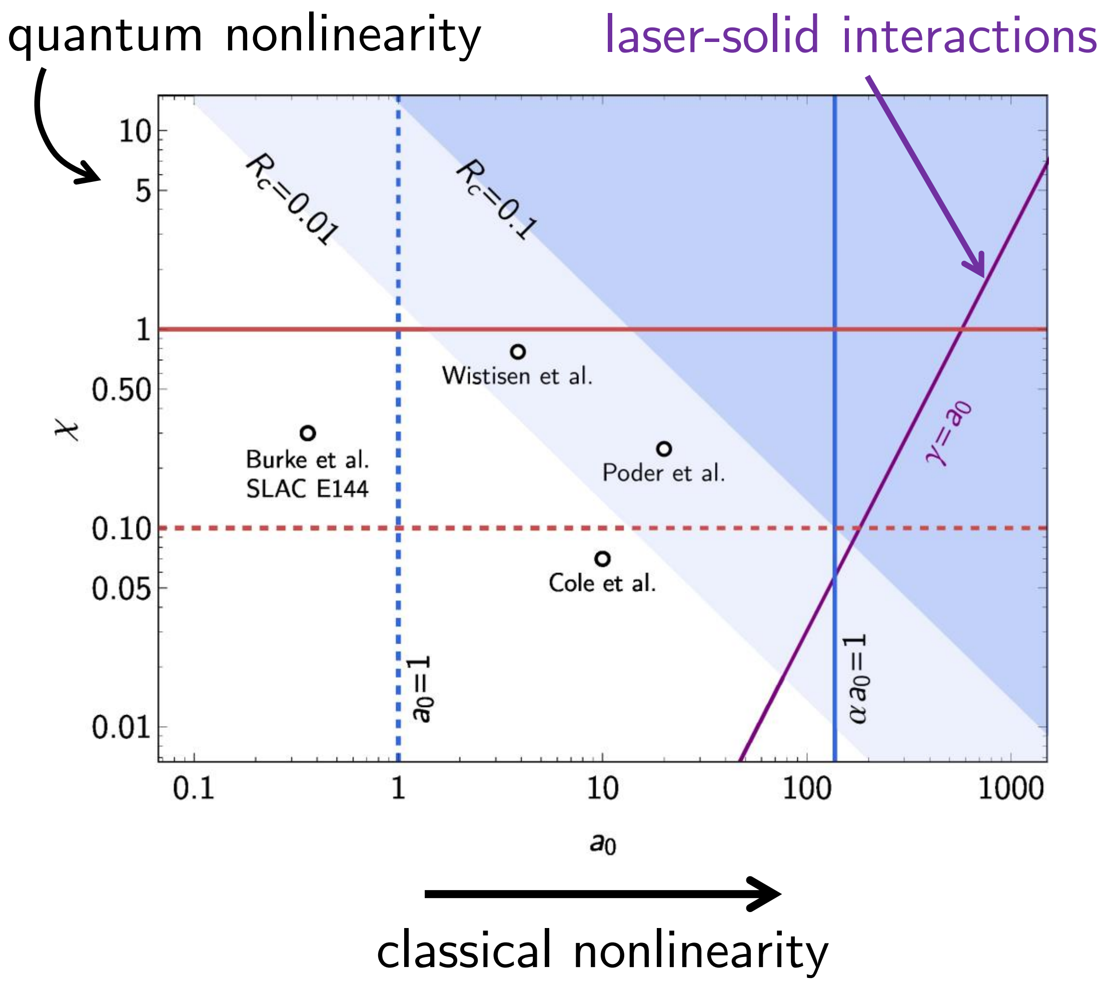
decreasing electron energy

- 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.

Cole et al, PRX 8, 011020 (2018)

Colliding beams

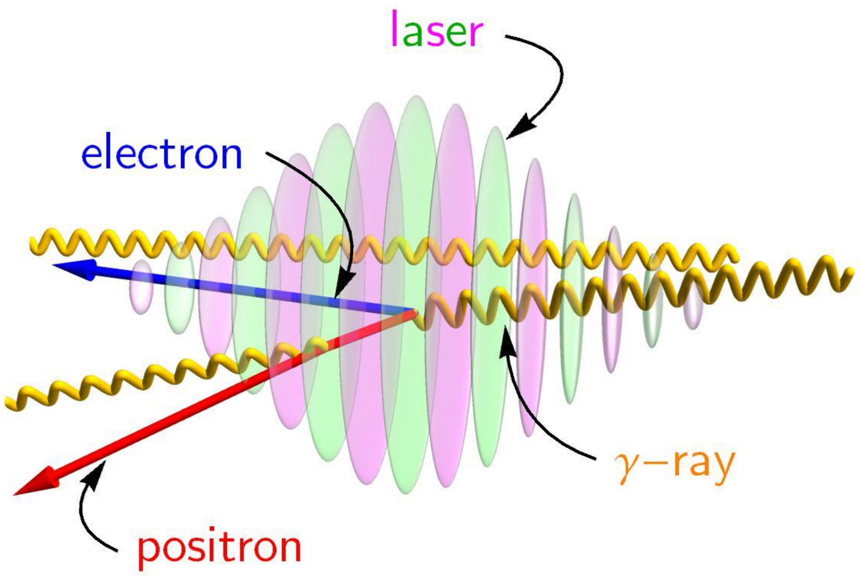
All-optical experiments



- Explore the full parameter space and tune the relative importance of RR, quantum effects etc.
- Advantages: natural synchronization of the two beams; matched size of high-charge electron bunch and target laser pulse.
- "Soon" @ $a_0 > 30$, $\chi > 0.1$: RR + nonlinear Breit-Wheeler pair creation

Photon-seeded cascades

Threshold



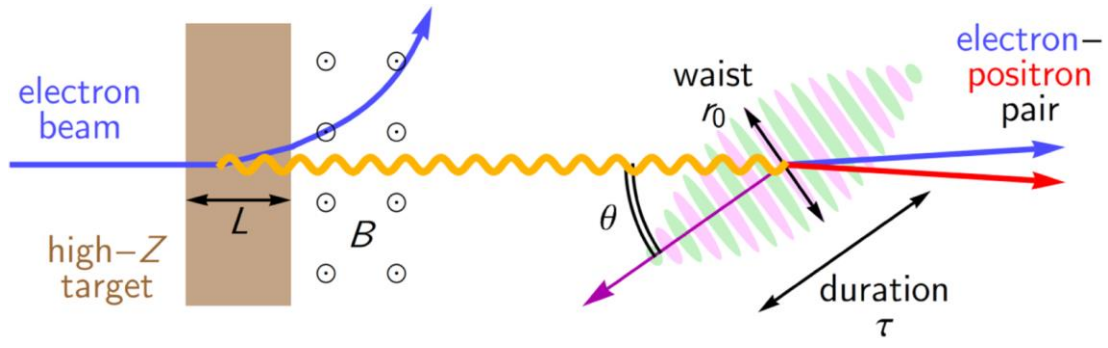
- Onset of nonlinear pair creation is approximately $\chi_\gamma > 0.1$.
- With optical lasers operating near the current intensity limit, necessary photon energy is in the GeV range:

$$\chi_\gamma = \frac{a_0 \omega_0 \omega (1 + \cos\theta)}{m^2}$$

$$\simeq 0.8 \left(\frac{\omega}{1\,\mathrm{GeV}}\right) \sqrt{\frac{I_0}{10^{22}\,\mathrm{W/cm}^2}}$$

Photon-seeded cascades

From bremsstrahlung

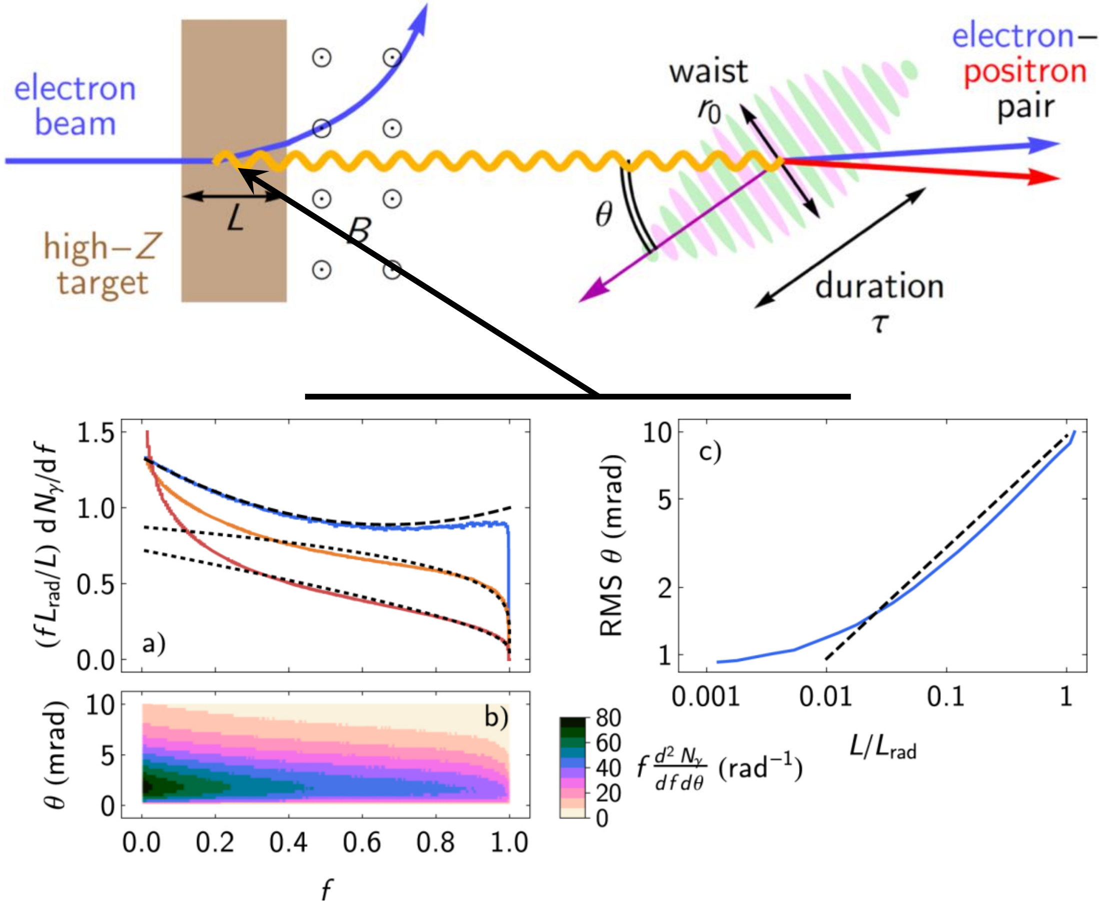


- Use bremsstrahlung of multi-GeV electron beam in a high-Z target.

TGB and Marklund, PPCF 60, 054009 (2018)

Photon-seeded cascades

From bremsstrahlung



- Use bremsstrahlung of multi-GeV electron beam in a high-Z target.
- Broad spectrum up to the initial energy of the electron E_0 ($f = \omega/E_0$ and $\ell = L/L_{rad}$):

$$\frac{dN_\gamma}{df} = \frac{(1-f)^{4\ell/3} - e^{-7\ell/9}}{f\left[\frac{7}{9} + \frac{4}{3}\ln(1-f)\right]}$$

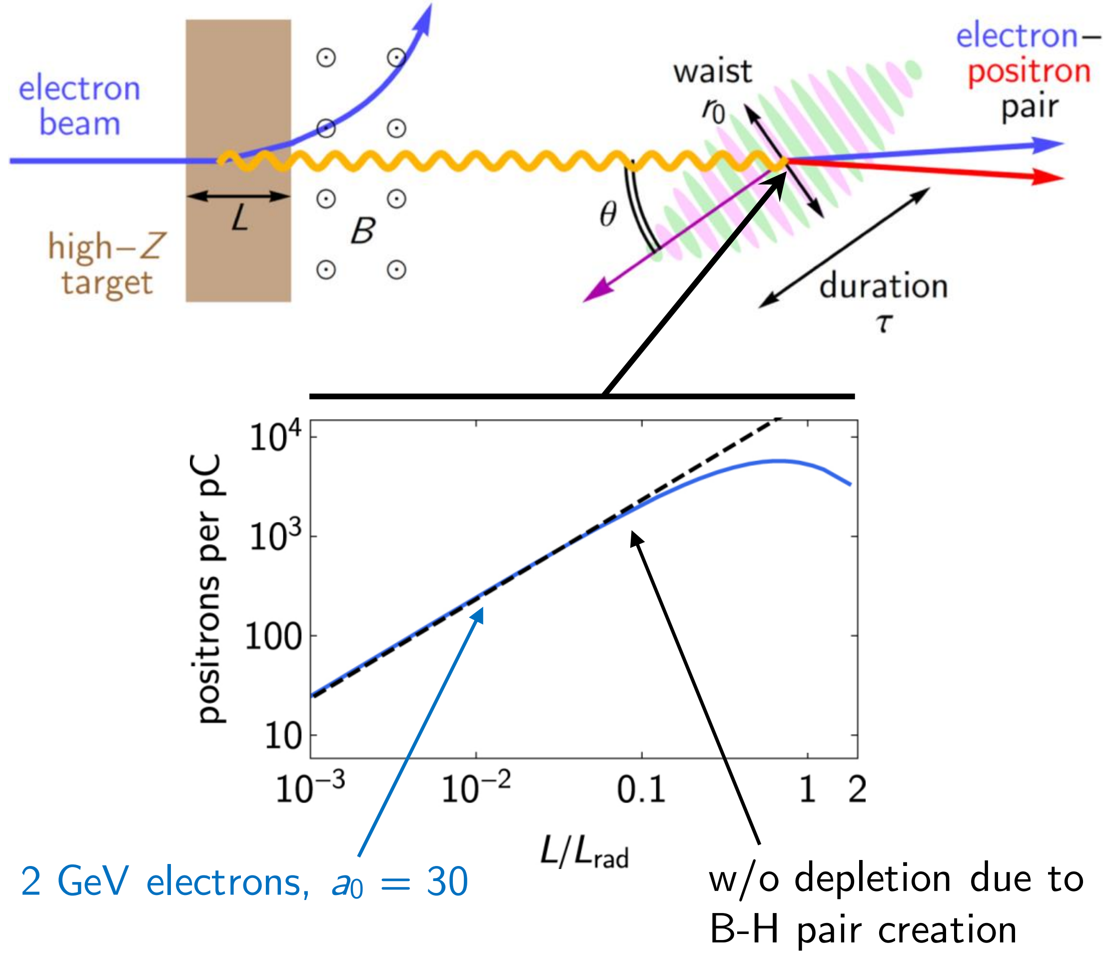
- Divergence θ scales as $\ell^{1/2}/E_0$

TGB and Marklund, PPCF 60, 054009 (2018)

Photon-seeded cascades

From bremsstrahlung

TGB and Marklund, PPCF 60, 054009 (2018)

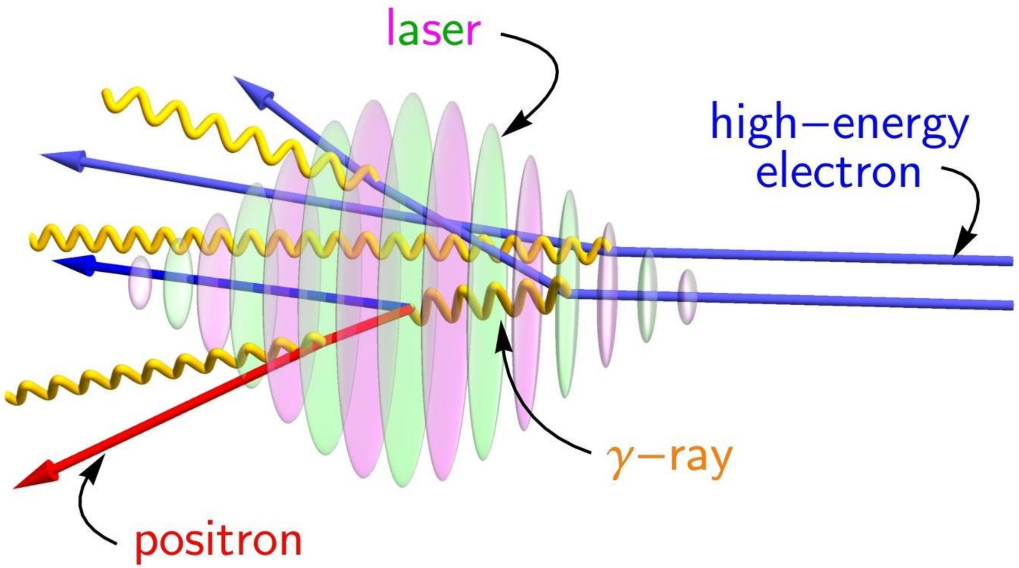


- Ideal target thickness is $0.7L_{\mathrm{rad}}$: thick enough to make lots of photons, but not so thick as to deplete the high-energy tail by Bethe-Heitler pair creation.
- Positron yield can be in the 1000s…
- But unless divergence of the photons is reduced, the overlap between the beams is too small.

TGB and Marklund, PPCF 60, 054009 (2018)

Electron-seeded cascades

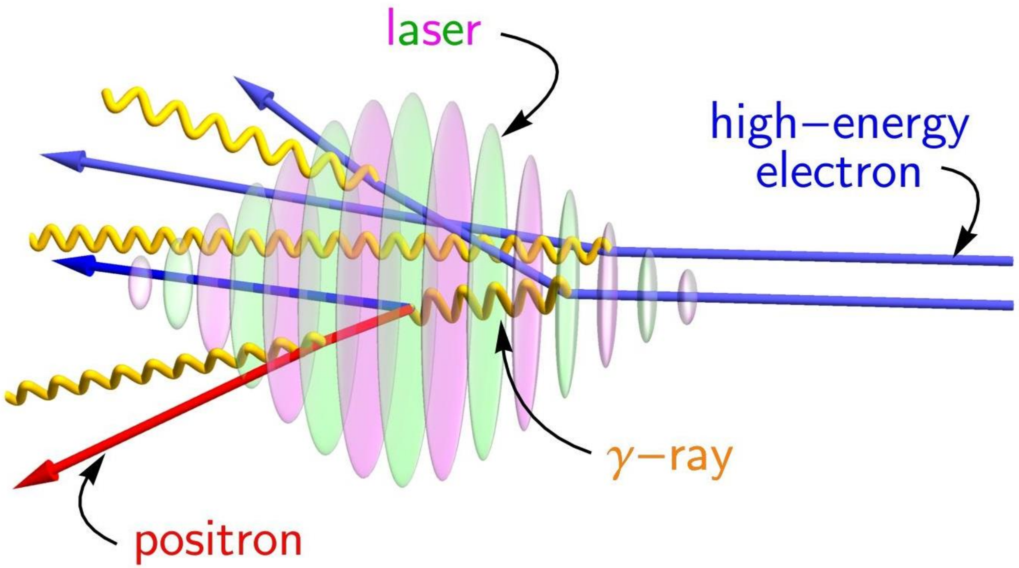
Motivation



- Consider making pairs using a high-energy electron beam, rather than a photon beam.
- To make pairs, need a laser pulse with $a_0 > 30$.
- But that laser pulse is also good at making high-energy photons, as in non-linear Compton scattering, the harmonic order scales as ${a_0}^3$.

Electron-seeded cascades

Motivation

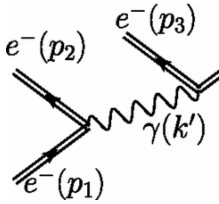


- A laser-electron beam collision creates photons where they are needed.
- The highest-energy photons are created in the rising edge of the pulse; pairs at the centre.
- Source and converter separated by microns, photon divergence scales like a_0/γ.

Electron-seeded cascades

Theory and simulation

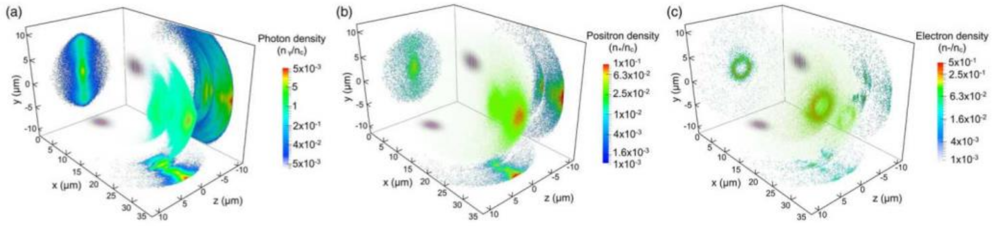
- Interaction can be modelled directly from QED [e.g. Ilderton, PRL 106, 020404 (2011)], but only at second order, i.e. electron emits only one photon.



$-\ (p_2 \leftrightarrow p_3)$

$$R = \frac{\alpha^2}{4\omega^2}\left[\prod_{p_3,p_4}\int\frac{d^2p_\perp}{(2\pi)^3}\int_0^\infty\frac{dp_-}{2p_-}\right]\frac{\theta(p_{2\_})}{p_{2\_}}\sum_{\text{spins}}|K|^2\bigg|_{\text{shell}}$$

- Integrated, full-scale QED-PIC simulations for wakefield acceleration plus photon and pair creation [Lobet et al, PRAB 20, 043401 (2017)].

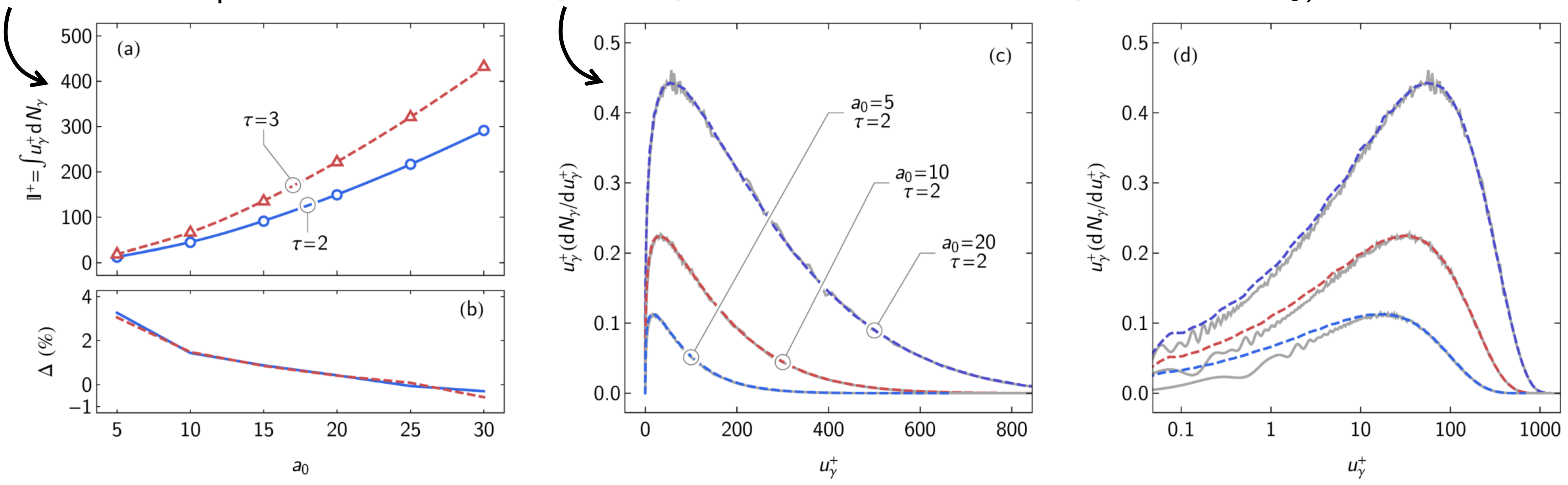


Electron-seeded cascades

How accurate are QED-PIC codes?

total radiated power

power spectrum of nonlinear Compton scattering)



- Compare PIC photon spectra with exact QED results.
- Power spectrum, total energy, laser absorption accurate to % level for $a_0 > 5$.

TGB, Seipt, Bulanov and Marklund, arXiv:1804.11085 [physics.plasm-ph]

Electron-seeded cascades

Scaling laws

$$\frac{dN_\gamma}{d\omega} \propto \frac{\exp\left(-\frac{2\omega}{3\chi_c(E_0-\omega)}\right)}{\sqrt{\chi_c(E_0-\omega)+4\omega}}$$

$$\omega_c \simeq E_0 \frac{\sqrt{\frac{2\chi_c m^2}{a_0 E_0 \omega_0}}}{1+\sqrt{\frac{2\chi_c m^2}{a_0 E_0 \omega_0}}}$$

$$E_+ \simeq \frac{\omega_c}{2}\left[1+\frac{1.6\alpha a_0^2 n \omega_0 \omega_c}{m^2} g\left(\frac{a_0 \omega_0 \omega_c}{m^2}\right)\right]^{-1}$$

$$\frac{N_\pm}{N_e} \simeq 3.8 P_\pm \chi_c \frac{(E_0-\omega_c)^2}{E_0} \left.\frac{dN_\gamma}{d\omega}\right|_{\omega=\omega_c}$$

- Positron yield from synchrotron spectrum $\times$ pair creation probability.
- For pair creation, we need a photon χ about 1, so we will end up with a positron χ of about 0.5.

TGB, Ilderton, Murphy and Marklund, PRA 96, 022128 (2017)

Electron-seeded cascades

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Electron-seeded cascades

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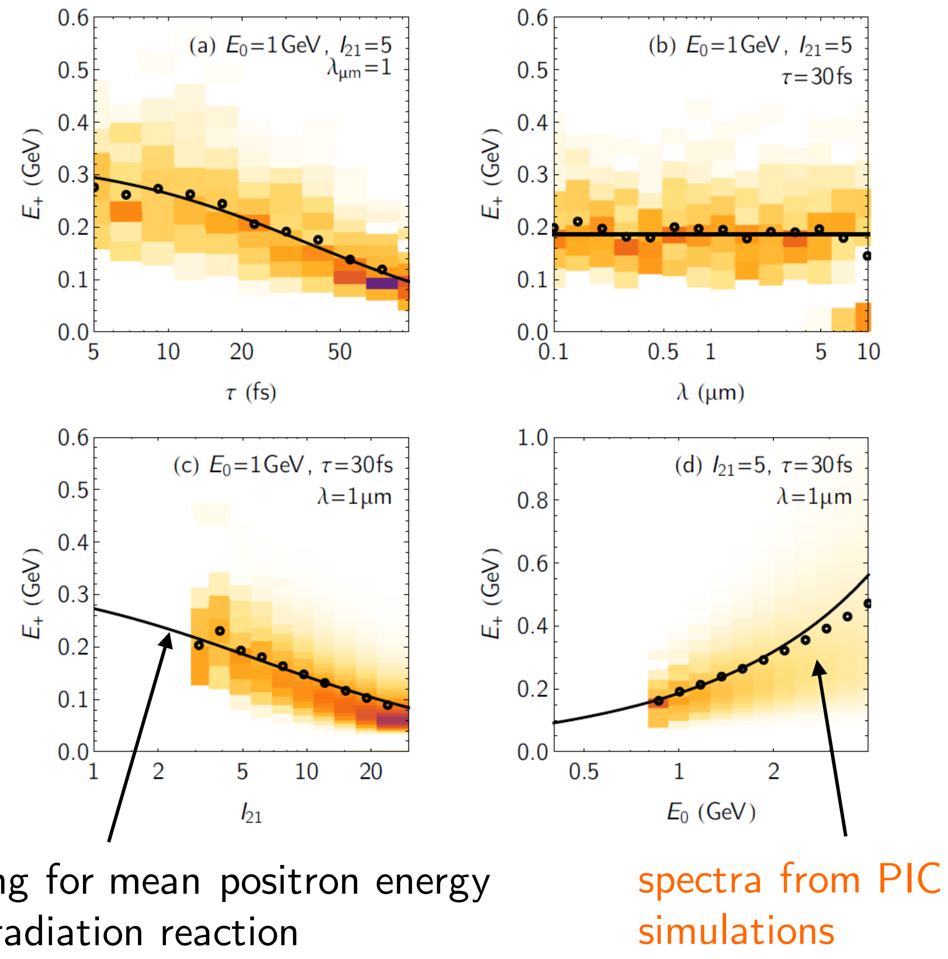

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Electron-seeded cascades
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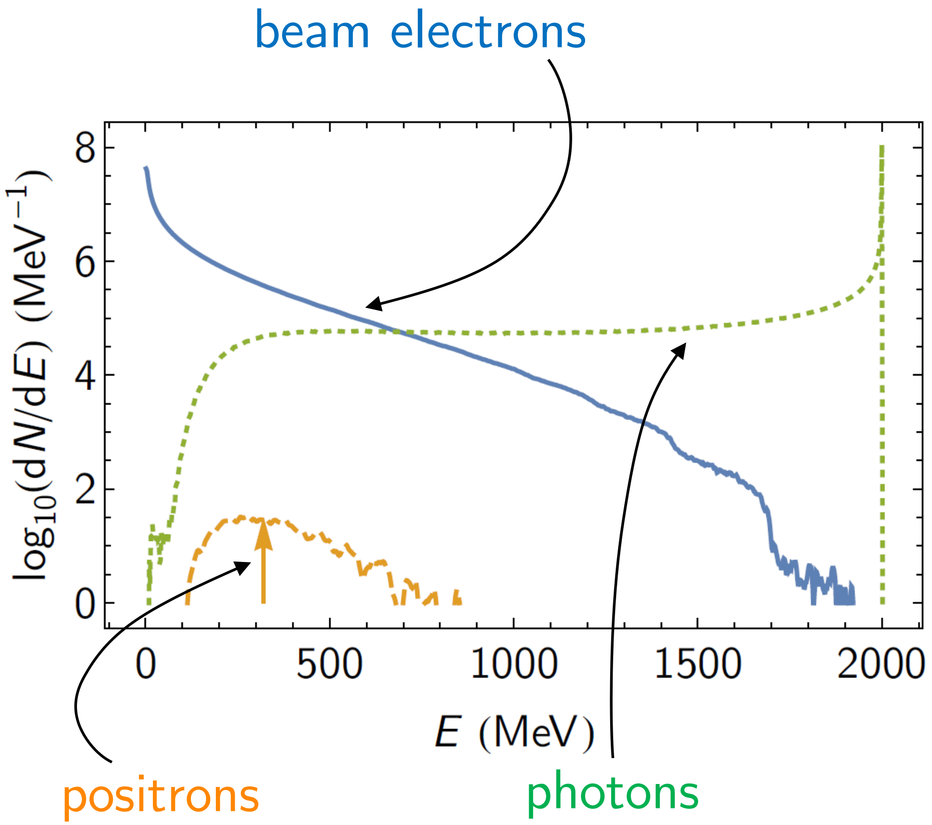

- To observe pair creation (say 1000 positrons for 10^9 electrons @ 30 fs)

$$\left(\frac{I_0}{10^{21}\,\mathrm{W/cm^2}}\right)\left(\frac{E_0}{2\,\mathrm{GeV}}\right) \gtrsim 1$$

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Electron-seeded cascades

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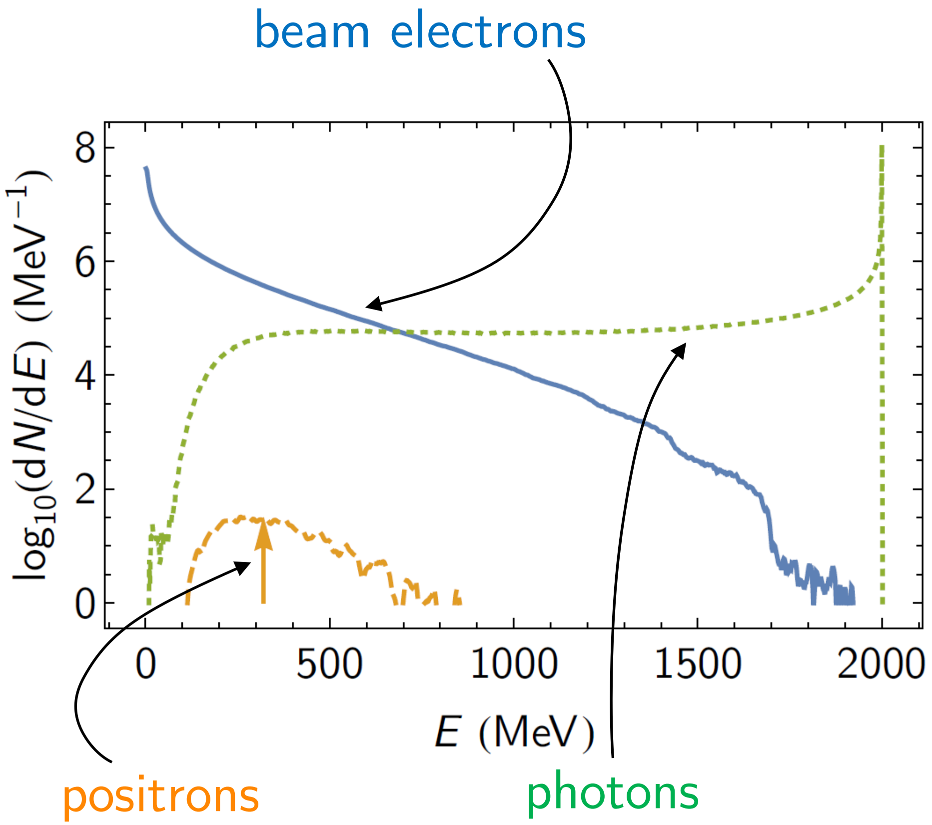

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- Use measurements of the gamma ray yield and critical energy to identify shots where a positron signal is expected.

TGB, Ilderton, Murphy and Marklund, PRA 96, 022128 (2017)

- Cascades (multiple QED events per incident particle) will be launched by high-energy photons or electrons in laser pulses at and above the current intensity limit.

- Dynamics in this regime is dominated by nonperturbative QED, for which no complete theoretical description exists.

- Coincidence measurements of electron, positron and photon spectra isolate successful collisions from shot-to-shot fluctuations.