LUXE: measure critical field without breaking down vacuum

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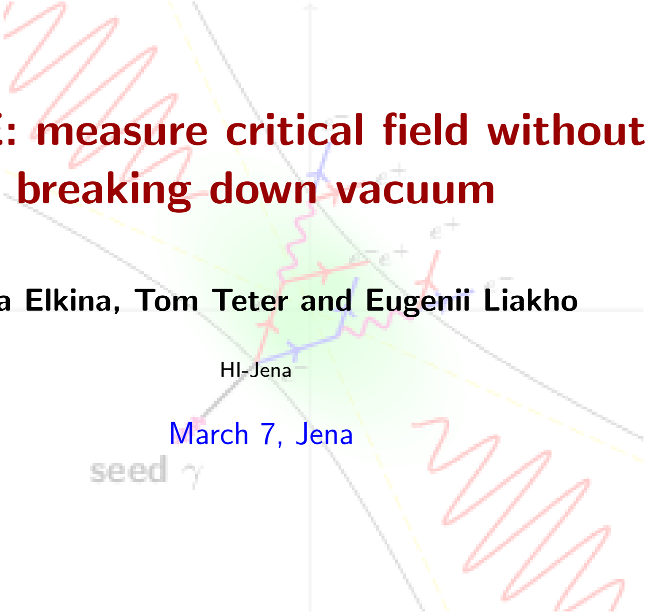


QED in External Field

Nonlinearity in classical picture

$$a_0 \frac{\sqrt{-\langle A^\mu A_\mu \rangle}}{mc} \sim \frac{eE_0}{mc\omega_0}$$

Dynamical quantum parameter

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

regimes	$a_0 << 1$	$a_0 \geq 1$
$\chi << 1$	classical non-relativistic	classical relativistic
$\chi \geq 1$	perturbative QED	non-perturbative QED

QED regime starts for Laser Field + particle ($\gamma \simeq a_0$)

$$\chi \simeq \frac{E_\perp}{E_S}\gamma \simeq \frac{\hbar\omega_0}{mc^2}a_0^2 \geq 1 \rightarrow a_0 \geq \sqrt{\frac{mc^2}{\hbar\omega}} \sim 700, \quad (I \geq 10^{24} W/cm^2)$$

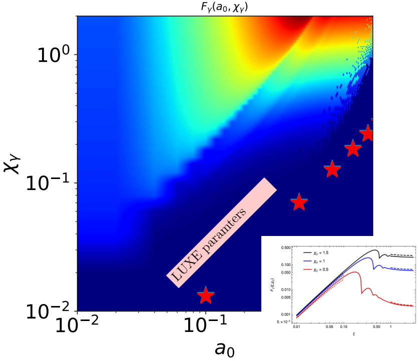
Critical field defined as $eE_{cr} l_C \simeq mc^2$

$$E_{cr} = \frac{m^2c^3}{e\hbar} = 1.3 \times 10^{16} V/cm, \quad I_L = \frac{c}{4\pi}E_{cr}^2 \simeq 5 \times 10^{29} W/cm^2$$

matching perturbative/non-perturbative QED

$$\Gamma = \frac{\alpha m_e^2}{4\omega_i} F_\gamma(a_0, \chi_\gamma),$$

$$F_\gamma(\xi_0, \chi_\gamma) = \sum_{n>n_0}^{\infty} \int_1^{v_n} \frac{dv}{v\sqrt{v(v-1)}} \Big[2J_n^2(z_v) - \\ - \xi^2 (2v-1)(J_{n+1}^2(z_v) + J_{n-1}^2(z_v) - 2J_n^2(z_v)) \Big]$$



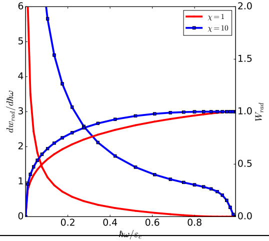
First order processes (with polarization effects)[1]

$$\frac{dW_\gamma}{d\varepsilon_\gamma} = \frac{-\alpha m^2}{\varepsilon_e^2}\left\{Ai_1(x) + \left[\frac{g(\phi)}{x} + \chi_\gamma\sqrt{x}\right]Ai'(x)\right\}, \quad (1)$$

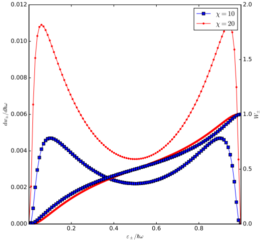
$$\frac{dW_e}{d\varepsilon_e} = \frac{+\alpha m^2}{\varepsilon_\gamma^2}\left\{Ai_1(x) + \left[\frac{g(\phi)}{x} - \chi_\gamma\sqrt{x}\right]Ai'(x)\right\}, \quad (2)$$

where polarization effects are in $g(\phi) = 2\cos^2\phi + 1$

photon emission



pair production



[1]B. King, N. Elkina, H. Ruhl, Photon polarization in electron-seeded pair-creation cascades, arXiv:1301.7001

Experimental measurement of critical field[2]

Rate of $e^{\pm}$ pair production $\xi << 1$ (but not to small)

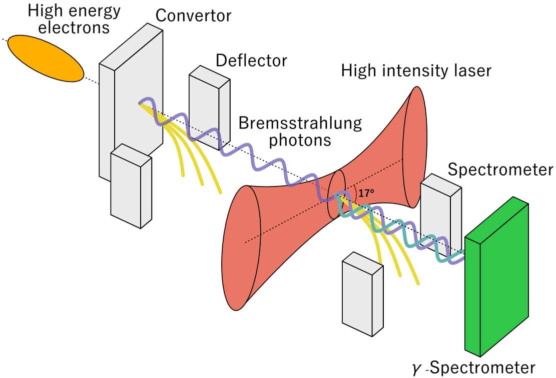
$$\Gamma_{\pm} \propto \frac{3}{16}\sqrt{\frac{3}{2}}\alpha m_e(1 - \cos(\theta))\frac{|\vec{E}|}{E_c} \exp\left[-\frac{8}{3}\frac{1}{1+\cos\theta}\frac{m_e c^2}{\hbar\omega}\frac{E_c}{|\vec{E}|}\right]$$

θ is angle between γ-quanta and laser pulse direction
Critical field E_c can be deduced if

1. have energetic enough γ source (10-20 GeV)
2. Descent laser intensity $I \geq 10^{20}\ W/cm^2$
3. if we know field structure in focus

[2] A. Hartin, 2018

LUXE project (Hamburg-Jena)

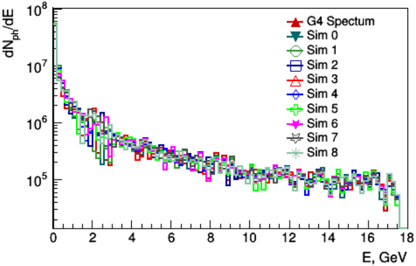


	λ	I, a_0	ε_e	ε_γ	χ_e/χ_γ	a_0
SLAC	527 nm	$10^{18} W/cm^2$	47 GeV	29.2GeV	0.3/0.2	0.3
LUXE	800 nm	$10^{20} W/cm^2$	17.5 GeV	17.5 GeV (?)	0.80109	4-6

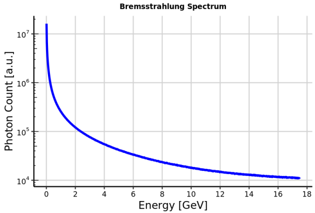
Brehmstrahlung spectra, e^-: 17.5 GeV (GEANT4)

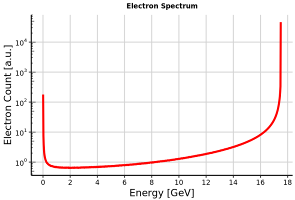
3

Sasha's Simulation



Evgenii's simulation





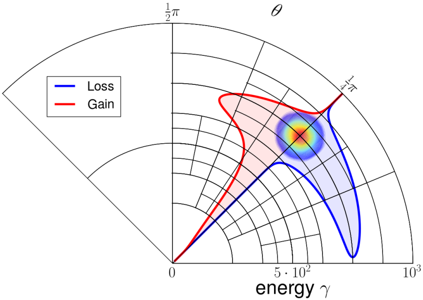
[3] O. Borysov, slides Dec.13, 2018

features of PIC-ANTARES code

$$\left(\frac{\partial}{\partial t} + \frac{\vec{p}}{\gamma m}\cdot\frac{\partial}{\partial \vec{r}} + \vec{F}\cdot\frac{\partial}{\partial \vec{p}}\right) f(\vec{r},\vec{p},t)$$

$$= \underbrace{\int d^3k\, w_{rad}^{\vec{E},\vec{B}}(\vec{k},\vec{p}+\vec{k})\, f(\vec{r},\vec{p}+\vec{k},t)}_{\textbf{GAIN}} - \overbrace{f(\vec{r},\vec{p},t)\int d^3k\, W_{rad}^{\vec{E},\vec{B}}(\vec{k},\vec{p}}^{\textbf{LOSS}}$$

- Specific features of PIC-ANTARES code
- Descent event generators
- polarization effects
- norm-conserving integrators
- Adaptive mesh and particles



Parameter for head on simulation (LUXE)

	$E_{pulse}, \mu J$	angle	focal spot, $\sigma_\perp \mu m$	duration, $\sigma_\parallel, ps$
given	$3.5 \cdot 10^6$	$(3/10)2\pi$	10	0.035
normed	$a_0 = 4.7577$		$12.5\lambda_0$	$13.116 \cdot T$

where $\lambda_0 = 2\pi(c/\omega_0) = 0.8\mu m$ and $T_0 = 2\pi/\omega_0 = 2.6685fs$

$$I = \frac{2E}{\pi w_0^2 \tau_0} = \frac{2 \cdot 3.5[J]}{\pi 10^2[\mu m]35[fs]} = 6.3662 \cdot 10^{19} W/cm^2$$

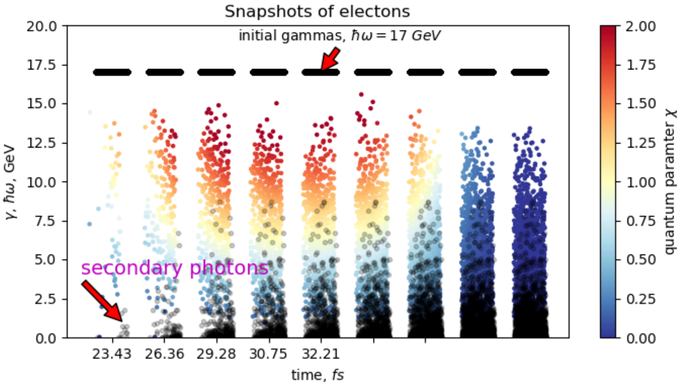
in terms of a_0

$$a_0 = \sqrt{\frac{I_0[W/cm^2] \cdot \lambda^2[\mu m]}{1.8 \cdot 10^{18}}} = 4.7577$$

Head on collision of thin photon bunch $\hbar\omega = 17GeV$ and duration of 8 fs

Head on collision

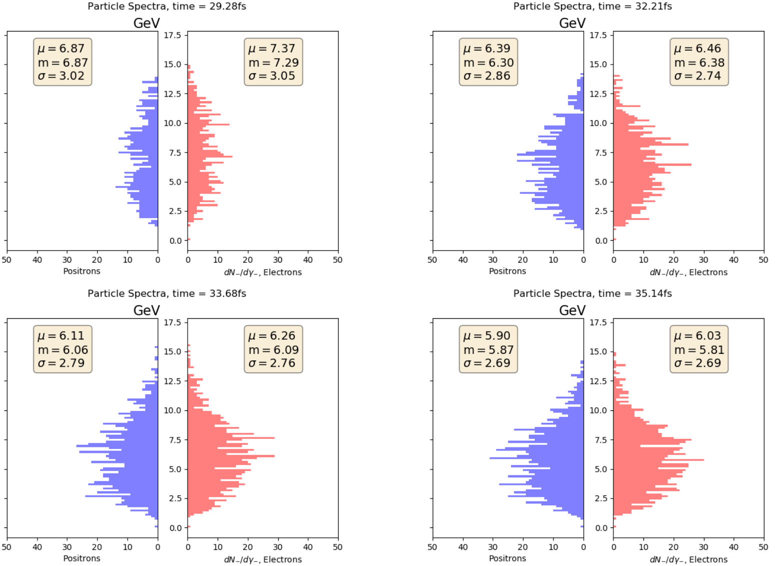
presence of laser pulse is illuminated by χ (color-coded)



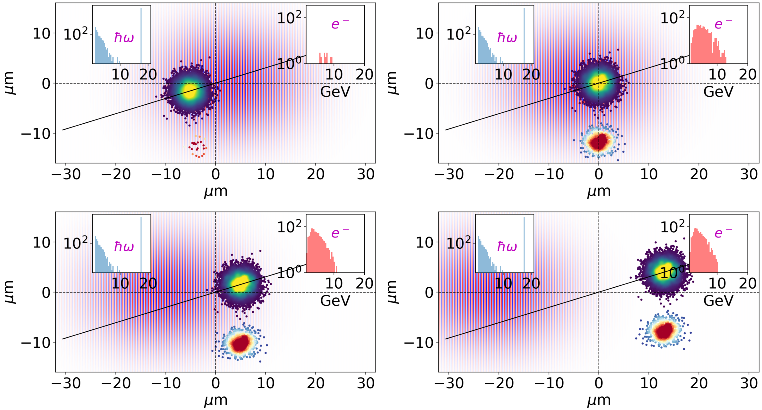
γ-bunch generates $e^{\pm}$ when χ is high enough (inside laser pulse)

efficiency: $N_{\gamma} = 10^4$ creates $N_{e^{\pm}} = 1092$

Particles spectra



Setup $\theta = 17^o$, $a_0 = 6$, $\hbar\omega = 17.5 GeV$, [4]



[4] partially simulated on herera cluster

Working program February-April

- Clear up theoretical consideration (Tom+Nina)
  1. How good cross-field approximation at $a_0 \sim 1$
  2. Space/time variation in laser pulse
  3. what about Trident processes (were small even in SLAC-144)
  4. number of absorbed photons are still countable, or not?
- still discrepancy in Bremstrahlung spectra (Tom+Evgenii)
- coding of everything (Nina)
  1. pre-fetching probabilities for Monte-Carlo (accelerate!)
  2. reducing noise via stratified sampling of distribution
  3. multiple emission of soft photons
  4. visualization and post-processing tools
  5. **40-80 cores of Hemera reserved for 15/03-1/04**
- Analysis of polarization effects on spectra (Nina+Tom)
- Prototype for Virtual Detector (VD)

Summary&Conclusion

- Measuring critical field E_c at the borderline between perturbative/non-perturbative QED
- based on nonlinear Breit-Wheeler $e^{\pm}$ pair production
- in colliding 17 GeV γ-beam with laser pulse
- work in progress:
  - Pairs are produced in rather moderate amount
  - only few 2nd and 3rd cascades step (but better then SLAC)
  - Effective colling of $e^{\pm}$ pairs due to nonlinear Compton scattering
- short term plans (for meeting in April)
  - Polarization effects
  - Characterization of higher order process (Trident, etc)
  - Developing virtual detectors
  - Reconstruction of laser field near focal plane