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LUXE: Investigating Nonperturbative QED with Lasers

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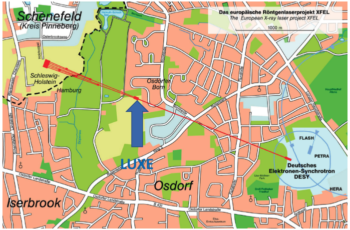
EMMI Workshop New Vistas in Photon Physics, 22 Sept 2022



What is LUXE?

- Proposed new experiment at DESY and EU.XFEL in Hamburg, Germany
- Collision of XFEL electron beam and high-power laser to study strong-field QED
- Growing international collaboration: Synergies between laser and particle physics

More documentation?

- LUXE website: `https://luxe.desy.de`
- LUXE CDR: EPJ-Special Topics **230**, 2445-2560 (2021).

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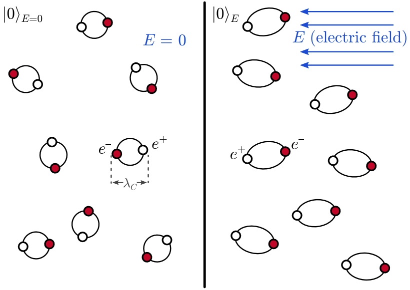
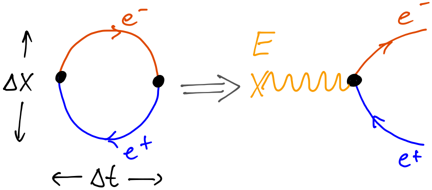
Quantum Effects in Strong Fields: The QED Critical Field



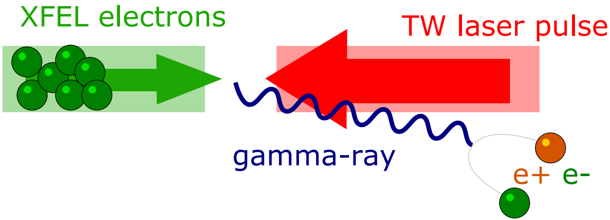


- Sauter & Schwinger's seminal result of vacuum breakdown: Sauter Z Phys (1931), Schwinger PR (1951)

$$E_S = \frac{m^2}{e} \simeq 1.3 \times 10^{18}\,\mathrm{V/m}\,, \quad I_S \sim 10^{29}\mathrm{W/cm}^2\,, \qquad \Rightarrow \Gamma_{pairs} = \frac{(eE)^2}{4\pi^3} \exp\left\{-\pi \frac{E_S}{E}\right\}$$

- Record laser intensity: $I_{record} \sim 10^{23}\mathrm{W/cm}^2$, $I_{record}/I_S \sim 10^{-6}$ Yoon et al, Optica 8, 860 (2021)

Collision of Electrons with Strong Laser Fields



$E = 16.5$ GeV

$I \lesssim 10^{21}\mathrm{W/cm^2}$

- Electric field in the *rest frame* of the particle boosted by the large γ factor
- Quantum nonlinearity parameter

$$\chi \equiv \frac{e}{m^3}\sqrt{|F_{\mu\nu}p^\nu|^2} = \frac{E_{\mathrm{rf}}}{E_S} \sim 2\gamma\frac{E}{E_S} \gtrsim 1$$

- Laser intensity parameter $\xi \simeq 6.8\sqrt{I[10^{22}\,\mathrm{W/cm^2}]} \rightsquigarrow 0.1\ldots 20$ (this is our main knob)
- Both parameters are related $\chi = \xi\,\frac{\omega_{\mathrm{rf}}}{m}$
- Similar quantum parameter χ_γ for photon-laser interaction

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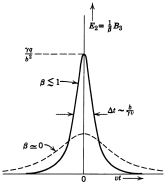
Complementarity of Heavy Ion Collisions and Lasers

Field of an ultrarelativistic HI or laser pulse seen by colliding particle

Ultrarelativistic HIC

- field strength $E/E_S \sim Z\alpha\gamma \gg 1$
- length-scale $\Delta L \sim \lambda_C/\gamma \ll \lambda_C$
- fixed profile, virtual photons, fixed ω distr.
- Keldysh parameter $\Gamma_{HIC} = \frac{1}{Z\alpha} > 1$

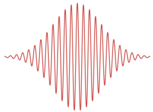


Jackson

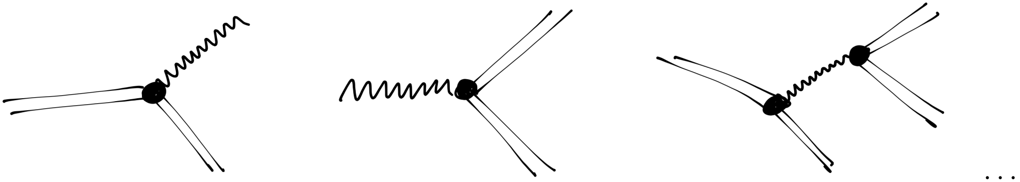
typical impact parameter $b \sim \lambda_C$, Baur, EPJD **55**, 265 (2009).

Laser Pulse

- field strength $\chi = E/E_S \gtrsim 1$
- length-time-scale $\Delta L \sim 10\,\mu\text{m}/\gamma \gg \lambda_C$
- real photons
- Keldysh parameter $\Gamma_{laser} = 1/\xi \gtrsim 1$
- χ, ξ independently controllable
- Chirp, polarization, spatial mode, ...



SFQED Processes



Nonlinear Compton   Nonlinear Breit-Wheeler   Trident   . . .

Nonperturbative effects, higher-orders, factorization, loops, quantum radiation reaction, . . .

Reviews

- A. Fedotov, [...], DS et al., `arXiv:2203.00019`.
- A. Gonoskov et al., `arXiv:2107.02161` (Rev. Mod. Phys. accepted).
- P. Zhang, [...], DS et al., Phys. Plasmas **27**, 050601 (2020)
- A. Di Piazza et al, Rev. Mod. Phys. **84**, 1177 (2012).

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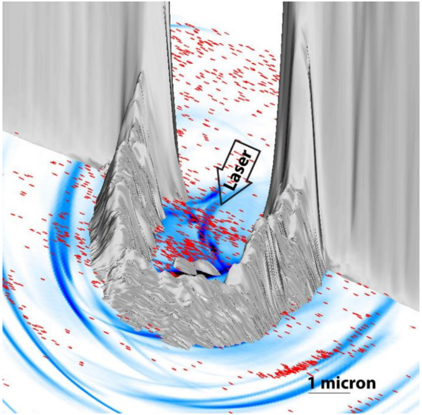
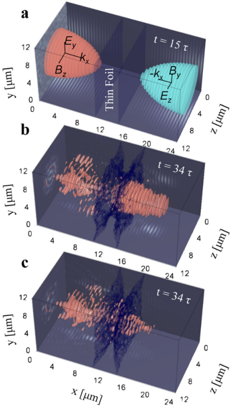
SFQED Effects in Laser Plasma Interactions



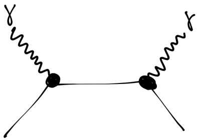


. . . QED cascades in laser-laser collisions, astrophysics, neutron star atmospheres, . . .

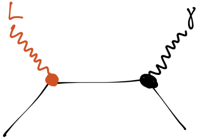
Figures courtesy of C. P. Ridgers

Nonperturbative Effects in Electron-Laser Interactions

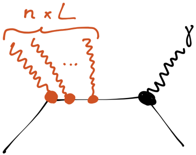
Interactions with strong laser field: Coupling strength $e \to \xi$



$P \sim \alpha^2$

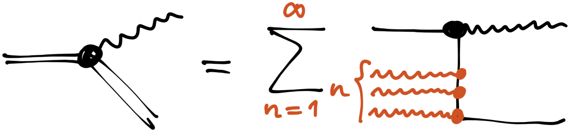


$P \sim \alpha\xi^2$



$P_n \sim \alpha\xi^{2n}$

Nonperturbative Furry-Picture QED:



Nonlinear Effects: Intensity dependent mass shift, shifted Compton edge, higher harmonics
Same same but different for pair production: Threshold effects

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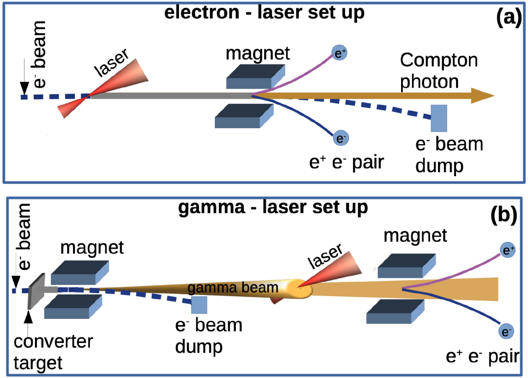
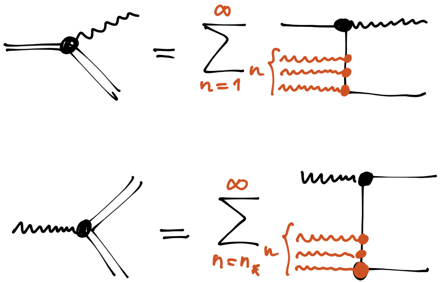




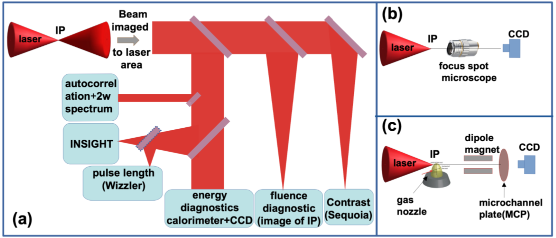
Challenge for detection system: Ability to deal with very small and large number of particles!

⇝ For detail about the experimental layout see talk by John Hallford

Laser Matters

	40 TW, 8μm	40 TW, 3μm	350 TW, 3μm
Laser energy after compression (J)	1.2	1.2	10
Laser pulse duration (fs)	30		
Laser focal spot waist w_0 (μm)	8	3	3
Fraction of ideal Gaussian intensity in focus (%)	0.5		
Peak intensity in focus ($\times 10^{20}$ Wcm^{-2})	0.19	1.33	12
Dimensionless peak intensity, ξ	3.0	7.9	23.6
Laser repetition rate (Hz)	1		
Electron-laser crossing angle (rad)	0.35		

Quantum parameter			
χ_e for $E_e = 14.0\,\mathrm{GeV}$	0.48	1.28	3.77
χ_e for $E_e = 16.5\,\mathrm{GeV}$	0.56	1.50	4.45
χ_e for $E_e = 17.5\,\mathrm{GeV}$	0.6	1.6	4.72



- Two-phase approach: 40 TW $\rightarrow$ 350 TW
- LUXE = High-precision experiment
- Precise laser diagnostics required
- Goal is to tag shots with ξ precision $< 1\%$
- Laser almost unchanged by SFQED interaction

Laser Diagnostics:

- Energy tagging
- Fluence tagging
- Pulse length tagging
- Full Field Reconstruction
- ...

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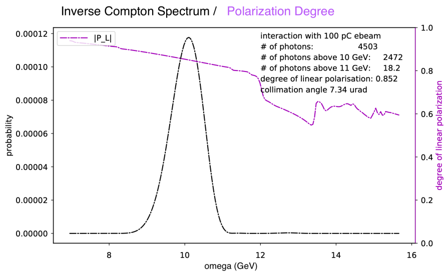
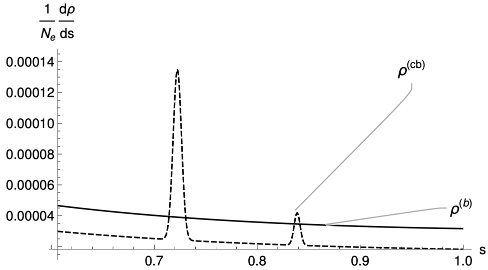
Only real photons interacting: No matter in interaction volume

For $\chi_\gamma \sim 1$ we need source of multi-GeV photons:

1. Bremsstrahlung
2. inverse Compton scattering
3. coherent Bremsstrahlung in oriented crystals

} monoenergetic, partially polarized





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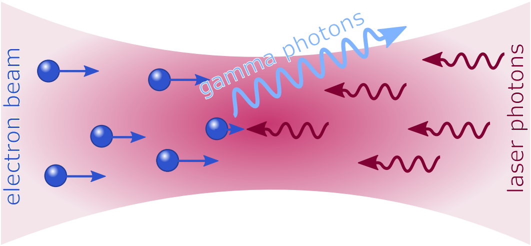
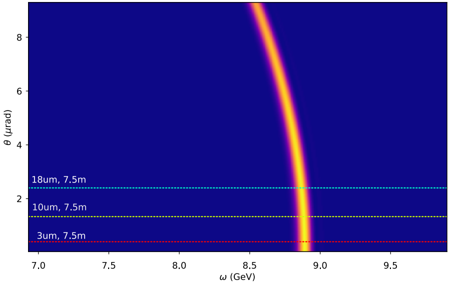
Inverse Compton Scattering Source



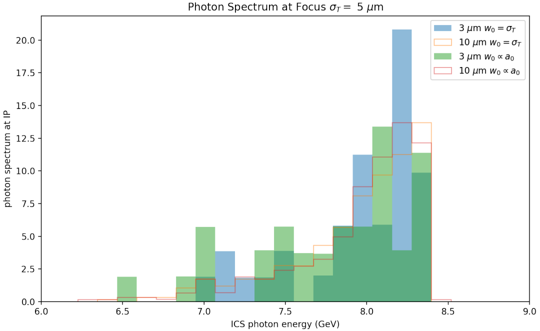
parameter	value
ω_L	4.1 eV
γ	32290
ξ	< 0.1
η	0.518
$\gamma\theta$	$\ll 0.1$
ω	≈ 8.4 GeV
E_L	100 mJ

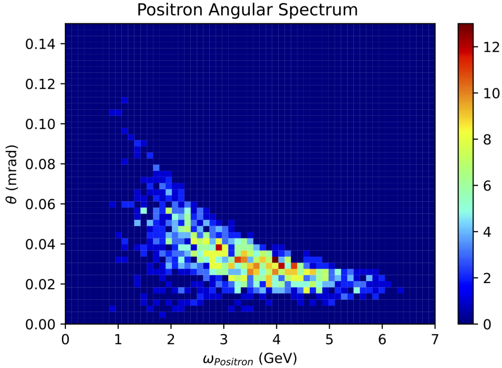


$$\omega \approx \frac{4\gamma^2\omega_L}{1+\frac{\xi^2}{2}+\gamma^2\theta^2+2\eta}$$

$$\chi_\gamma = 0.012\,\omega[\mathrm{GeV}]\,\xi$$

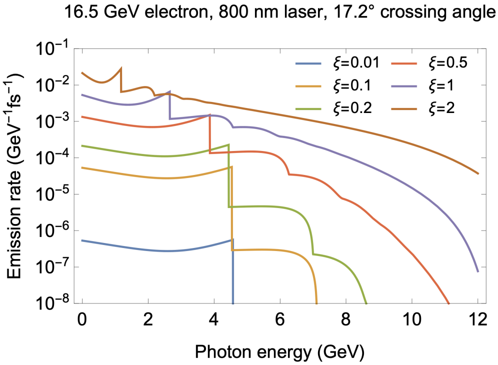
Inverse Compton Scattering Source Results

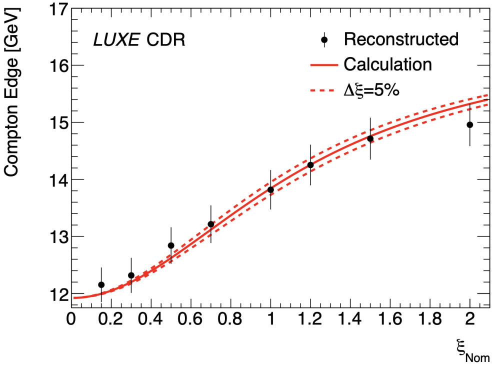




Photon density at IP: $\geq$ 65 photons/μm^2, comparable to Bremsstrahlung but monoenergetic

Simulations: github.com/danielseipt/luxeics, github.com/tgblackburn/ptarmigan





Objectives:

1. Nonlinear red-shift of the Compton edges: intensity (ξ) dependent mass shift
2. High harmonics $P_n \sim \xi^{2n}$

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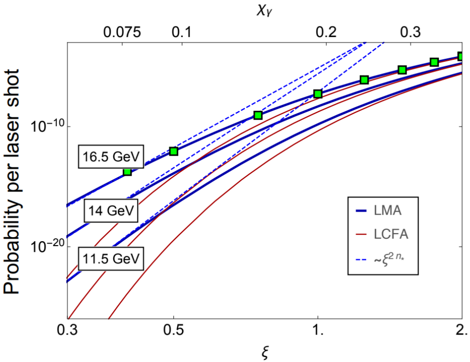
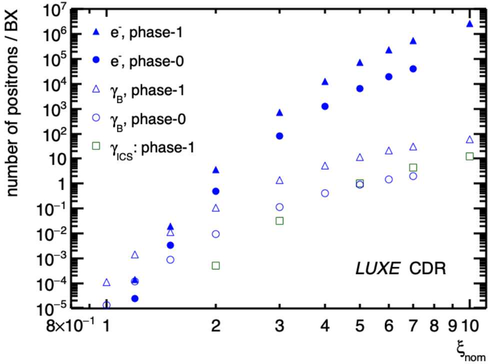
LUXE Predictions and Expected Results: Pair Production





Objectives:

1. Detect abundant pairs in γ–L collisions
2. Transition from perturbative ξ^{2n} to nonperturbative scalings $\chi_\gamma e^{8/3\chi_\gamma} \to \chi_\gamma^{2/3}$
3. Polarization dependence: $P_\parallel$, $P_\perp$ $\to$ vacuum birefringence via Kramers-Kroning

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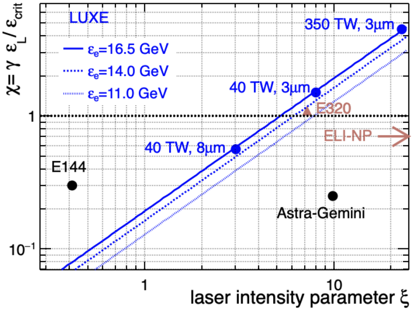
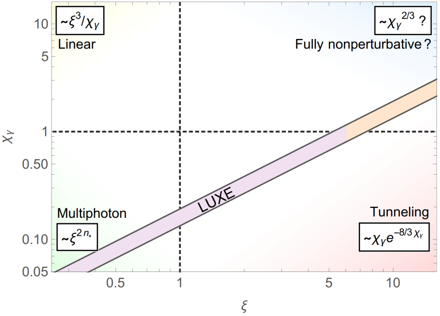
LUXE in SFQED Parameter Space





LUXE:

- First time reach deep into the nonperturbative quantum regime $\chi > 1$, $\xi \gg 1$ ($\Gamma \ll 1$)
- Long-runtime at high rep-rate, high-precision, transition pert–nonpert

Other experiments:

- SLAC E-144: seminal experiment in 1990s, $\xi < 1$, $\chi \sim 0.25$, O(100) positrons detected
- SLAC E-320: smaller χ, limited beamtime → lower statistics, no γ-laser operation
- all-optical (multi-PW laser) experiments: larger ξ, smaller χ

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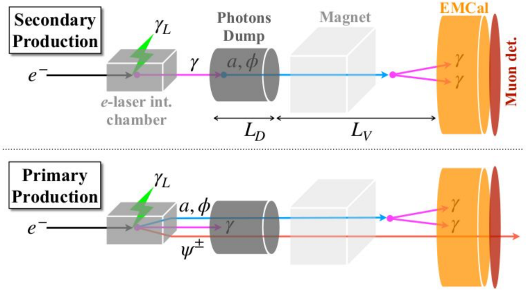
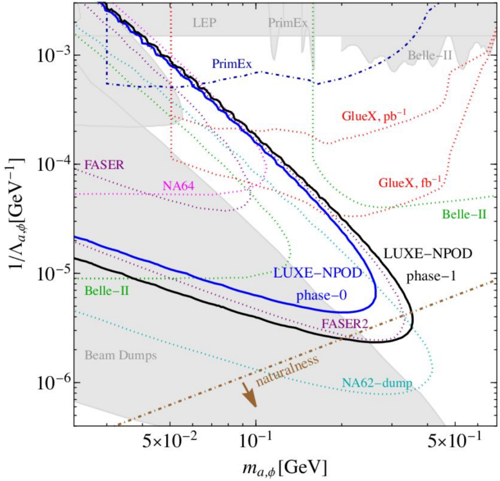
But There's More: BSM Physics at LUXE

LUXE IP is abundant source of high-energy photons: Coupling to axion-like particles

$$\mathcal{L} = \frac{a}{4\Lambda_a} F^{\mu\nu}\tilde{F}_{\mu\nu} + \ldots$$





arXiv:2107.13554

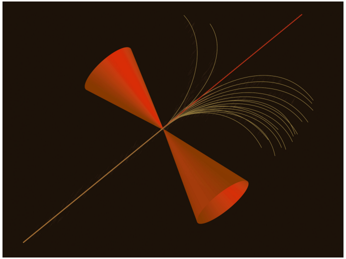
Summary & Conclusion

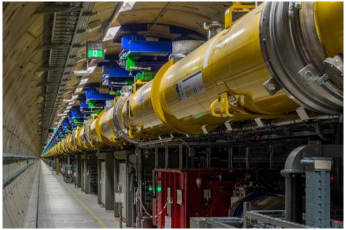
LUXE will explore QED in uncharted high-intensity regime

- Transition from perturbative to non-perturbative regimes of QED
- Directly observe pair production from *real* photons
- High-precision experiment
- Search for BSM physics (photon beam dump)

Goal: Installation during 2025 extended XFEL shutdown

- CDR released 2021 (arXiv:2102.02032)
- TDR to appear soon
- Review process is ongoing





Got interested? Join us!

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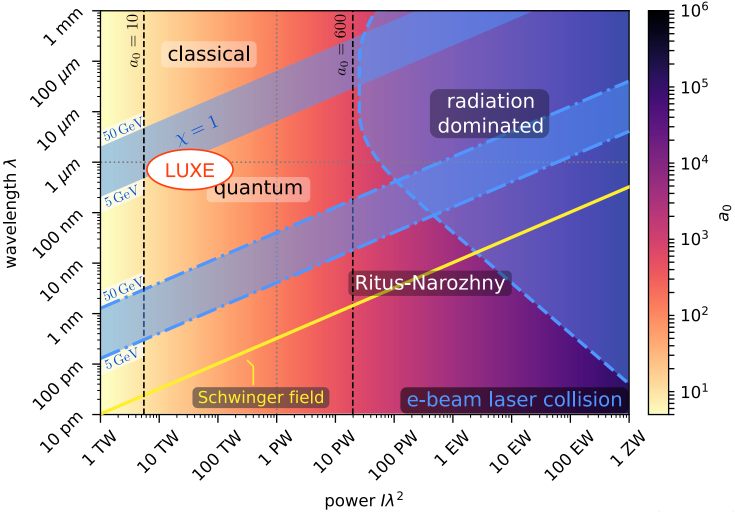
Backup

Parameter Regimes of QED Plasma Physics



Zhang et al, PoP 2020

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Quantum Radiation Reaction

- Quantum-corrected classical radiation reaction

$$\frac{du^\mu}{d\tau} = f^{\mu\nu} u_\nu + \tau_{RR}\, g(\chi) \, [\eta^{\mu\nu} - u^\mu u^\nu] f_{\nu\kappa} f^{\kappa\lambda} u_\lambda$$

- Gaunt-factor models reduced radiated power

Ridgers JPP 2017, Niel PRE 2018

$$g(\chi) = \frac{\mathbb{I}(\chi)}{\mathbb{I}_{\mathrm{class}}} \approx 1 - \chi \left(\frac{55\sqrt{3}}{16} + \frac{3}{2} s \right) + \chi^2 \left(48 + \frac{105\sqrt{3}}{8} s \right)$$

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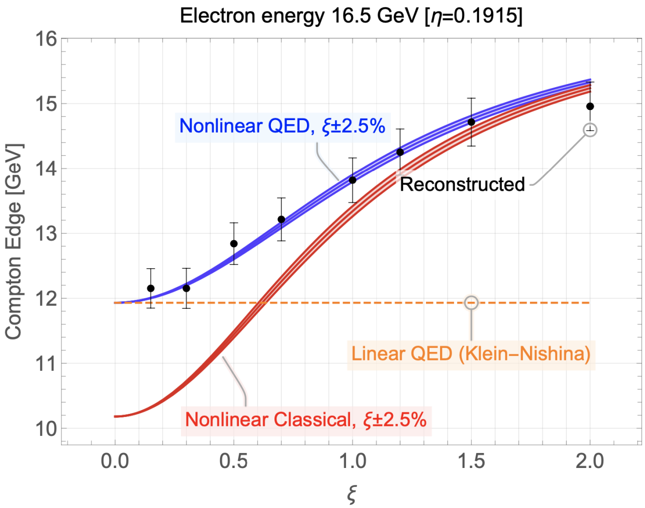
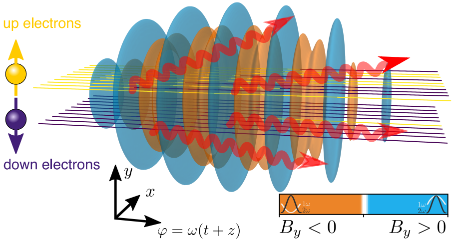
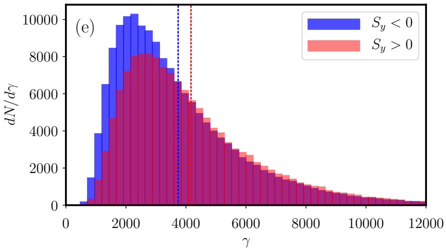
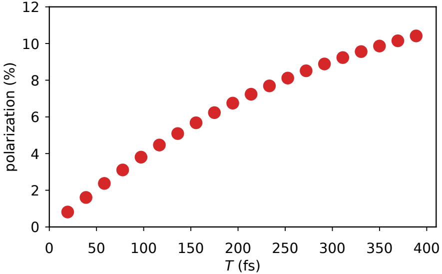
Compton Edge Reconstruction



Radiative Electron Polarization







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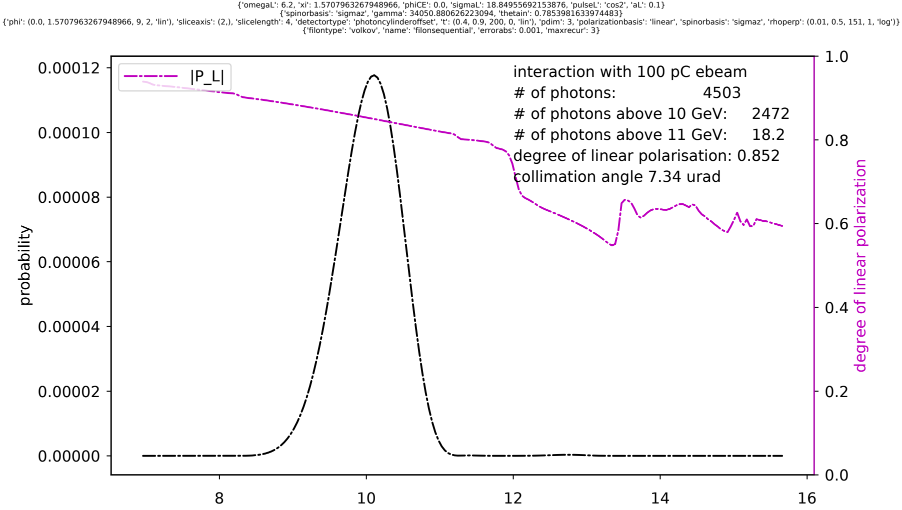
Polarized Photons from ICS



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How to achieve large χ?

1. Collider regime

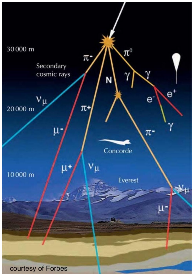
- High-energy beam ($\gamma \gg 1$) colliding with laser
  $\chi = \frac{\gamma a_0}{a_S}(1 - \beta \cos\theta) \sim \frac{2\gamma a_0}{a_S}$
- Field *can not* reaccelerate particles to high energy
  $\chi_\gamma \approx \chi_{e^+} + \chi_{e^-}$

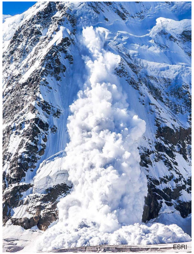
$\Rightarrow$ Shower-type cascades

2. Multiple colliding laser pulses

- Field itself accelerates particles to $\gamma \sim a_0$
  $\chi = \frac{\gamma a_0}{a_S}\sqrt{1 - \beta^2 \cos^2\theta_e} \sim \frac{a_0^2}{a_S}$
- $\chi \sim 1$ requires $a_0 \sim \sqrt{a_S} \sim 600$

$\Rightarrow$ Avalanche-type cascades





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