LUXE-NPOD: new physics searches with an optical dump at LUXE

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LUXE-NPOD 2107.13554

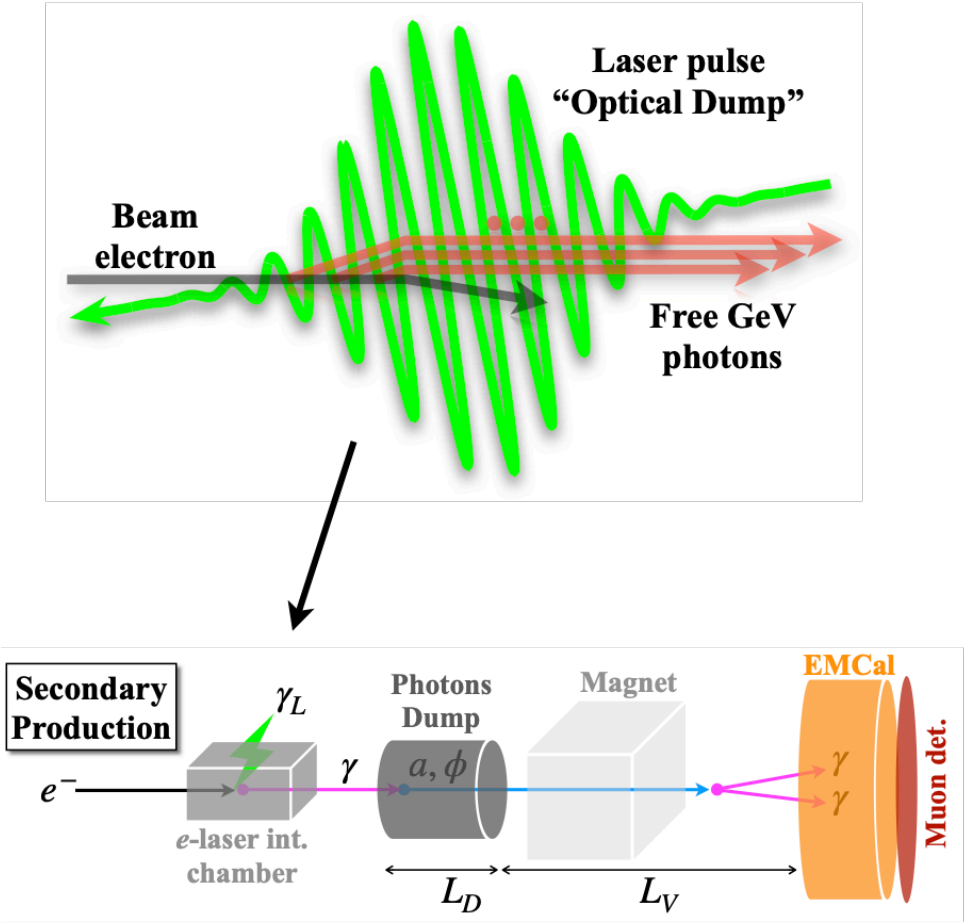
Bai, Blackburn, Borysov, Davidi, Hartin, Heinemann, Ma, GP, Santra, Soreq, Hod

LUXE CDR

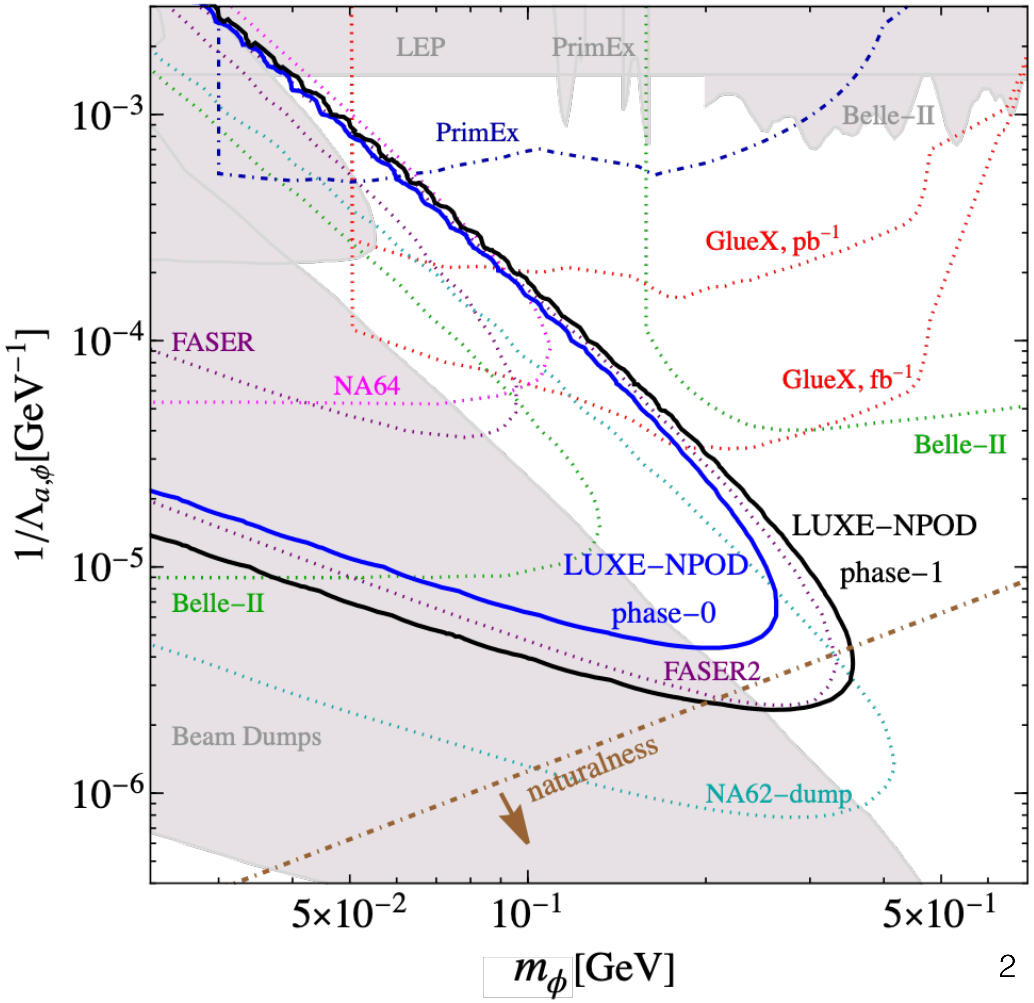
ILCX2021 ILC Workshop on Potential Experiments

Final goal of this combined talk is to understand:

See followup talk by Y. Soreq
Complete the picture and discuss ILC-NPOD



LUXE-NPOD



Outline

- Intro, strong field QED, electron in a strong laser
- The optical-dump concept & LUXE
- LUXE-NPOD sensitivity to new spin-0 fields
- Summary

Introduction #1, classical electrodynamics with matter

- Electrodynamics (ED) by itself is a boring (free) theory

- Adding matter (electrons) even classical ED becomes interesting, for instance:

(i) At energies below the electron mass ED becomes non-linear (quartic) Heisenberg and H. Euler (34)

$$\mathscr{L}_{\rm EFT} \approx \frac{1}{(10\, m_e)^4} \left[\left(F_{\mu\nu} F^{\mu\nu} \right)^2 + \frac{7}{4} \left(F_{\mu\nu} \tilde{F}^{\mu\nu} \right)^2 \right] \quad \left(\text{with } \; \frac{1}{2} F_{\mu\nu} F^{\mu\nu} = E^2 - B^2 \; \text{ and } \; \frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} = E \cdot B \right)$$

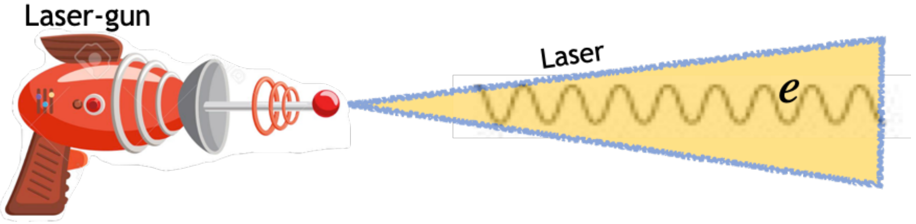
(ii) Placing electron at rest in a weak (circularised polarised) laser: Kibble (65)

$$P^T_{1,2} \approx \frac{e\mathscr{E}_L}{\omega} \left(\cos \omega t, \sin \omega t \right); \quad P^L \approx 0; \quad E \approx m_e \left(1 + \xi^2/2 \right)$$

with $\mathscr{E}_L$ and ω are the laser RMS field and frequency respectively and $\xi \equiv e\mathscr{E}_L/\omega m_e \ll 1$

Interaction of electron with laser

- Averaging over many oscillations gives $\langle P^T_{1,2}, P^L \rangle \approx 0; \quad \langle E \rangle \approx \bar{m}_e = m_e\left(1 + \xi^2/2\right)$

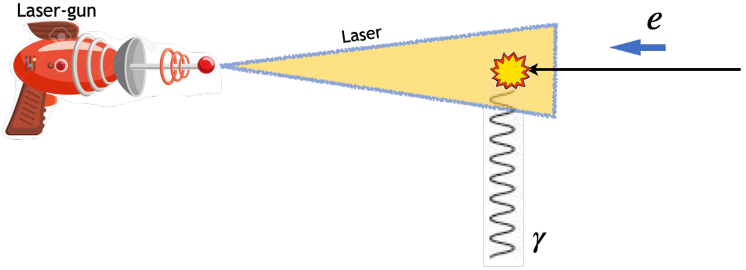


$\left(\text{for} \quad \xi \equiv e\mathscr{E}_L/\omega m_e \ll 1\right)$ Kibble (65)

- Electron's transverse circular motion leads to radiation's pattern denoted as mass-dep.-Compton edges.

  Classically: radiation from the electron's harmonic; QM: n-laser-photons-electron scattering:

Let's assume that in lab-frame we shoot the electron on the laser:



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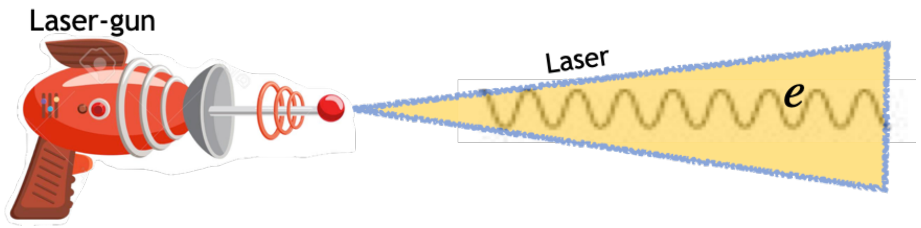

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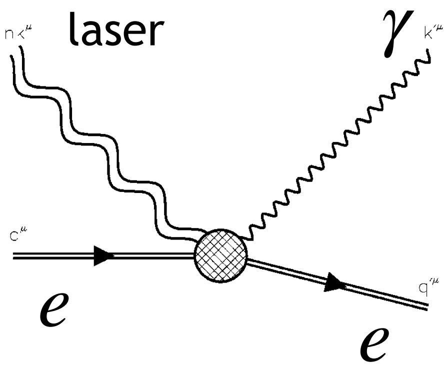
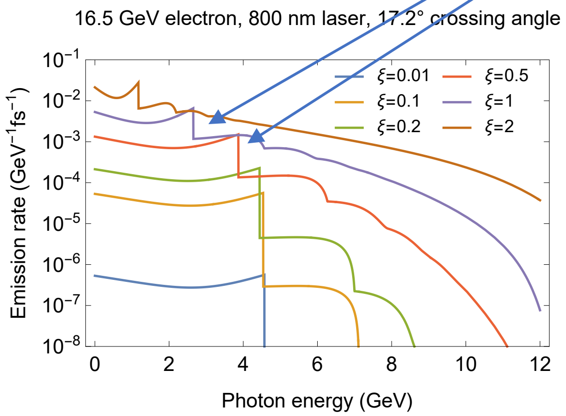


$$s_{\rm COM} \approx 2E_e n_\gamma \omega \;\Rightarrow\; E_\gamma \sim \sqrt{s}_{\rm COM} \times \frac{E_e}{\bar{m}_e} \propto \frac{1}{1+\xi^2}$$



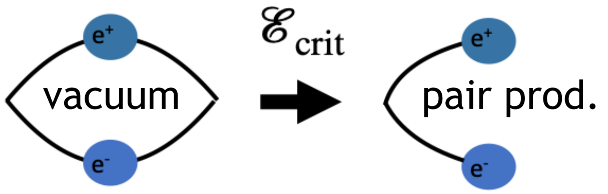
SLAC, E144 (96)

Understanding the intense laser limit

- What if strong laser reach $\xi \equiv e\mathscr{E}_L/\omega m_e \gtrsim 1$? (for the 1st time LUXE will reach up to $\xi \sim 10$)

- Recall that in a strong field QED is subject to non-perturbative effects: Schwinger (51)

$$P_{e^+e^-} \propto \exp\left(-\pi\frac{\mathscr{E}_{\rm crit}}{\mathscr{E}}\right)\,, \quad \mathscr{E}_{\rm crit} \equiv \frac{m_e^2}{e} \approx 10^{16}\,\frac{\rm V}{\rm cm}$$

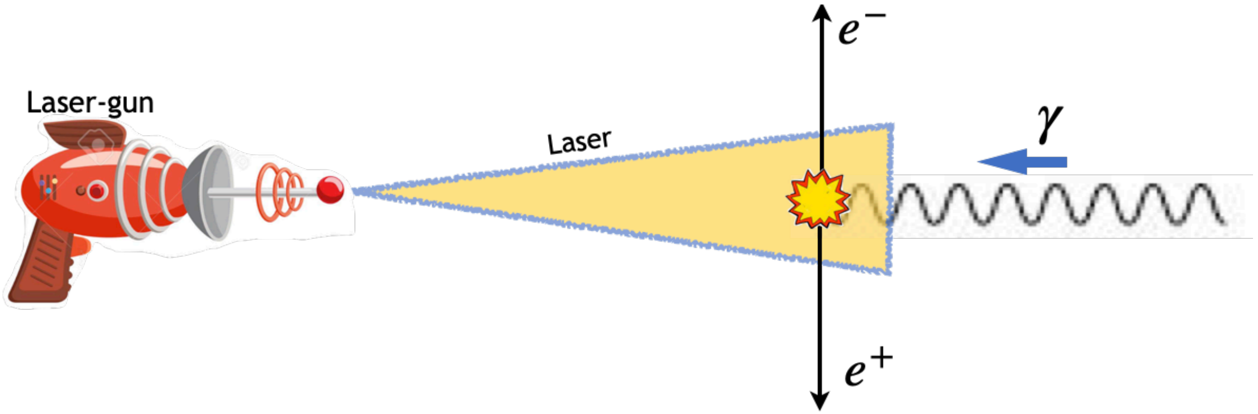


- Such static fields can't be obtained in labs however we can use intense laser + accelerated electrons such that in their rest frame they will obtain large effective fields:

$$\chi_e \equiv \frac{E_e}{m_e} \times \frac{\mathscr{E}_L}{\mathscr{E}_{\rm crit}}$$ is the quantum non-linearity para', \w E_e electron energy in lab frame.

Large e-boost + intense laser => new non-perturbative processes

- Pair production, from “probed-photon” (nonlinear Breit-Wheeler, one photon-pair-prod.)



ZEL'DOVICH (66); modern approach: e.g.: Hartin, Ringwald & Tapia (19)

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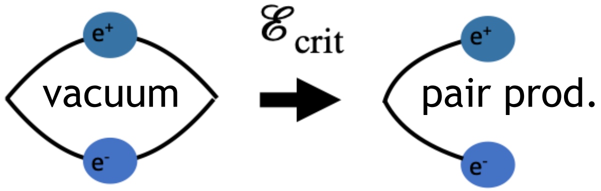

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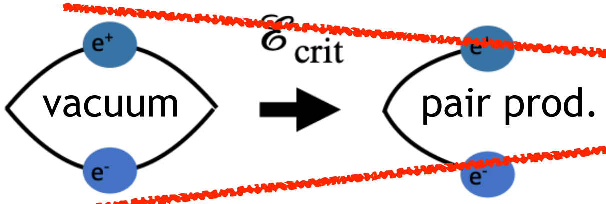

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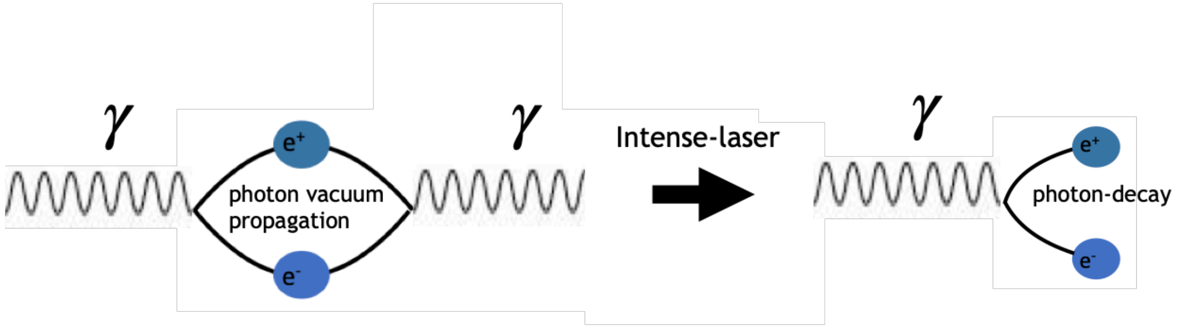

$$P_{e^+e^-} \propto \exp\left(-\frac{8}{3\chi_{e,\gamma}}\right), \quad \text{for } \xi^2 \gtrsim \gg 1\,,\ \chi_{e,\gamma} \equiv \frac{E_{e,\gamma}}{m_e} \times \frac{\mathscr{E}_L}{\mathscr{E}_{\text{crit}}}$$

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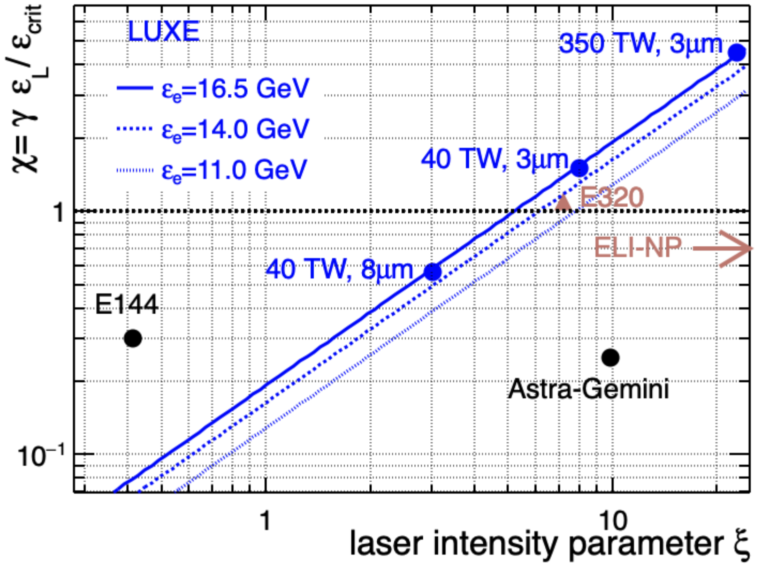

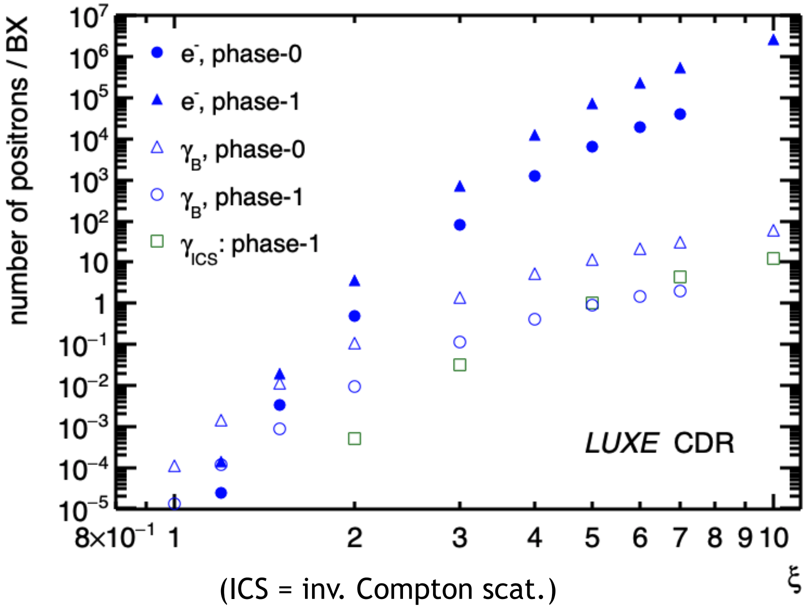

(ICS = inv. Compton scat.)

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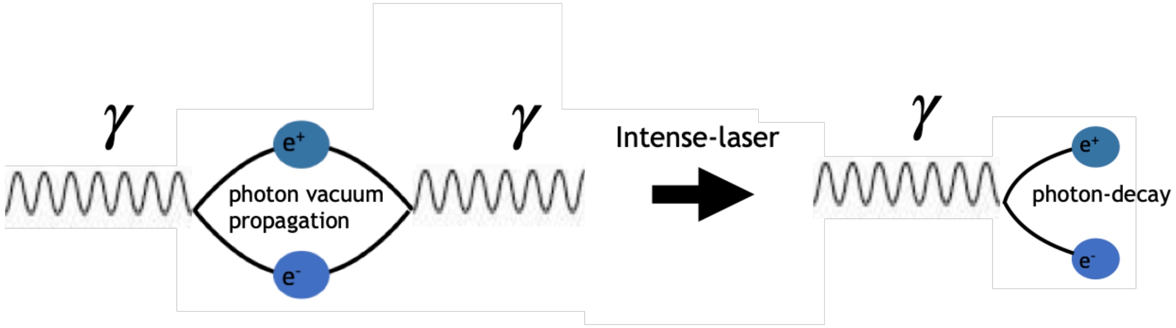

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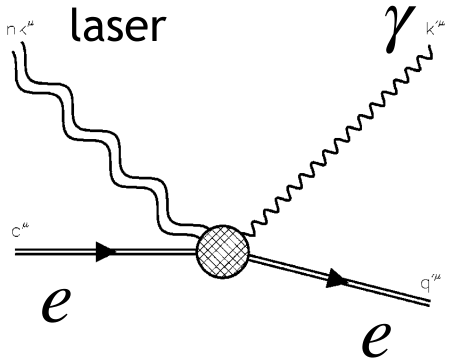
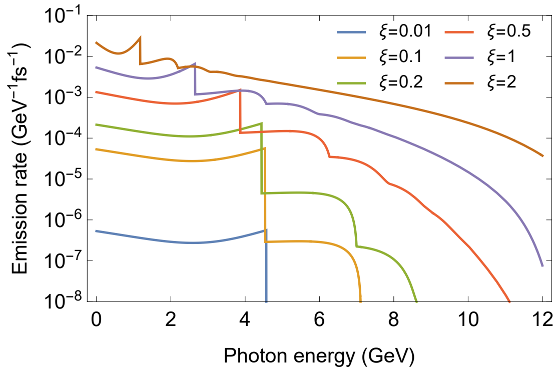
- Non-linear & non-pertur. Compton scattering:



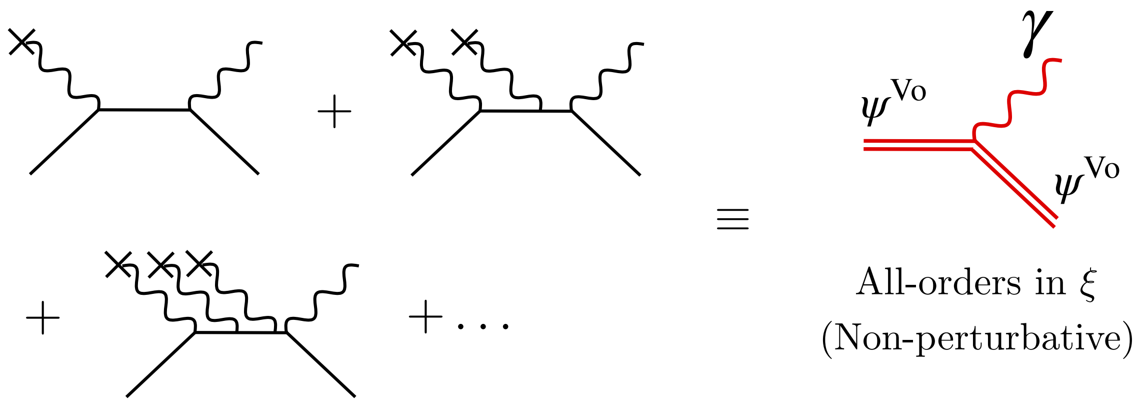


Electron intense-laser (strong field) formalism

- Electron traveling inside intense long laser pulse is described by treating the laser as a background field (Furry Picture), denoted as Volkov states:

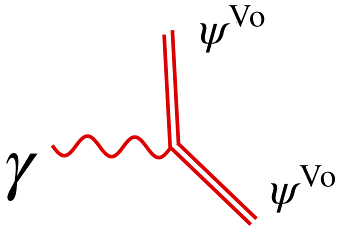
Volkov (35)

$$\psi^{\mathrm{Vo}} : (i\not{\partial} - e\not{A}_{\mathrm{ext}} - m)\psi^{\mathrm{Vo}} = 0$$



- The rest is done via (tree-level) perturbation th., where photons are described as perturbative (vacuum) propagating fields, interacting with Volkov states:

Ritus (85)



Time-scales & photon emission in LUXE

- Calculation of the Compton process & pair production relevant to LUXE shows:

Bai, et al. (21)

  - The relevant time scale of LUXE's 800 nm laser itself is $\omega_L^{-1} \sim 0.4$ fs
  - The laser pulse duration is $t_L \sim \mathcal{O}(10 - 200)$ fs
  - The (Compton scattering) photon production timescale is $\tau_\gamma \sim \mathcal{O}(10)$ fs
  - The (Breit-Wheeler) pair production timescale is $\tau_{ee} \sim \mathcal{O}(10^4 - 10^6)$ fs

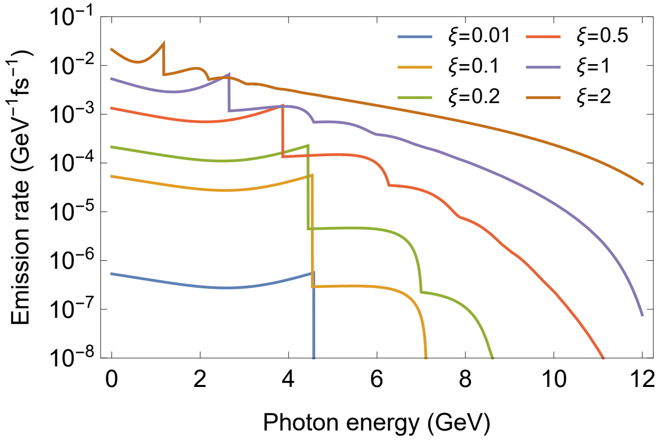
To conclude: $\omega_L^{-1} \ll \tau_\gamma \ll t_L \ll \tau_{ee}$

- Specifically, for $\xi^2 \gg 1$ photon emission rate is extremely high, the laser act as amplifier:

Ritus, 1985

$$\xi = \frac{eE_{\text{Laser}}}{\omega_{\text{Laser}}\, m_e} = \frac{m_e}{\omega_{\text{Laser}}} \times \frac{E_{\text{Laser}}}{E_{\text{Schwinger}}}$$

16.5 GeV electron, 800 nm laser, 17.2° crossing angle

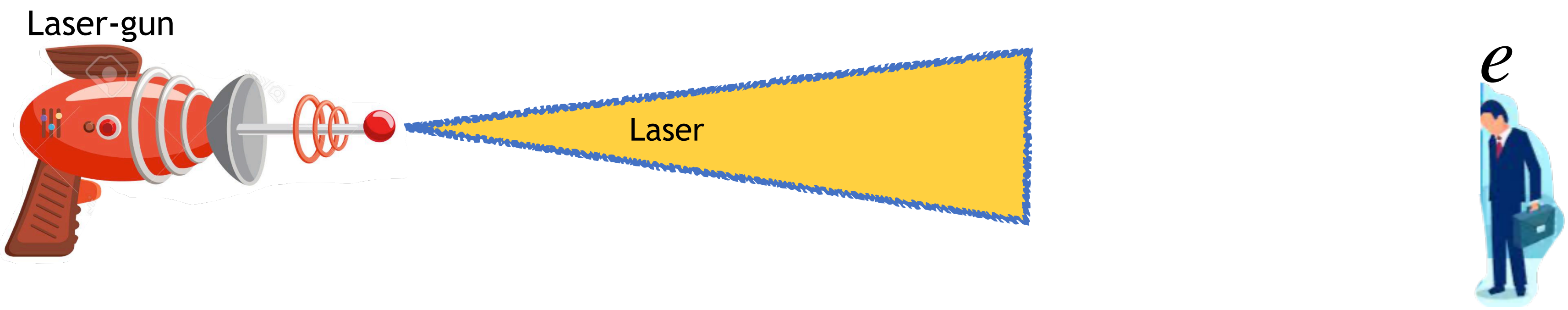


LUXE as an efficient source of hard photons

- We can transform LUXE into an optical dump:

The strong laser act as a dump for the electron

(LUXE: relevant mean free path is O(1))



Electron strong-laser collision @ LUXE

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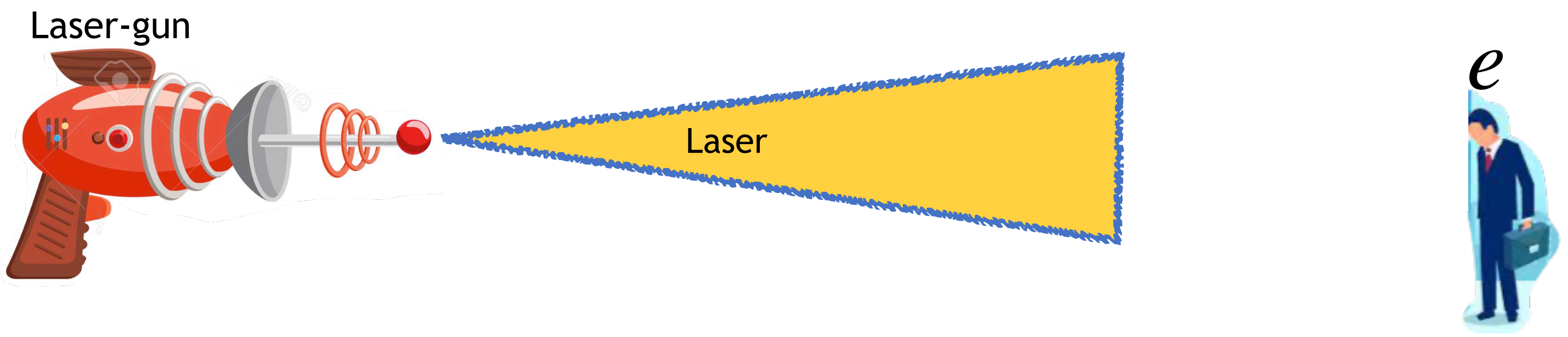

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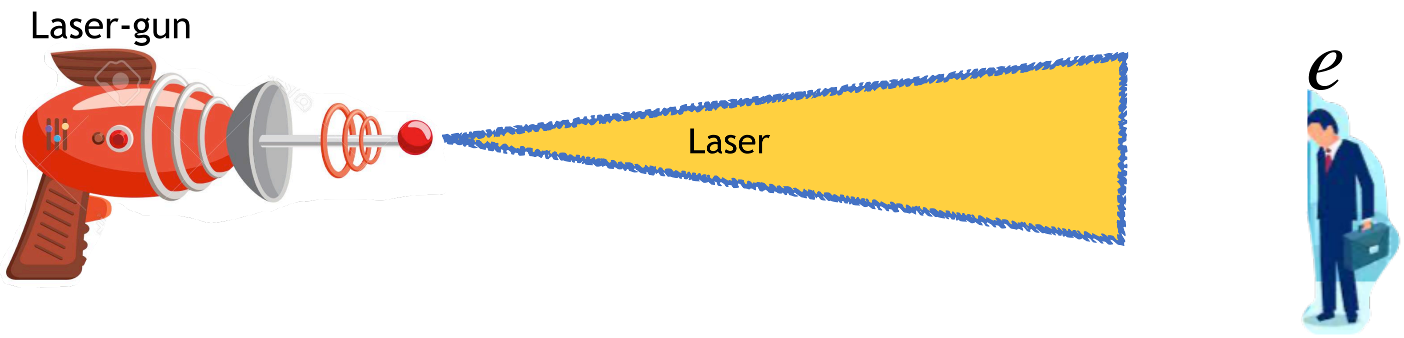

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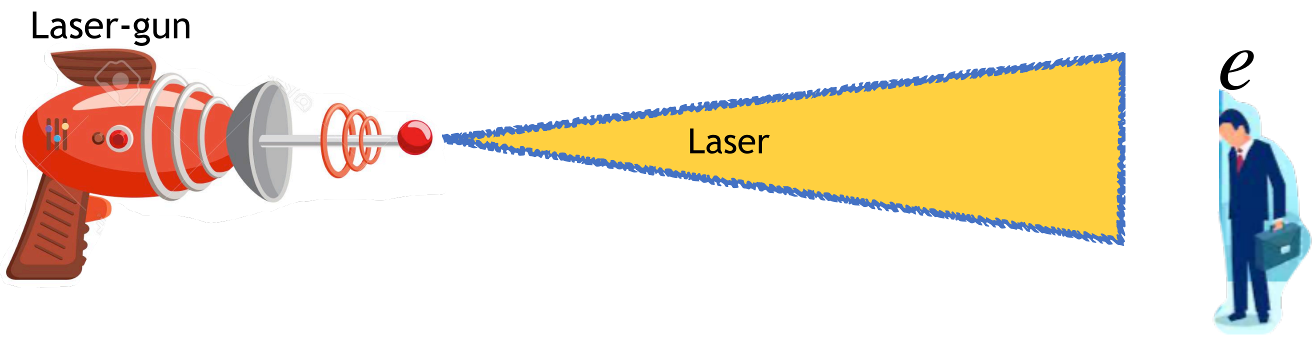

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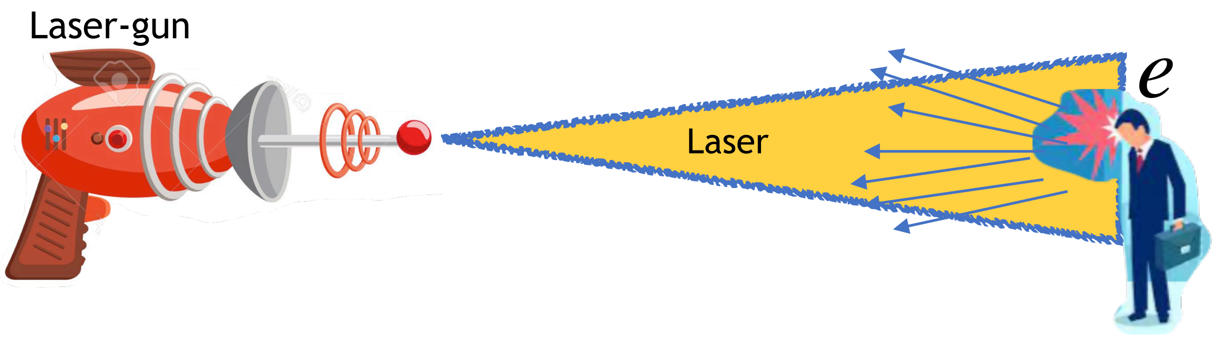
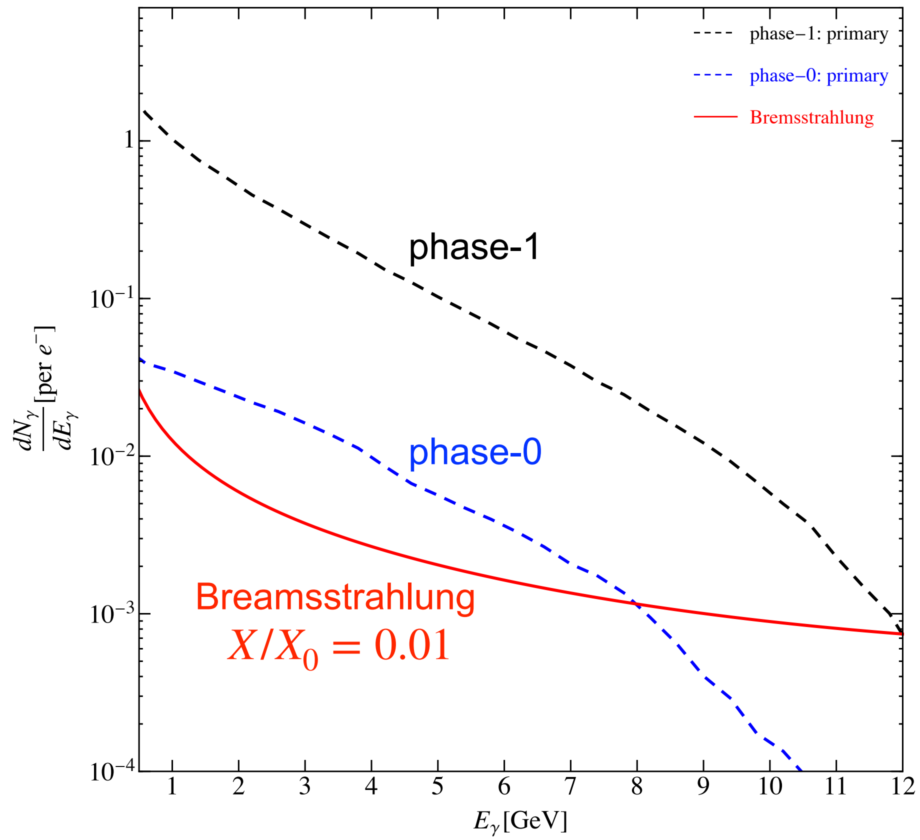
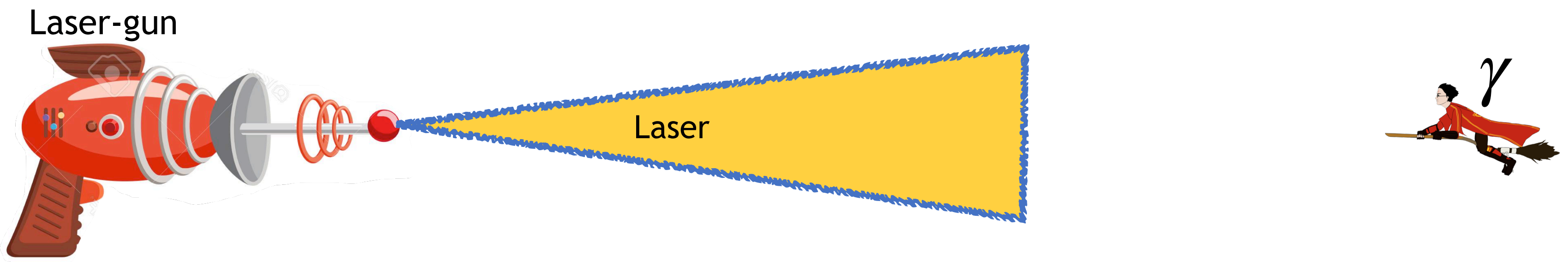


Actual emission spectrum, after collisions \w laser pulse, LUXE vs physical thin-dumps



Photons strong-laser (effectively no)-collision @ LUXE

Unlike the electron case, photons free streaming in the strong laser (LUXE: relevant mean free path is O(10^4))



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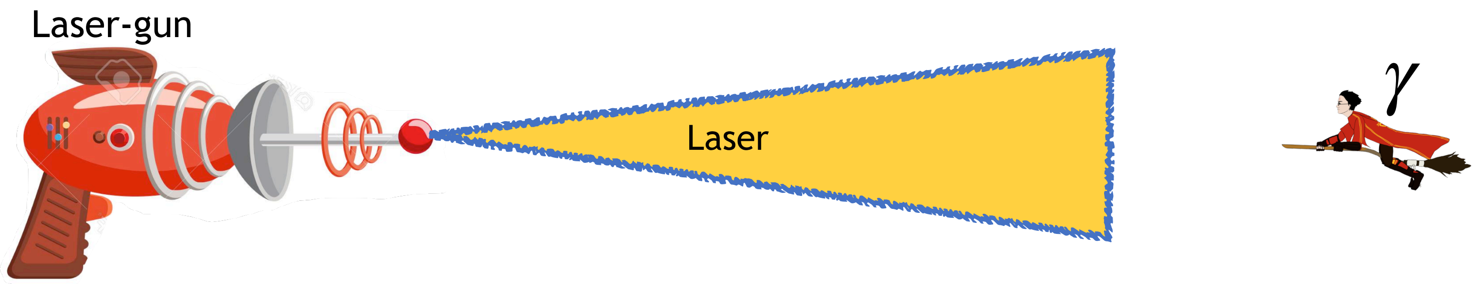

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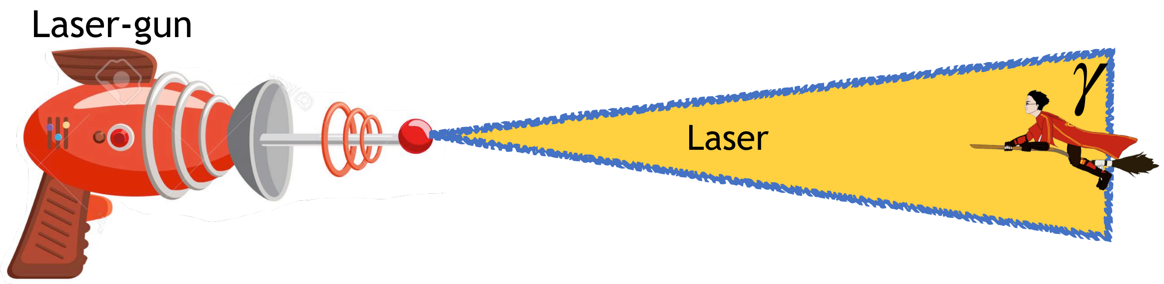
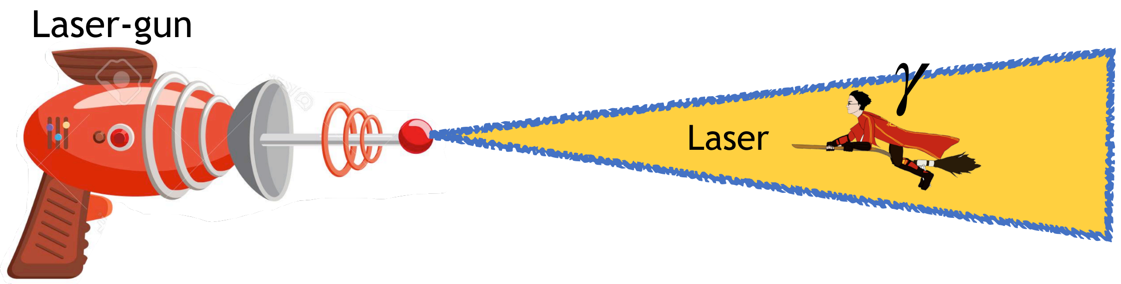


Photons strong-laser (effectively no)-collision @ LUXE

Unlike the electron case, photons free streaming in the strong laser (LUXE: relevant mean free path is > 10^4)

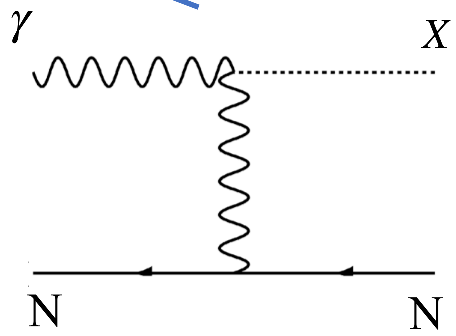


NPOD-LUXE: new physics searches with optical dump at LUXE

- Consider models with effective axion a and scalar ϕ coupling to photons:

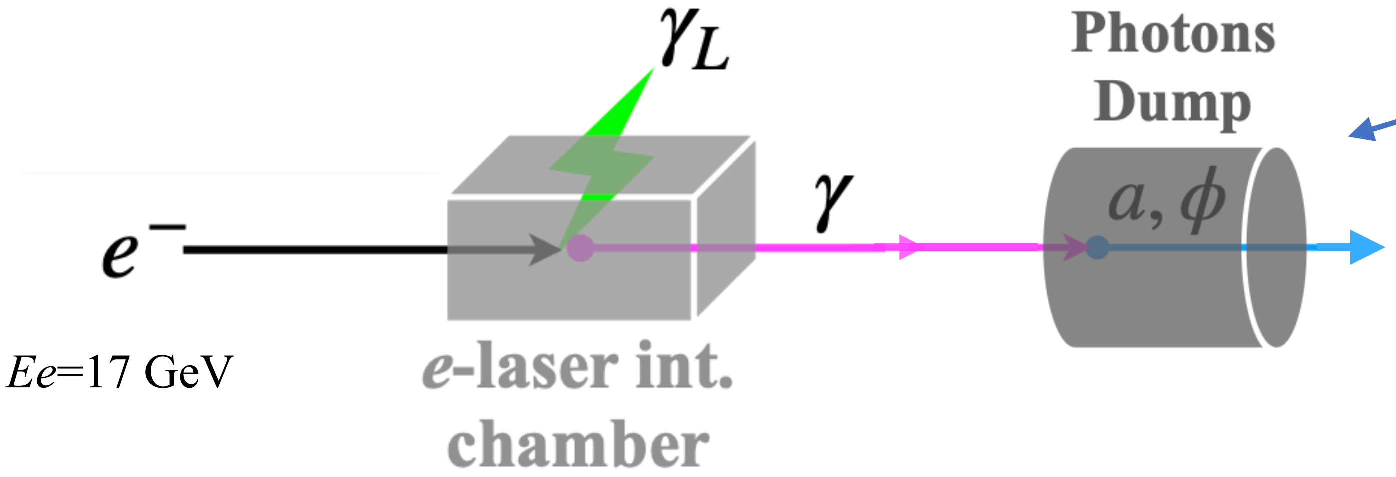
$$\mathcal{L}_{a,\phi} = \frac{a}{4\Lambda_a} F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\phi}{4\Lambda_\phi} F_{\mu\nu}F^{\mu\nu}$$

- The search is expressed as sensitivity to Λ_X, $X = a, \phi$



1st module: collision of hard electron on laser to produce hard photon beam:

2nd module: physical dump, photons interact \w dump to produce X's:



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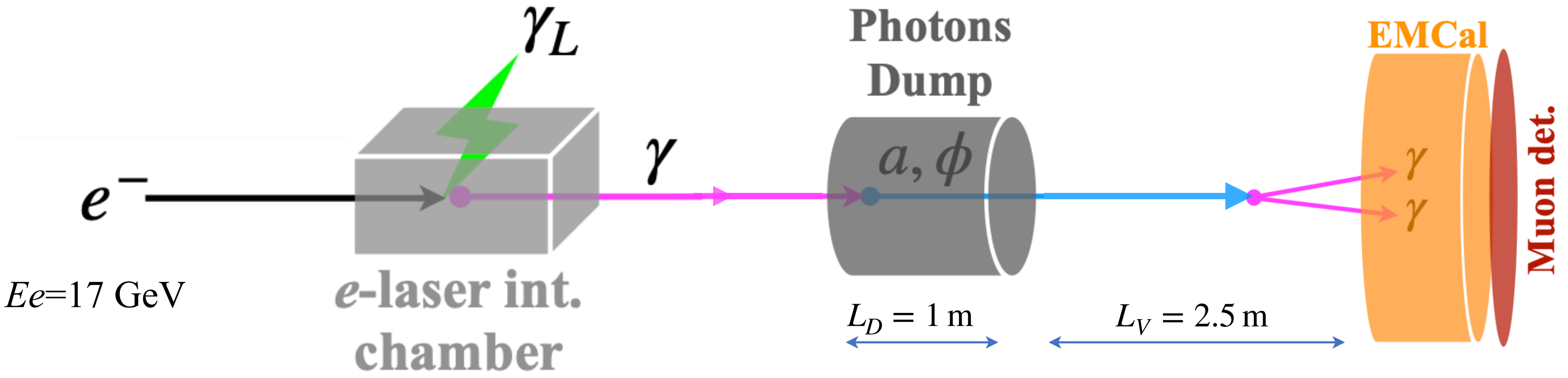
2nd module: physical dump, photons interact \w dump to produce X's:

3rd module: detector to observe $X \to \gamma\gamma$ decay



Intermediate Summary & Outlook

- LUXE: 1st time direct & clean look at non-perturbative QED processes
- Spinoff: use the strong-field-electron system to construct an optical-dump, an amplifier convert electrons to large-hard flux of free-photons
- This + down-stream dump + detector => search for new particles couple to photons => cover uncharted territories
- Can extend concept to other couplings (gluons, dark-photon, non-linear QED) and other experiments (SLAC, LBNL, ILC …)

Backups

The new physics sensitivity, for background free experiment

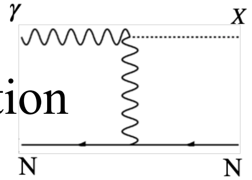
- The number of produced X's at LUXE-NPOD is:

$$N_X \approx \mathcal{L}_{\rm eff} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \sigma_X(E_\gamma) \left(e^{-\frac{L_D}{L_X}} - e^{-\frac{L_V + L_D}{L_X}} \right) = 3$$

$10^{14\text{-}16}$ e's on target

incoming photon's spec.

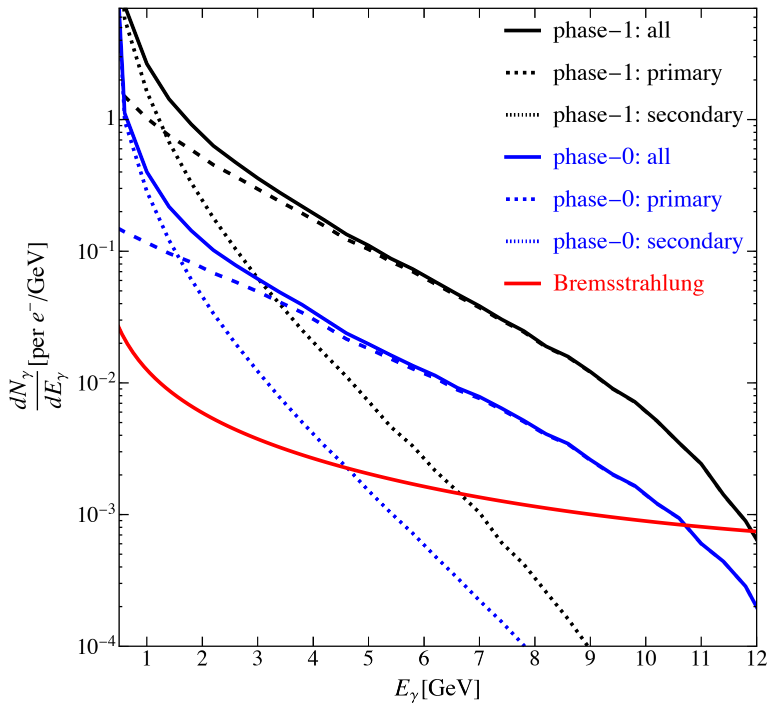
prod. X-section



ensures decay in volume

$L_{D,V} = 1\,, 2.5\,\mathrm{m}$

$$L_X = \tau_X \frac{p_X}{m_X} \propto \frac{\Lambda_X^2}{m_X^4}$$



source	# photons, E>1 GeV	backgrounds
LUXE-0/1	0.4 / 2.5	effectively free
e-beam thin	0.03	effectively free
e-beam thick	6.7	O(100) larger

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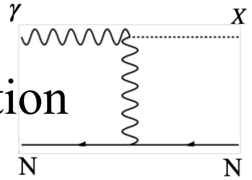

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