Understanding the Fully Non-Perturbative Strong-Field Regime of QED.
LoI to Theory Frontier

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Abstract: Although perturbative QED with small background fields is well-understood and well-tested, there is much less understanding of QED in the regime of strong fields. At the Schwinger critical field, $E_c = m^2c^3/e\hbar \sim 10^{18}$ V/m, the vacuum becomes unstable to pair production. For stronger fields, such that $\alpha(E/E_c)^{2/3} > 1$, QED perturbation theory breaks down. These regimes are relevant to environments found in high-energy astrophysics and to physics in the collisions of high-energy electron and heavy ion beams. We plan to investigate problems in beam simulation and basic QED theory related to QED at strong fields, to analyze experiments that can test QED in this regime, and to explore applications to astrophysics and particle physics.

Perturbative QED is characterized by the vacuum electron/positron mass scale, $m \sim$ MeV, a large mass gap between fermions and the massless photon, and a very small coupling constant $\alpha = e^2/(4\pi)$, which facilitates the perturbative expansion. For many quantities in fundamental lepton and atomic physics, the QED perturbation expansion is extremely accurate. Indeed, the precise agreement between theory and experiment for these quantities is a triumph of modern physics [1].

This picture changes profoundly in the presence of very strong background fields [2–8]. The background field introduces a new mass scale $\sqrt{eE^*}$, where E^* is the rest-frame electric field experienced by an electron/positron with charge $\mp e$. A background electric field of size $eE_c = m^2$, the "Schwinger critical field" [9], makes the QED vacuum unstable with respect to spontaneous e^+e^- pair production. It is useful to define a quantum nonlinearity parameter, $\chi = eE^*/m^2 = E^*/E_c$, which characterizes the non-perturbative strong-field regime. New collective effects can appear when χ is of order 1. Another threshold appears when $\chi \sim 1/\alpha^{3/2}$. Since both photons and electrons receive mass corrections of order $\delta m^2 \sim \alpha\chi^{2/3}m^2$, the conventional QED perturbation expansion breaks down at this point [10]. The leading effects of these corrections can be controlled by resummation of self-energy diagrams [11], but a fully self-consistent approach to this very strong field regime remains an important open problem.

Understanding the new physics of strong-field QED is important in a number of experimental contexts. We propose to study the new aspects of the QED strong field regime in a unified way that supports the following applications:

Direct probes of Schwinger critical field phenomena. In the 1990's the SLAC experiment E-144 measured nonlinear Compton scattering and pair production in the interaction of a high-energy electron beam with an intense laser in the multi-photon regime, where perturbation theory still applies [12, 13]. Recently, there are several initiatives to explore non-perturbative effects with respect to the laser field in the regime $\chi \sim 1$ [14]. These include upcoming experiments at DESY (LUXE [15]), SLAC (E-320 at FACET II [16]) and a number of all-optical laser facilities [17]. The opportunity to create such beam-laser photon collisions has been strongly endorsed by both the high-intensity laser [18] and the plasma physics community [19]. This LoI proposes to explore strong-field QED predictions for new experiments in the $\chi \gg 1$ regime, which could be provided, for example, by a 30 GeV electron beam at SLAC interacting with a multi-Petawatt laser, and with high-intensity short bunch beam-beam collisions [20–23]. These experiments will enable precision comparisons of theory and experiment in such strong-field regimes.

Relativistic quantum plasmas. The understanding of the e^+e^- plasma that is formed in fields at and above the Schwinger critical field is still at an early stage. This "QED plasma regime" is encountered in extreme astrophysical

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plasmas [24, 25], *e.g.*, those around pulsars and accreting black holes. The interplay between the strong-field pair-production rates and collective plasma effects in this regime is an active field of current research [20, 26–28]. A more advanced question is that of whether the quantum coherence of pair-production plays a significant role. The astrophysical aspects of this topic are discussed further in the accompanying LoI [29].

Beam-beam interaction in lepton colliders. The strong-field regime is relevant to beam-beam interactions and the theory of disruption and "beamstrahlung" radiation at high energy and high luminosity lepton colliders. The basic theoretical understanding of beamstrahlung is due to seminal work carried out in the 1980s [30–32]. These calculations are incorporated into the simulation codes CAIN [33] and Guinea-Pig [34, 35]. The basic theory here needs further development. A 3 TeV e^+e^- collider with circular beams of radius $\sigma_r \approx 1$ nm, bunch charge of 10^{10}, and bunch length of 10 nm would reach the Schwinger critical field in the lab frame and $\chi \sim 10^7$ in the frame of the leptons. Such extreme parameters have not been envisioned before, and several of the approximations used previously fail in this regime. This analysis also requires a deeper understanding of fundamental physics questions related to non-perturbative and non-equilibrium phenomena in extreme environments, physics that displays remarkable universality, from heavy-ion collisions to cold atoms and astrophysics [36, 37].

Importance of high-energy coherence effects. This aspect is completely unaddressed so far in the large χ regimes. The existing literature on beam-beam collisions focuses on the interaction of a single particle/photon from one bunch with the collective electromagnetic field generated by the other [30–32, 38]. However, the extreme densities of high-energy particles/photons and the extremely strong background fields will induce important modifications of this analysis. If the interaction with the beam particles itself became non-perturbative, the accessible center-of-momentum energy could be significantly increased.

Modelling of plasmas in the strong-field regime. Both the astrophysics and the accelerator applications rely on numerical codes to propagate charged particles in the presence of strong electromagntic fields. Current codes all use the Local Constant Field Approximation (LCFA), which computes the probability of emission of photons from charged particles under the assumption that the background field is uniform. This approximation must break down, though, when the scale of variation of the plasma density or, in accelerator applications, the bunch length, becomes shorter than the formation length for the emitted photons [32]. It should be noted that the near-term experiments discussed above will probe the region where the LCFA begins to break down, motivating deeper consideration of the treatment of this issue [39,40]. In addition, new physical effects, such as direct pair production through the trident process, need to be included in the strong-field regime [41]. In the regime of very large χ, higher-multiplicity processes must also be included.

Beamstrahlung in the extreme quantum limit. All of these issues are important to the study of beam-beam interactions with intense, high energy beams with very short bunch length. In an accompanying LoI, this limit is proposed as the basis for a $\gamma\gamma$ collider based on the creation of photons through beamstrahlung in the extreme quantum limit [42]. One aspect of this idea is that beamstrahlung of low-energy photons will be suppressed for bunches shorter than the corresponding formation lengths. This idea has very strong promise, but its quantitative analysis requires theoretical developments along all of the lines discussed in this report.

All of these open questions in the study of QED in strong-field backgrounds would benefit very much from detailed analysis in the course of the Snowmass process.

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