Next great challenge beyond SLAC E144: probing a fully non-perturbative QED with electron-laser interaction

Probing strong-field QED in electron-photon interactions

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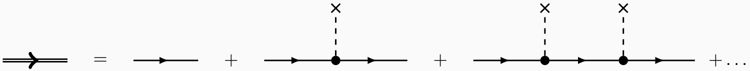
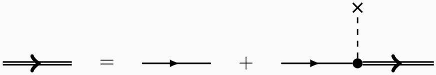
Introduction

Intense Field QED (IFQED)

- In QED electron motion in **external EM field** is described by

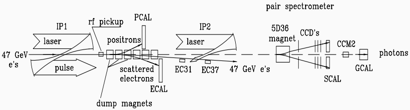


- Expansion parameter: $a_0 \simeq \frac{e}{m}\mathscr{A}$ can be $\gtrsim 1 \quad \Longrightarrow$ **IFQED**!
- IFQED effects reveal for $a_0 \gg 1$, for laser intensity $I \gtrsim 10^{18}$W/cm^2
- **Dressed propagator**



  can be solved *exactly* for certain field configurations: *plane wave, constant field (including CCF), Coulomb field*, etc.
- Physical quantities (probability rates, cross sections) are computed as in ordinary QED, but replacing *bare* propagators with **dressed** ones
- Such **IFQED dressing takes into account exactly only interaction with an external field, but not radiative corrections** (see below)...

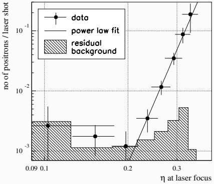
The landmark SLAC E144 experiment (mid 1990's)
https://www.slac.stanford.edu/exp/e144/e144.html



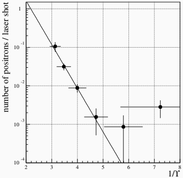
Main goals:

- First experimental study of IFQED (by **optical high-power laser** $I \sim 10^{18}$W/cm^2 + **linac**)

- Direct observation of:
    - **nonlinear Compton scattering** $e^- + n\gamma_L \to e^- + \gamma'$



    - **multiphoton Breit-Wheeler** process $\gamma' + n\gamma_L \to e^+e^-$



Parameters of laser-matter interaction at extreme intensities

Classical non-linearity parameter:

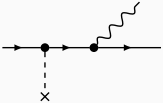
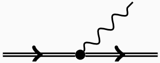
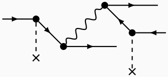
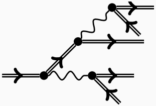
$a_0 = \frac{e\sqrt{-\langle A^\mu A_\mu \rangle}}{mc} \sim \frac{eE_0}{mc\omega}$

(non-)perturbativity w.r.t. ext. field

Dynamical quantum parameter:

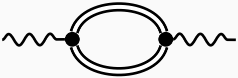
$\chi = \frac{e\hbar\sqrt{-(F^{\mu\nu}p_\nu)^2}}{m^3c^4} \sim \gamma\frac{E_\perp}{E_S}$

importance of quantum recoil

Regime	$a_0 \ll 1$	$a_0 \gtrsim 1$
$\chi \ll 1$	classical non-relativistic 	classical relativistic 
$\chi \gtrsim 1$	fully perturbative QED 	IFQED **(SLAC E144; cascades)** 
Next challenge: $\chi \gtrsim 1600$	–	Radiative corrections (loops) become also important: **perturbation theory breakdown!**

Radiative corrections in CCF (universal model for a single particle in subcritical field $F \ll m^2/e$ if $a_0 \gg 1$ and $\chi \gtrsim 1$)

One-loop radiative corrections in CCF



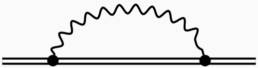
Polarization operator

$$\mathscr{P}_{\mu\nu}(x,x') = e^2 \mathrm{Tr}\,\left[\gamma_\mu\, S^e(x,x')\,\gamma_\nu\, S^e(x',x)\right]$$

Physical effect: **photon mass**:

$$m^2_{\gamma\,\|,\perp}(\chi) = \frac{\alpha m^2}{6\sqrt{\pi}} \int_1^\infty du\, \frac{8u+1\mp 3}{zu\sqrt{u(u-1)}}\, f'(z)$$
$$\simeq \frac{5\mp 1}{28\pi^2} 3^{7/6}\,\Gamma^4\left(\frac{2}{3}\right)(1-i\sqrt{3})\alpha m^2 \chi^{2/3}, \quad \chi \gg 1,$$
$$z = \left(\frac{4u}{\chi}\right)^{2/3}, \quad f(z) = \frac{i}{\sqrt{\pi}} \int_0^\infty dt\, e^{-i(zt+t^3/3)}.$$

N.B. Narozhnyi, JETP **28**, 371 (1969); V.I. Ritus, JETP **30**, 1181 (1970).



Similarly, **mass operator** modifies electron mass m by $\sim \alpha m \chi^{2/3}$

V.I. Ritus, JETP **30**, 1181 (1970); Ann. Phys. **69**, 555 (1972).

Implication: perturbative theory breakdown at $\alpha\chi^{2/3} \gtrsim 1$

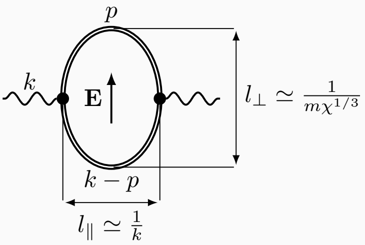
- If $\alpha\chi^{2/3} \simeq 1$ then **radiative corrections cease being small**:

  $$m_\gamma^2 \simeq \alpha m^2 \chi^{2/3} \simeq m^2, \quad \Delta m_e \simeq \alpha m \chi^{2/3} \simeq m$$

  Moreover, the free path in a rest frame $(\alpha m \chi^{2/3})^{-1}$ is sub-Compton!

  Indicates **IFQED perturbation theory breakdown** for $\alpha\chi^{2/3} \gtrsim 1$ (explicitly: for $\chi \gtrsim 1600$)!
- First realized by N. Narozhny and V. Ritus ~ 50 years ago. Hence the name **Ritus-Narozhny conjecture** (themselves they called it **enhancement of radiative corrections in external field**).
- Recall that in ordinary QED the radiative corrections use to scale like $\propto \alpha \log \gamma$ and can never compare to bare quantities at any reasonable energy scale (the PT breakdown corresponds to a Landau pole). **Physical reasons for enhancement in CCF?!**

Intuitive insight: loop scale



- In a transverse field $\mathbf{p}_\perp \sim e\mathbf{E}t$ and:

$$\varepsilon = \sqrt{p_\parallel^2 + e^2E^2t^2 + \cancelto{0}{m^2}} \approx p_\parallel + \frac{e^2E^2t^2}{2p_\parallel}$$

- The **uncertainty principle** ($p_\parallel \sim k$):

$$\Delta\varepsilon \cdot t \simeq \frac{e^2E^2t^3}{k} \simeq 1$$

$$\implies \quad \boxed{t_{loop} \simeq \left(\frac{k}{e^2E^2}\right)^{1/3} \simeq \frac{k}{m^2\chi^{2/3}}}$$

- Corresponding transverse momentum gain and transverse size of the loop (for further details see arXiv:1807.09271):

$$p_\perp \simeq eEt_{loop} \simeq m\chi^{1/3}, \quad \boxed{l_\perp \simeq \frac{1}{p_\perp} \simeq \frac{1}{m\chi^{1/3}}} \quad \text{and} \quad \boxed{l_\parallel \simeq \frac{1}{p_\parallel} \sim \frac{1}{k}}$$

(indeed $m \ll p_\perp \ll k$, justifying the initial expansion).

Intuitive insight: loop value

- In a strong transverse field the loop becomes squeezed to sub-Compton scale ($l_{\|}, l_{\perp} \ll 1/m$) – an example of a general duality:

$$\boxed{\textbf{STRONG FIELD} \leftrightarrow \textbf{SMALL DISTANCE}}$$

- Having estimated the loop dimensions, we can estimate the loop volume:

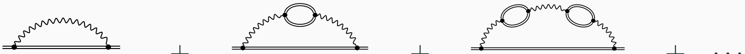
$$V_{loop} \simeq \pi l_{\perp}^2 l_{\|} \simeq \frac{1}{m\chi^{1/3}} \times \frac{1}{m\chi^{1/3}} \times \frac{1}{k} \simeq \frac{1}{km^2\chi^{2/3}}$$

and the photon mass as the **plasma frequency of a 'relativistic plasma of virtual pairs'**:

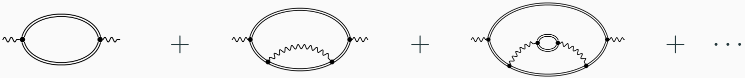
$$\boxed{m_{\gamma}^2 \simeq \omega_p^2 \equiv \frac{8\pi e^2}{m\gamma} n_{e^+e^-} \simeq \frac{\alpha}{k}\frac{1}{V_{loop}} \simeq \alpha m^2 \chi^{2/3}}$$

Direct calculation of higher-order corrections

- Some higher (up to 3-loop) order diagrams were also computed:



$\sim \alpha\chi^{2/3}$ (Ritus, 1970) $\quad$ $\sim \alpha^2\chi\log\chi$ (Ritus, 1972) $\quad$ $\sim \alpha^3\chi^{5/3}$ (Narozhny, 1980)



$\sim \alpha\chi^{2/3}$ (Narozhny, 1968) $\quad$ $\sim \alpha^2\chi^{2/3}\log\chi$ (Morozov, 1977) $\quad$ $\sim \alpha^3\chi\log^2\chi$ (Narozhny, 1980)

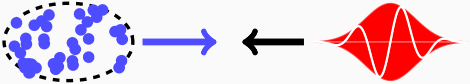
[only dominant contributions shown, for review see A.M.F., J. Phys.: Conf. Ser. 826, 012027 (2017)]

- This is in agreement with the **Ritus-Narozhny conjecture** that the expansion parameter is $\alpha\chi^{2/3}$.

Towards experiments

How to probe experimentally? Option 1

- **Option 1: laser-beam collisions:**



- Assuming $\omega_L = 1$eV ($\lambda = 1.24\mu$m) and (sub-)period laser pulse:

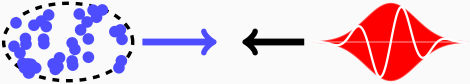
γ (ε_e [GeV])	10^7 (5000)	10^6 (500)	10^5 (50)	10^4 (5)	10^3 (0.5)
a_0	50	500	5000	5×10^4	5×10^5
I_L [W/cm^2]	2.5×10^{21}	2.5×10^{23}	2.5×10^{25}	2.5×10^{27}	2.5×10^{29}
$\chi \sim 2\frac{\omega}{m} a_0 \gamma$	2000	2000	2000	2000	2000
$\alpha\chi^{2/3}$	1.16	1.16	1.16	1.16	1.16
Radiation loss $\delta \sim \frac{\alpha m}{\gamma} \chi^{2/3} \cdot \frac{\pi}{\omega}$	0.182	1.82	18.2	182	1820

- Some options look prospective, but would require **multi-TeV** class electron accelerator...

  [Xie, Tajima, Yokoya & Chattopadhyay, AIP Conf. Proc. 398, 233, 242 (1997)]

How to probe experimentally? Option 2

- **Option 2: same, but using pulse compression or XFEL**

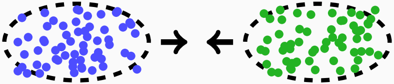


- Assuming $\omega_L = 10$keV ($\lambda = 0.12$nm) and (sub-)period laser pulse:

γ (ε_e [GeV])	10^7 (5000)	10^6 (500)	10^5 (50)	10^4 (5)	10^3 (0.5)
a_0	5×10^{-3}	5×10^{-2}	0.5	5	50
I_L [W/cm^2]	2.5×10^{21}	2.5×10^{23}	2.5×10^{25}	2.5×10^{27}	2.5×10^{29}
$\chi \sim 2\frac{\omega}{m}a_0\gamma$	2000	2000	2000	2000	2000
$\alpha\chi^{2/3}$	1.16	1.16	1.16	1.16	1.16
Radiation loss $\delta \sim \frac{\alpha m}{\gamma}\chi^{2/3} \cdot \frac{\pi}{\omega}$	1.82×10^{-5}	1.82×10^{-4}	1.82×10^{-3}	1.82×10^{-2}	0.182

- All options are prospective and requirements for electron accelerator maybe relaxed, but at cost of further progress in X-ray intensity...Sub-period X-rays also a challenge...

Option 3: beam-beam collisions (arXiv:1807.09271)



- Beams: 100GeV, $I = 10^6$A, $\sigma_z = 100$nm $(N_e \sim 10^9)$, $\sigma_r = 10$nm
- Probe beam sees beam density

$$\tilde{n}_e \sim \frac{N_e}{\pi\sigma_r^2(\sigma_z/\gamma)} \sim 10^{31}\text{cm}^{-3} \simeq \lambdabar_C^{-3}$$

- Beam disruption parameter:

$$D = \frac{2N_e r_e \sigma_z}{\gamma\sigma_r^2} \simeq 0.1$$

- Average energy loss in quantum regime:

$$\delta \simeq W_{rad}(\chi \sim 1) \cdot \sigma_z \simeq \frac{\alpha\sigma_z}{\gamma\lambdabar_C} \sim 0.1$$

- Nonlinearity and beamstrahlung parameter:

$$a_0 \simeq \frac{r_e N_e}{\sigma_r} \simeq 10^3, \quad \boxed{\chi \equiv \Upsilon \simeq \frac{r_e^2 N_e \gamma}{\alpha\sigma_r\sigma_z} \simeq 10^3}$$

Proposal (arXiv:1807.09271)

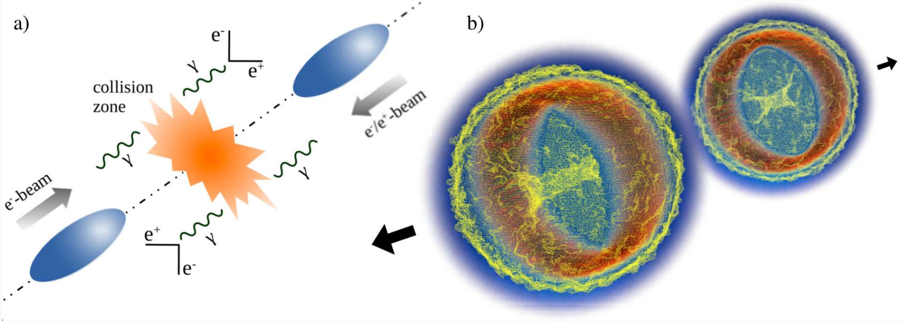
Parameter	[Unit]	NpQED Collider	FACET-II	ILC	CLIC
Machine Length	[km]	5	1	31	48
Beam Energy	[GeV]	125	10	250	1500
Bunch Charge	[nC]	1.4	1.2	3.2	0.6
Peak Current	[kA]	1700	300	1.3	12.1
rms Energy Spread	[%]	0.1	0.85	0.12	0.34
rms Bunch Length	[μm]	0.01	0.48	300	44
rms Bunch Size	σ_x[μm]	0.01	3	0.47	0.045
	σ_y[μm]	0.01	2	0.006	0.001
Beamstrahlung	χ_{av}	969	–	0.06	5
Parameter	χ_{max}	1721	–	0.15	12
Disruption	D_x	0.001	–	0.3	0.15
Parameters	D_y	0.001	–	24.4	6.8
Peak electric field	[TV/m]	4500	3.2	0.2	2.7
Beam Power	[MW]	10^{-3}	10^{-4}	5	14
Luminosity	[$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	10^{30}	–	10^{34}	10^{34}

3D simulation with OSIRIS (see arXiv:1807.09271)

electrons

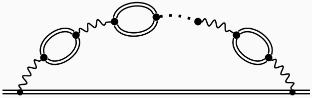
electrons with $\alpha\chi^{2/3} > 1$

photons with $\hbar\omega > 2mc^2$

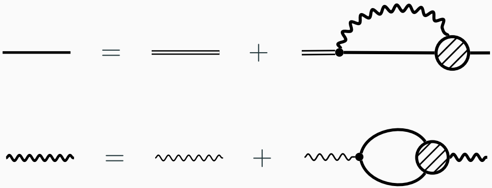


Theoretical challenges and working program

- Main challenge: **missing theory**
- Preliminary steps [currently we are **here**]:
  - Simplified building blocks (**dressed propagators**) for $\chi \gg 1$
  - Calculation of all-order bubble correction

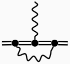
    

    (conjectured as leading) to confirm/reject the RN conjecture
  - Explicit and accurate reconsideration of **renormalization** in IFQED, especially of its **finite part** (with the possible insight into the **IFQED renormgroup flow**)
- Genuine self-consistent non-perturbative solution of IFQED SDEs



- **Vertex problem:**

Disagreement in the literature:



$$= \begin{cases} \mathcal{O}\left(\alpha\chi^{2/3}\right), & \text{Morozov et al, JETP 53, 1103 (1981)} \; ☹ \\ \exists \text{ gauge} : \mathcal{O}\left(\alpha\right), & \text{Gusynin et al, NPB 563, 361 (1999)} \; ☺ \end{cases}$$

Refinement needed!

- Prediction of novel **physical effects/signatures** for the non-perturbative regime

Questions?