We thank the FACET PAC for reviewing our strong-field QED program (E-320). Our responses to your questions are provided below. Please feel free to contact us if you require additional information, and especially if you think we misinterpreted either question.

Question 1

Explain the competitive advantage of doing the experiment at SLAC and not at ZEUS, Korea, etc.

Multi-PW laser science and technology as well and multi-GeV electron laser wakefield acceleration (LWFA) is advancing rapidly. Given that all-optical laser facilities might soon have access to $\gtrsim 10\,\mathrm{GeV}$ electron beams, this is a very important question. As we substantiate below, the approach that we are taking at FACET-II offers a decisive competitive advantage to PW laser-based approaches for strong-field QED, in no small part arising from the relatively well-defined beams and high repetition-rate that conventional accelerators can provide. Similar to most experiments on FACET this will allow us to pursue much more controlled experiments, and in particular to E-320, it will soon allow us to reach the QED critical field even with the modest 10-TW laser currently available at FACET — with much better defined collisions and lower backgrounds. We also benefit from the advanced diagnostics, beamline optics, detectors, etc. available at a dedicated accelerator test facility. Furthermore, we envision a number of improvements and upgrades that will allow us to maintain this advantage for the foreseeable future.

Not surprisingly, strong-field QED has been held out as one of the flagship experiments on many ultrahigh intensity laser facilities. Ideally, we would have a multi-PW laser co-located with a high-quality ultrarelativistic electron beam from an RF-LINAC to probe strong-field QED [1]. As such a facility doesn't yet exist, we have to compare two existing approaches that currently are capable of accessing SFQED: a) RF-LINAC combined with multi-TW laser system (E-320 at FACET-II and hopefully soon LUXE at DESY) and b) LWFA-based experiments at multi-PW facilities (Apollon, CoReLS, ELI-NP, ZEUS etc.).

The clear advantage of multi-PW laser facilities is their ability to probe novel regimes of light-matter interactions, for example QED cascades and prolific pair production at intensities $\gtrsim 10^{24}\,\mathrm{W/cm^2}$ [2]. The RF-LINAC based approach, however, will provide data of much higher quality. In particular, any analysis demanding a substantial amount of statistical data (shots) will be virtually impossible at a multi-PW facility due to the severely limited repetition rate. In this sense, the experiments that we are pursuing on FACET are much better suited for high precision studies of the transition region from perturbative to non-perturbative Compton scattering, including the observation of the effective mass increase that we are already beginning to explore (more details are given in our answer to your second question below). Even more excitingly we have the opportunity to study pair-production in the tunneling regime, trident pair production, the onsets of QED cascades, as well as coherent recollision physics and vacuum birefringence, that are unpractical at best on PW-facilities.

A major challenge in SFQED experiments lies in the extensive phase space that governs the outcomes of collisions. This includes the parameters of each beam, for example, the electron beam's spectrum, charge, emittance, and pointing and the laser beam's peak intensity, spot size, and wavefront. Additionally, the two transverse impact parameters of the collision and the relative timing between both beams significantly influence the key observables. For meaningful comparisons with theoretical predictions, it is essential to accurately characterize all these parameters. Moreover, due to drifts and jitter, many of these parameters must be measured on a shot-to-shot basis. While it may seem counterintuitive we can mitigate focal averaging affects to some extent by having independent control over the laser and electron beams, and have a path to significantly lower backgrounds such that we can ultimately reconstruct individual collisions between the laser and electron and/or gammas.

For the foreseeable future, the accelerator-based approach will enable much more controlled experiments, due to the outstanding stability of all key beam parameters. Here we emphasize some of these aspects:

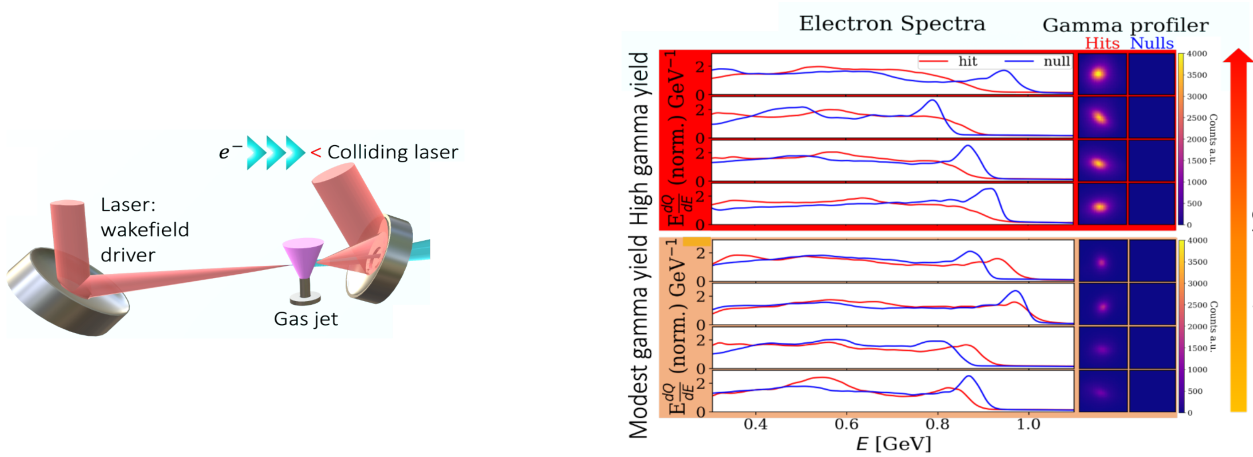


Fig. 1: Most recent LWFA-based experimental results from the Gemini laser in the UK [3]. **Left**: experimental setup; **Right**: examples of measured pre/post collision spectra.

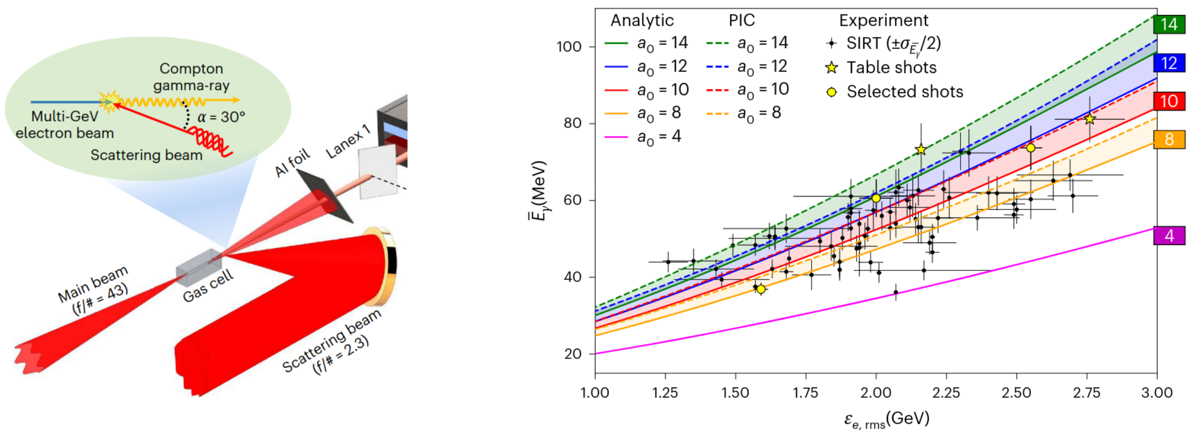


Fig. 2: The most recent LWFA-based publication on SFQED from the Korean 4 PW laser (CoReLS) [4]. **Left**: experimental setup; **Right**: overview of the 74 successful scattering shots on which the paper is based.

- **Monoenergetic electron beam**. Even when compressed, the FACET-II electron beam maintains an energy spread of $\lesssim 1\,\%$. This is a significant advantage for observing laser-induced changes in the electron-beam spectrum. In contrast, the fluctuating pre-collision electron spectra – unavoidable with multi-PW lasers operating at low repetition rates – present a major impediment, particularly when comparing different models of radiation reaction (see, e.g., [3] and Fig. 1). The approach to use a neural network to predict the pre-collision spectra on a shot-to-shot basis from secondary observables is innovative [6]. However, it cannot reach the precision achievable with stable RF beams and has been met with skepticism by parts of the community due to the limited amount of available training data.

- **Orders of magnitude higher repetition rate**. The FACET-II 10 TW laser operates at 10 Hz, whereas existing multi-PW facilities can only provide one high-intensity shot every few minutes. The high repetition rate of FACET-II enables precise alignment and calibration procedures that require a large number of shots, especially if several independent parameters are optimized. For instance, the position-timing scan shown in Fig. 3 involves 4400 shots and was completed in less than 10 minutes. In contrast, as an example, the multi-PW laser Apollon delivers only 200 high-intensity shots per day, with typical campaigns being limited to 4 weeks. These restrictions significantly reduce the amount of recordable data. For example, the most recent Korean study reports only 74 successful

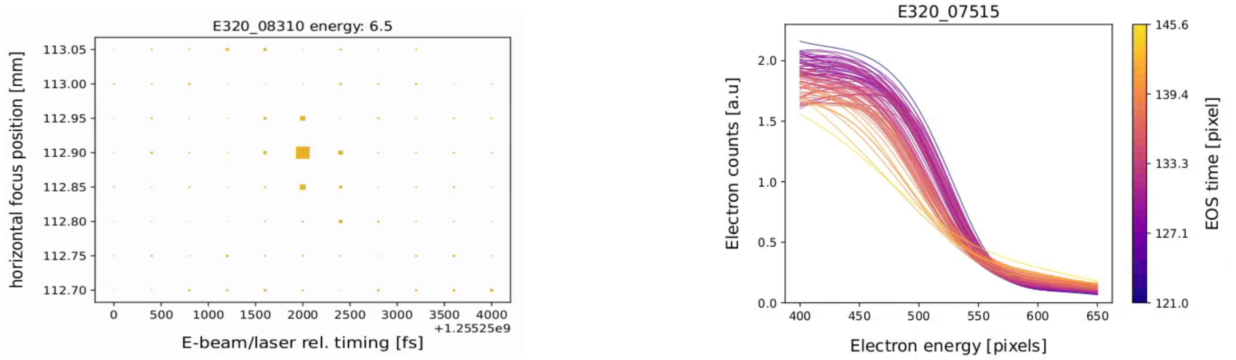


Fig. 3: E-320 data taken in FY24. **Left**: position-time scan to find optimal collision parameters: 8×11 data points, 50 shots each; **Right**: impact of the relative electron-laser timing on the effective laser intensity and thus the spectrum of the scattered electrons. This plot shows the 2$^{\text{nd}}$ Compton edge that separates the kinematic regions for 2-photon (left) and 3-photon (right) *net absorption*, respectively.

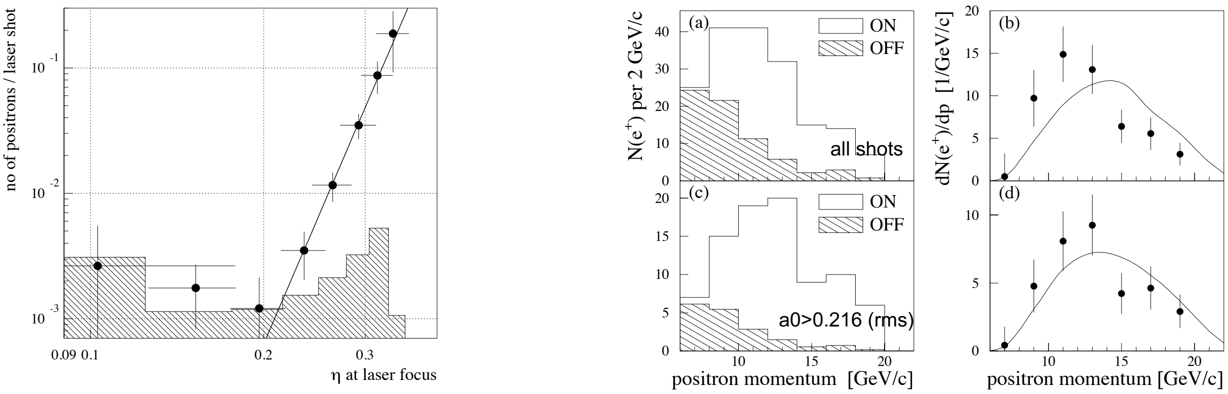


Fig. 4: Nonlinear (multi-photon) Breit-Wheeler Pair Production observed on SLAC E-144 [5]. **Left**: rate of positron production in the collision of a doubled TW Nd:glass laser (2.35 eV) with the 46.6 GeV electrons in the SLAC FFTB. The rate scales as the 5$^{\text{th}}$ power of the laser intensity consistent with kinematic considerations for multi-step (nonlinear Compton followed by Breit-Wheeler) pair production within the laser focus. Note that the peak rate was much less than one positron per shot, requiring exquisite background suppression. **Right**: positron spectrum integrated over all shots (upper) and for only the highest laser shots ($\eta = \langle a_0 \rangle_{\text{rms}} > 0.216$).

scattering events (see [4] and Fig. 2). This constraint renders a sophisticated post-selection of shots, based on correlations with other collision parameters, infeasible. Such a post-selection analysis is, however, vital for overcoming limitations induced by unavoidable jitter and/or drifts. In addition, we note that the Korean study did not measure the energy transfer to the electrons, and only indirectly reconstructed the gamma spectrum based on differential stopping power.

- **Conventional beamline optics provide a high degree of control and enable high-performance diagnostics and detectors**. The 10 GeV FACET-II beamline in sector 20 requires a significant amount of space (approximately $\sim 20\,\text{m}$) to deliver a well-defined beam into the interaction point and to properly re-image the scattered electrons onto the detectors. As this amount of space is not available at most multi-PW laser facilities, none of the existing LWFA-based SFQED experiments implements a beam transport between the LWFA and the high-intensity interaction point (see, e.g., Fig. 2 and 1). The ability to operate non-destructive beam diagnostics, such as EOS for relative timing and multiple beam-position monitors (BPMs), which record the beam vector, is essential for reliably knowing the collision parameters for each shot. The importance of this data is evident from Fig. 3: the relative electron-laser timing has a decisive impact on the effective laser intensity and, consequently, the observed radiation spectra. A similar quality of data analysis is far from achievable at currently existing multi-PW laser facilities. Finally we note that conventional accelerators are capable of achieving very low backgrounds. This was essential, for example, in the original SLAC E-144 experiment, where multi-photon Breit-Wheeler pair production was observed through positron detection, with a peak rate of approximately 0.2 positrons per shot and a background level of about 0.001 positrons per shot (see [5] and Fig. 4).

Question 2

What is the measurable signature to demonstrate the difference between classical and perturbative/non-perturbative theory.

Analogy with FEL science. The difference between perturbative and non-perturbative Compton scattering is qualitatively similar to the difference between synchrotron radiation in the undulator and wiggler limit in terms of the nonlinear motion of the classical trajectories. Recall that in classical synchrotron radiation in the undulator limit, the on-axis spectrum consists of a series of odd harmonics of the doppler shifted Larmor radiation of the electron wiggling in the magnetic field [7]. In this case the transverse motion of the electrons is small such that the ratio of the transverse momentum to the longitudinal momentum is much less than the characteristic $1/\gamma$ cone of the radiation, leading to constructive interference and thus well defined harmonics. As you increase the normalized vector potential (undulator K-parameter), the motion becomes anharmonic and the spectrum red-shifts as the longitudinal momentum decreases in favor of an increased transveres momentum. As a result, the electron takes longer to traverse a single period of the magnets. However, when the transverse momentum exceeds the threshold where the angle becomes large compared to $1/\gamma$, the spectrum begins to resemble the incoherent emissions of a continuous synchrotron spectrum. In either case, as long as the characteristic wavelength is large compared to the Compton wavelength (as in the case of x-ray light sources), the primary distinction in the quantum theory is that the emission becomes stochastic. This is because the energy carried away by each photon represents only a small fraction of the electron's energy, leaving the electron's trajectory unaffected by individual emissions. Even in FELs where a single electron can radiation on order of a thousand photons, quantum effects are not important (although the energy loss can be significant enough that the electrons fall out of resonance with the previous emitted radiation if you don't taper the undulator field to compensate).

E-320. In our case, quantum effects are essential in describing even the scattering of a single laser photon from the ultrarelativistic electron beam, already in the weak-field limit (Compton scattering). This is due to the finite electron mass and consequently strong recoil. Under our conditions, the maximum energy loss to the gamma photon for linear Compton scattering is approximately 1.8 GeV, compared to about 2.2 GeV when recoil is neglected [see Eq. (2)]. As you increase the laser intensity such that the classical trajectories become nonlinear, the scattering of multiple photons becomes possible. However, due to the recoil, the maximum energy of the emitted gamma photons does not follow a harmonic progression (nor is it limited to odd orders). The maximum gamma energy for scattering from two photons would be about 3.1 GeV compared to 4.4 GeV ignoring recoil, and so on. As the field is increased more and more, we see a redshift in the emitted photons, and eventually the different orders begin to merge together, qualitatively like the undulator/wiggler transition, but now modified by quantum corrections induced by the recoil. In all cases the classical trajectories are dramatically altered by the emission of hard photons. There are other notable differences, including the fact that a static magnetic field differs from a plane electromagnetic wave, but qualitatively we can expect the primary measures to be as we described above: a shift in the kinematic edges, ultimately transitioning to a more continuous spectrum, all corrected for recoil. Below we provide a more rigorous and quantitative description.

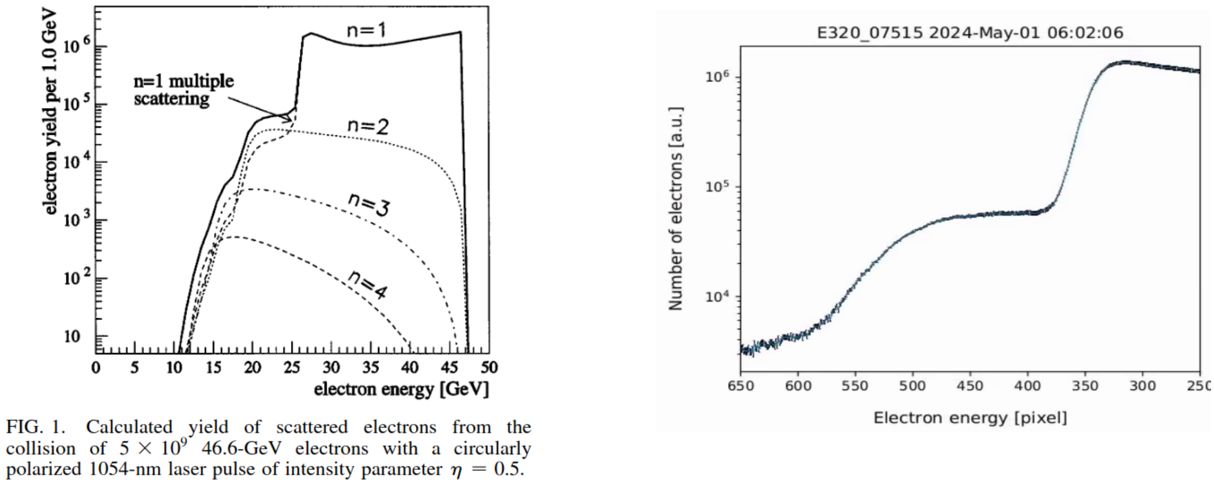


Fig. 5: Comparison between the perturbative spectrum predicted for E-144 [9] and the one measured by E-320 (first and second Compton edge). Note that for E-320 the laser pulses are significantly shorter (E-320: $\sim 50\,\mathrm{fs}$ vs. E-144: $\sim$ ps), which implies that the probability for multiple linear ($n=1$) scattering events is negligible in the regime $a_0^2 \lesssim 1$ for E-320.

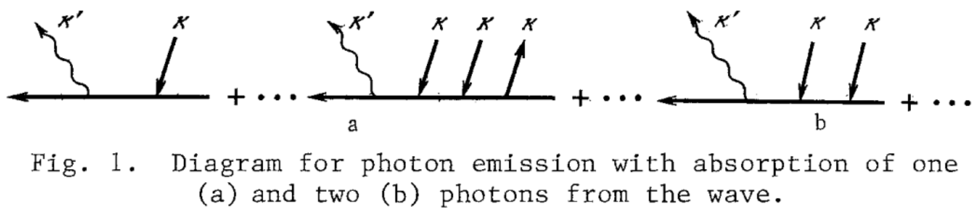


Fig. 6: Perturbative picture of (non-linear) electron-laser interactions: the electron can i) absorb photons from the laser and ii) return photons into the highly occupied laser mode(s) via stimulated emission. The exchange of laser photons without net absorption gives rise to a mass dressing, similar to the Higgs mechanism. Diagram taken from [10].

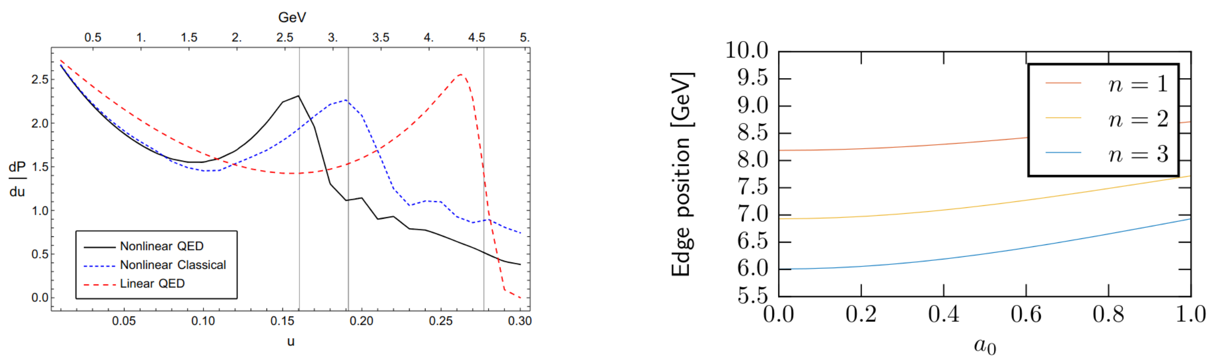


Fig. 7: **Left**: prediction of the expected $n=1$ edge shift for LUXE [11]. Here, the following distinctions are made: "linear QED" — Eq. (2) with $n=1$ (linear) and thus $u_1 = u_\mathrm{q}$ (QED); "nonlinear classical" — Eq. (2) with $u_n = u_\mathrm{cl}$; and "nonlinear QED" — Eq. (2) with $u_n = u_\mathrm{q}$. **Right**: expected edge shift for $n=1$ to $n=3$ at E-320, based on Eq. (2) with $u_n = u_\mathrm{q}$.

The two key parameters of SFQED are the classical intensity parameter a_0 – often called reduced vector potential (analagous to the undulator parameter K) – and the quantum parameter[1] χ [8]

$$a_0 = \frac{eE}{mc\omega} \approx 0.6 \frac{\lambda}{\mu\mathrm{m}} \sqrt{\frac{2I}{10^{18}\,\mathrm{Wcm}^{-2}}}, \qquad \chi = \frac{E^*}{E_{\mathrm{cr}}} \approx \frac{\epsilon\hbar\omega}{(mc^2)^2}(1+\cos\theta_c)a_0. \tag{1}$$

Here, ϵ is the energy of the colliding electron beam, $\hbar\omega$ is the (average) laser-photon energy, and θ_c is the collision angle.

The quantum paramter χ measures the electric field in the rest frame of the ultra-relativistic electron beam, E^*, in units of the QED critical field $E_{\mathrm{cr}} = m^2c^3/(\hbar e) \approx 1.3 \times 10^{18}\,\mathrm{V/m}$. It determines whether one can use the classical synchrotron spectrum ($\chi \ll 0.1$) or if already a single photon emission induces a significant recoil ($\chi \gtrsim 0.1$). Furthermore, tunneling pair production becomes sizable once $\chi \gtrsim 1$. Therefore, χ is the primary figure-of-merit of an SFQED experiment. Due to the difference in scaling with energy ($\chi \propto \epsilon$) and intensity ($\chi \propto a_0 \propto \sqrt{I}$), it is more advantageous to invest in increasing the electron energy ϵ rather than the laser intensity I to maximize χ. This explains why having a high-energy electron beam is a key advantage (E-320: 10 GeV; LUXE: 17 GeV, E-144: $\approx$ 50 GeV); it is most likely also the reason why the high-energy laser arm was used for LWFA in the most recent Korean paper [4] (note that this is not always the best choice; it strongly depends on which effect one wants to study).

Even though it might seem counter-intuitive, the classical intensity parameter determines the average number of photons an electron interacts with [10]:

- $a_0^2 \ll 1$: the interaction with the laser is perturbative and we expect to see mainly linear Compton scattering
- $a_0^2 \lesssim 1$: the probability for non-linear interactions becomes sizable, i.e., one expects to see electrons that simultaneously interact with two or more laser photons. Here, one has to distinguish between the number of *net absorbed* laser photons n and the total amount of exchanged photons. As the former dictates the total energy-momentum balance of the process, it determines the leading-order position of the kinematic edge (see Fig. 5).

  In general, however, the total amount of photons exchanged with the laser is significantly higher, as the electron can return photons into the laser mode(s) via stimulated emission (see Fig. 6). The exchange of laser photons *without net absorption* increases the effective electron mass, analogous to the Higgs mechanism. This is a non-perturbative effect, which shifts (renormalizes) the position of the kinematic edge with respect to the perturbative prediction (see, e.g., [10] and Fig. 3).

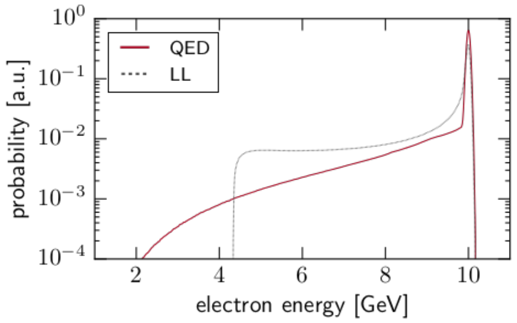
  Depending on the description used we obtain two different definitions for the kinematic parameter u and hence also for the position of the kinematic edge for n^{th}-order Compton scattering, defined by $u = u_n$ [10]: $u = u_{\mathrm{cl}}$ appears in classical electrodynamics whereas $u = u_{\mathrm{q}}$ is the definition emerging from the full quantum theory, which properly takes the recoil induced by a single photon emission into account

$$u_{\mathrm{q}} = \frac{\hbar\omega'}{\epsilon - \hbar\omega'}, \qquad u_{\mathrm{cl}} = \frac{\hbar\omega'}{\epsilon}, \qquad u_n = \frac{2n\chi}{a_0(1+a_0^2/2)}. \tag{2}$$

  Here, $\hbar\omega'$ is the energy of the emitted photon and u_n denotes the kinematic threshold for the *net absorption* of n laser photons. Note that the ratio χ/a_0 is independent of the laser intensity and the appearance of the term $1 + a_0^2/2$ is a direct consequence of the non-perturbative electron mass dressing. The non-linearities predicted by classical electrodynamics from the relation $u_{\mathrm{cl}} = u_n$ have been measured, e.g., in[2] [12]. The difference between perturbative QED, nonlinear classical electrodynamics, and nonlinear QED is illustrated in Fig. 7.

[1] E: electric field (lab frame); $I = \epsilon_0 c E^2/2$: intensity (lab frame); ω: (average) laser angular frequency; $\lambda = 2\pi c/\omega$: (average) laser wavelength; m: electron/positron rest mass; e: elementary charge; c: speed of light in vacuum; $\hbar$: reduced Planck constant.

[2] They collided 65 MeV electrons with a CO^2 laser that reached $a_0 = 0.5 - 0.7$. Thus we see that the experiment probed only classical non-linearities, as $\chi \ll 0.1$.



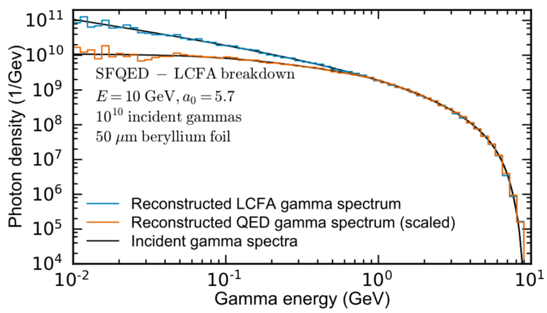


Fig. 8: **Left**: comparison between the predictions for radiation reaction based on classical electrodynamics / Landau-Lifshitz equation and a full QED calculation. In this plot $a_0 = 7.2$ is considered, but the same qualitative difference is visible as soon as $a_0^2 \gtrsim 10$ and $\chi \gtrsim 0.1$ (see, e.g., [13]; simulation: M. Tamburini). **Right**: generally speaking, the formation length for photon emission is small for $a_0^2 \gtrsim 10$ and we can employ the so-called "Local Constant Field Approximation" (LCFA), which is currently used in all state-of-the-art PIC codes. At the low-energy end of the emission spectrum, however, the LCFA breaks down. This effect will become measurable once the UCLA gamma pair spectrometer is installed [14].

E-320 aims at measuring, for the first time, the transition from linear to non-perturbative Compton scattering *while quantum effects are important*. Probing the transition from $a_0^2 \ll 1$ to $a_0^2 \gg 1$ requires $a_0 = 0.32 - 3.2$ for E-320, which is well within the current capabilities of the FACET-II laser system. Note that the amount of shift in the different Compton edges allows one to distinguish between classical and quantum electrodynamics (see Fig. 7).

- $a_0^2 \gg 1$ the electron interacts, on average, with a large number of laser photons, and the radiation spectrum becomes quasi-continuous. In this regime we can, to leading order, neglect the quantum nature of the laser photons and consider the interaction with a classical background field instead (dressed-state formalism) [8]. The magnitude of the quantum parameter χ determines whether the spectrum and thus the energy losses due to multiple emissions (radiation reaction) can be determined from classical electrodynamics ($\chi \ll 0.1$) or if recoil, stochasticity, and other quantum effects play a significant role ($\chi \gtrsim 0.1$). Whereas LWFA-based experiments are struggling to unambiguously show the difference between different models/descriptions (see [3, 15, 16]), simulations show a very clear quantitative and qualitative difference for E-320, mainly due to the monochromatic spectrum of the initial electron beam (see Fig. 8). Notably, we will also be able to observe the breakdown of the "Local Constant Field Approximation" (LCFA) at the infrared end of the photon spectrum. This will be an important measurement, as this approximation is used in all state-of-the-art QED-PIC codes (see Fig. 8).

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