Probing for light new particles with the LUXE experiment

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on behalf of the LUXE Collaboration
Department of Particle Physics and Astrophysics
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SUSY2023 Conference

Outline

1. Introduction to LUXE.

2. The LUXE Physics and Experimental Setup.

3. New Physics at the Optical Dump (NPOD).

4. Summary

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THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

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Review

Conceptual design report for the LUXE experiment

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LUXE CDR: Eur. Phys. J. Spec. Top. (2021) 230:2445–2560

PHYSICAL REVIEW D **106,** 115034 (2022)

New physics searches with an optical dump at LUXE

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We propose a novel way to search for feebly interacting massive particles, exploiting two properties of systems involving collisions between high energy electrons and intense laser pulses. The first property is that the electron-laser collision results in a large flux of hard photons, as the laser behaves effectively as a thick medium. The second property is that the emitted photons free-stream inside the laser and thus for them the laser behaves effectively as a very thin medium. Combining these two features implies that the electron-intense-laser collision is an apparatus, which can efficiently convert $\mathcal{O}(10\ \mathrm{GeV})$ electrons to a large flux of hard, collinear photons. The photons are directed onto a solid dump in which feebly interacting massive particles may be produced. With the much smaller backgrounds induced by the photon beam compared to those expected in electron- or proton-beam dump experiments and combined with a relatively shorter dump used here, the sensitivity to short lifetimes is unparalleled. We denote this novel apparatus as "optical dump" or NPOD (new physics search with optical dump). The proposed LUXE experiment at the European XFEL has all the basic required ingredients to realize this experimental concept for the first time. Moreover, the NPOD extension of LUXE is essentially parasitic to the main experiment and thus, practically it does not have any bearing on its main program. We discuss how the NPOD concept can be realized in practice by adding a detector after the last physical dump of the experiment to reconstruct the two-photon decay of a new spin-0 particle. We show that even with a relatively short dump, the search can still be background-free. Remarkably, even with a few days of data taking with a 40 TW laser corresponding to its initial run, LUXE-NPOD will be able to probe an uncharted territory of models with pseudoscalars and scalars. Furthermore, with a 350 TW laser of the main run, LUXE-NPOD will have a unique reach for these models. In particular it can probe natural scalar theories for masses above 100 MeV. We note that the new NPOD concept may be ported to other existing or future facilities worldwide, including, e.g., future lepton colliders.

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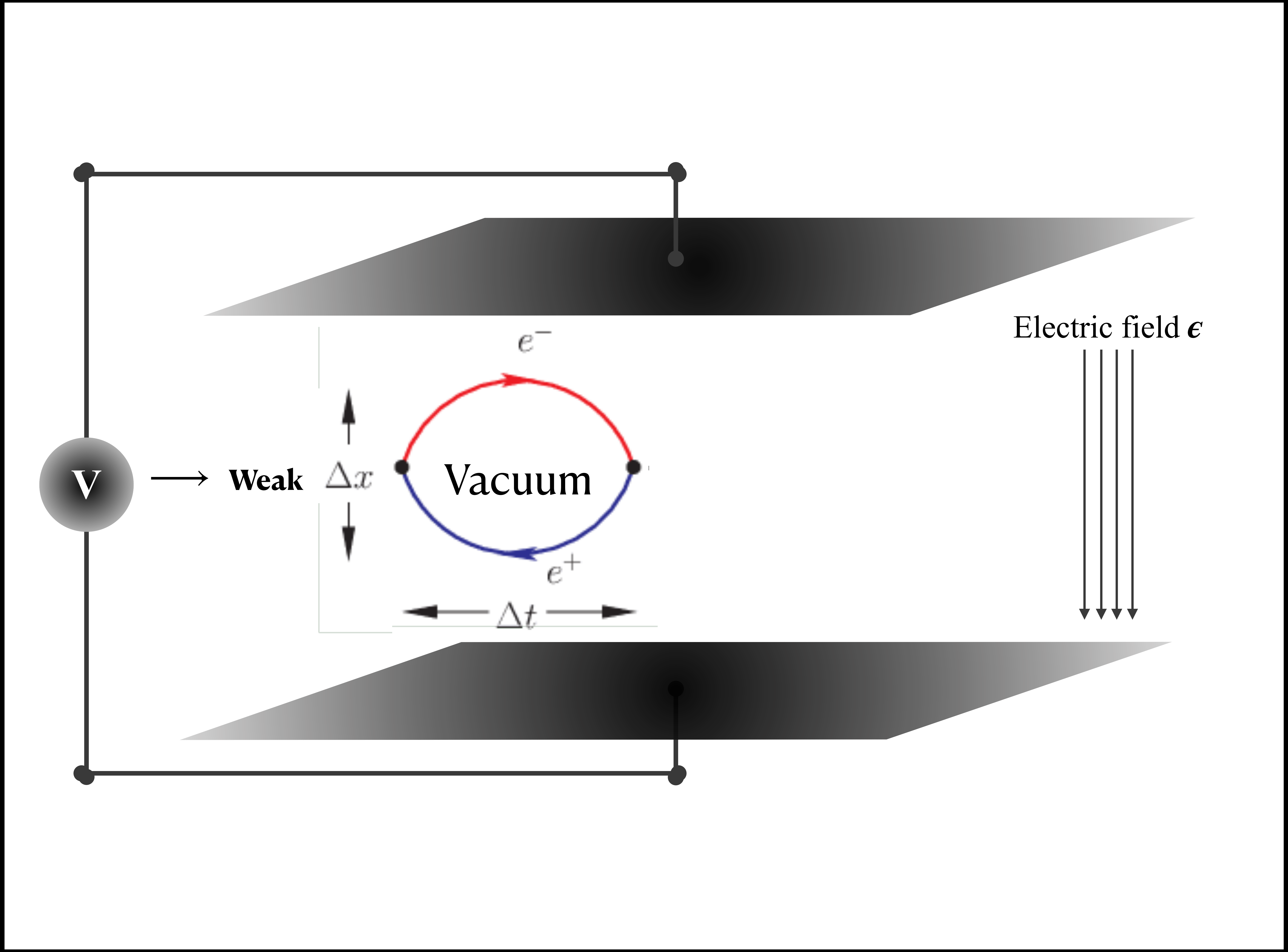
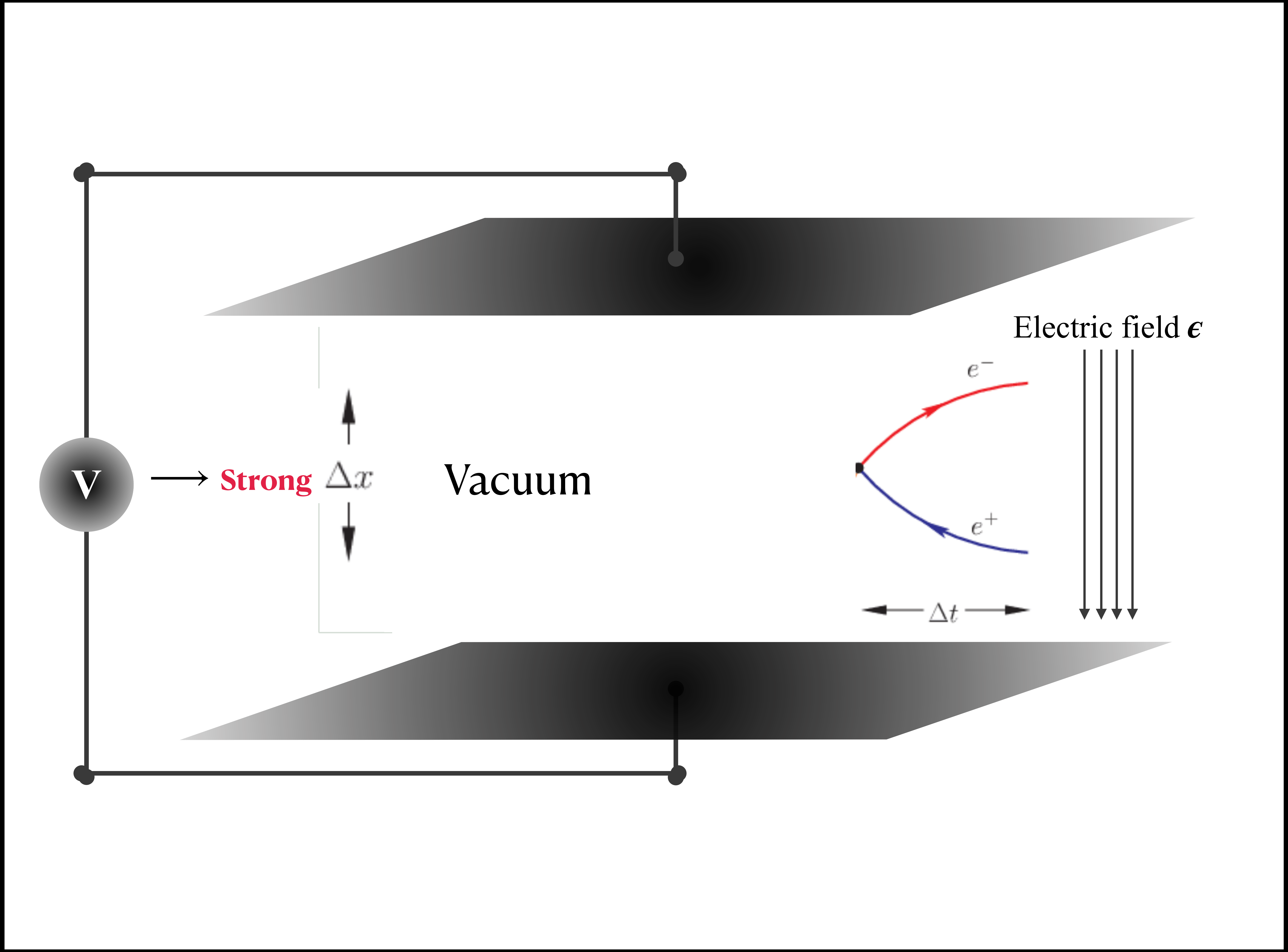
LUXE NPOD paper: Phys. Rev. D 106, 115034 (2022)

Pair Production from Vacuum

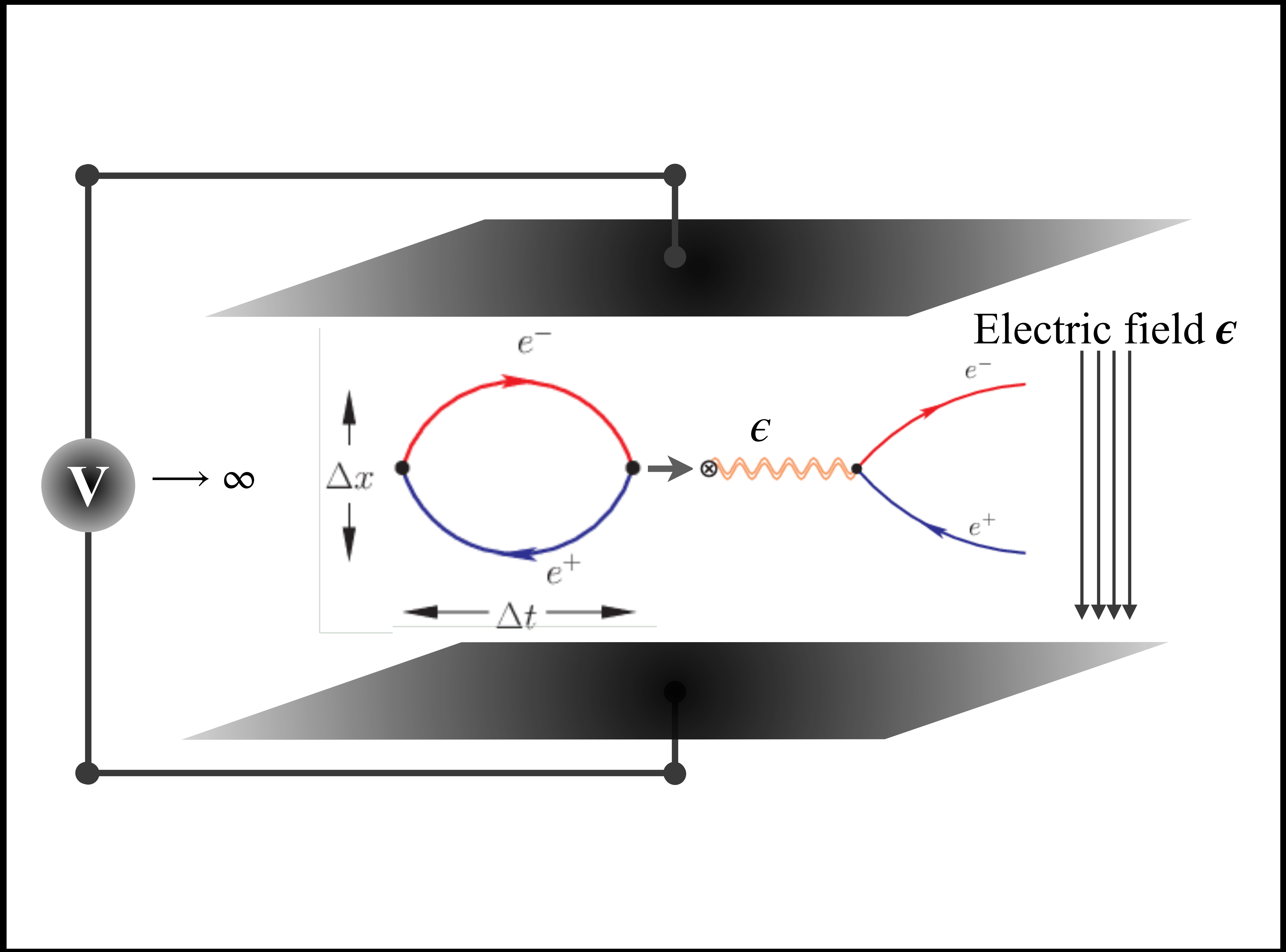


Pair Production from Vacuum



LUXE: tests of strong-field QED

- ✦ Schwinger critical field: $\epsilon_S = m_e^2 c^3 / e\hbar \simeq 1.32 \cdot 10^{18}$ V/m.
  - ✦Not achievable statically in terrestrial laboratories.
  - ✦May use lasers - in certain rest frames the field of lasers can be enhanced by the system's boost.

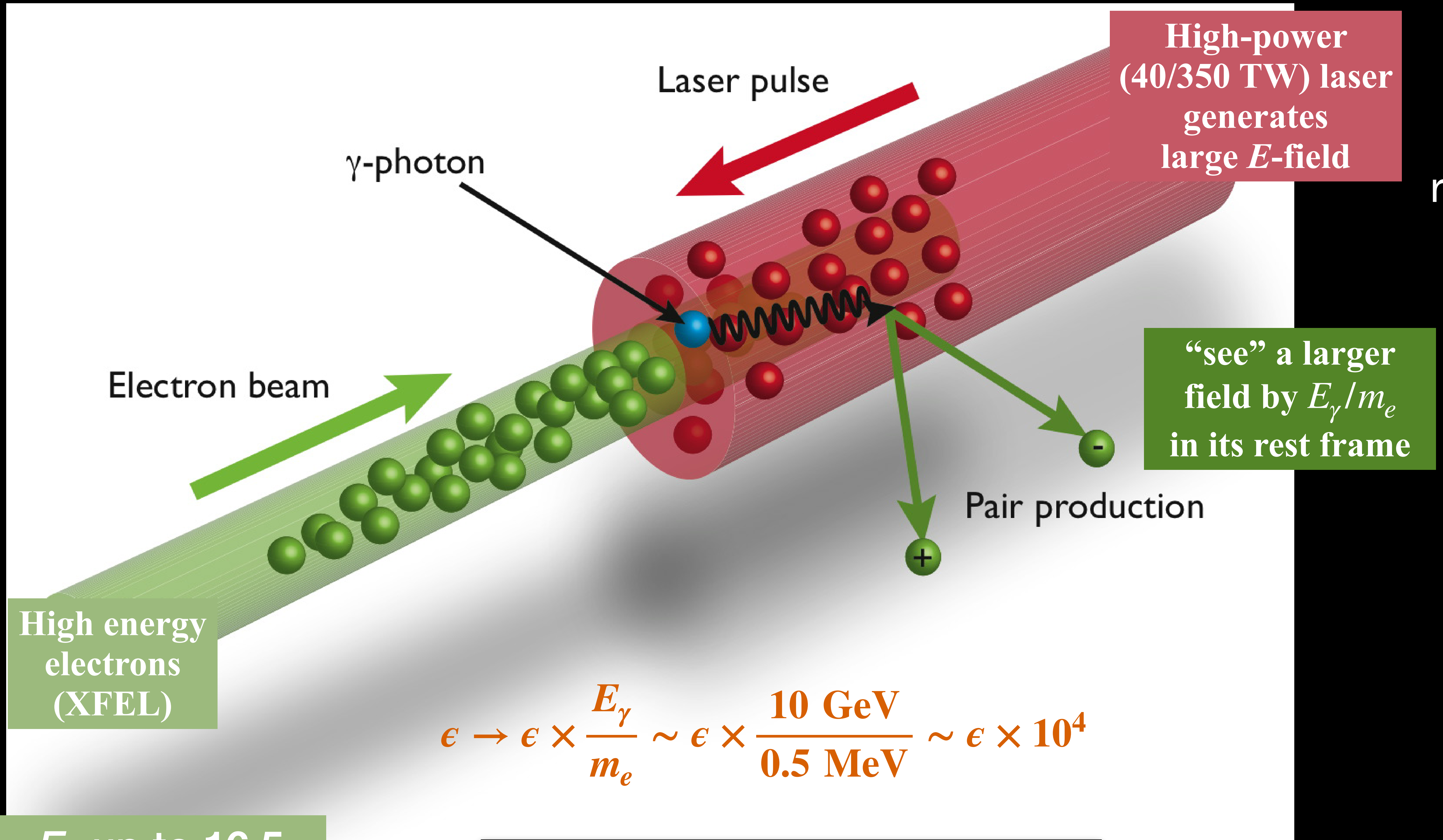


1930s	**First discussions by Sauter, Heisenberg & Euler**
1951	**First calculations by Schwinger: ϵ_S**
1990s	**E144 at SLAC first to approach ϵ_S (reached $\epsilon \rightarrow \epsilon_S/4$)**
2020s	**LUXE: reach ϵ_S and beyond**

- ✦ **Goal of LUXE experiment:**
  - ✦ Effort to reach ϵ_s and beyond
  - ✦ Make precision measurements of electron-photon and photon-photon interactions in a transition from the **perturbative to the non-perturbative regime** of quantum electrodynamics (QED)
  - ✦ **Search for New Physics enhanced by the strong field**

A Brief Idea about the LUXE physics

Laser Und XFEL Experiment



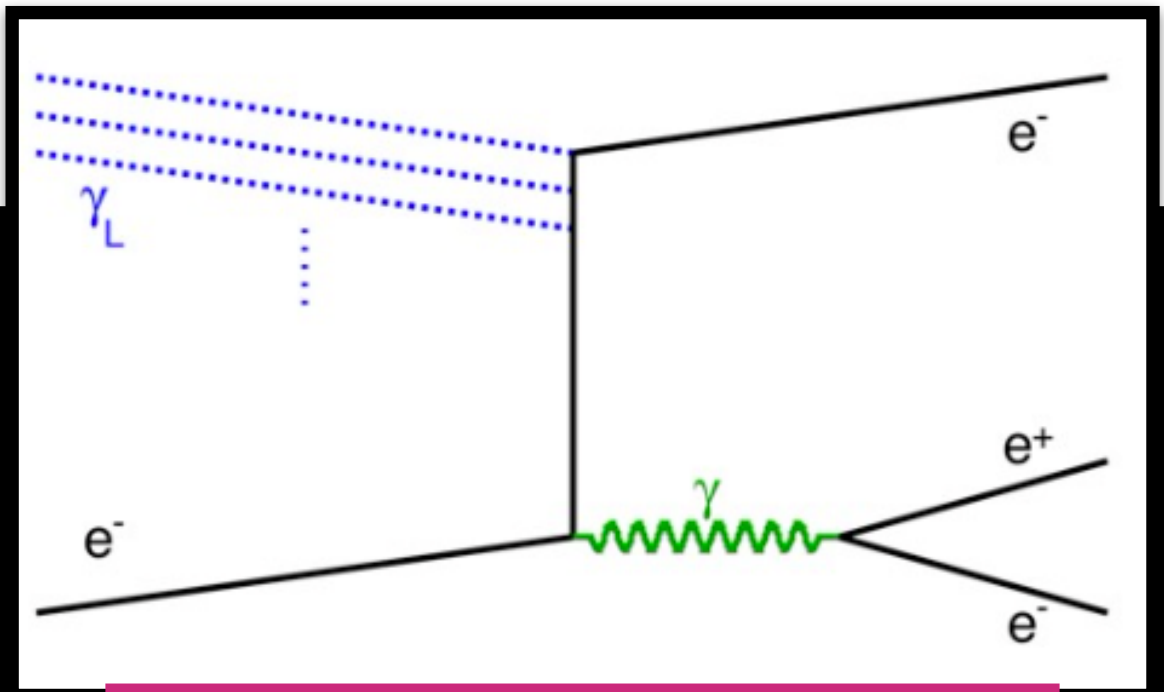
High-power (40/350 TW) laser generates large *E*-field

“see” a larger field by E_γ/m_e in its rest frame

High energy electrons (XFEL)

$$\epsilon \to \epsilon \times \frac{E_\gamma}{m_e} \sim \epsilon \times \frac{10\ \text{GeV}}{0.5\ \text{MeV}} \sim \epsilon \times 10^4$$

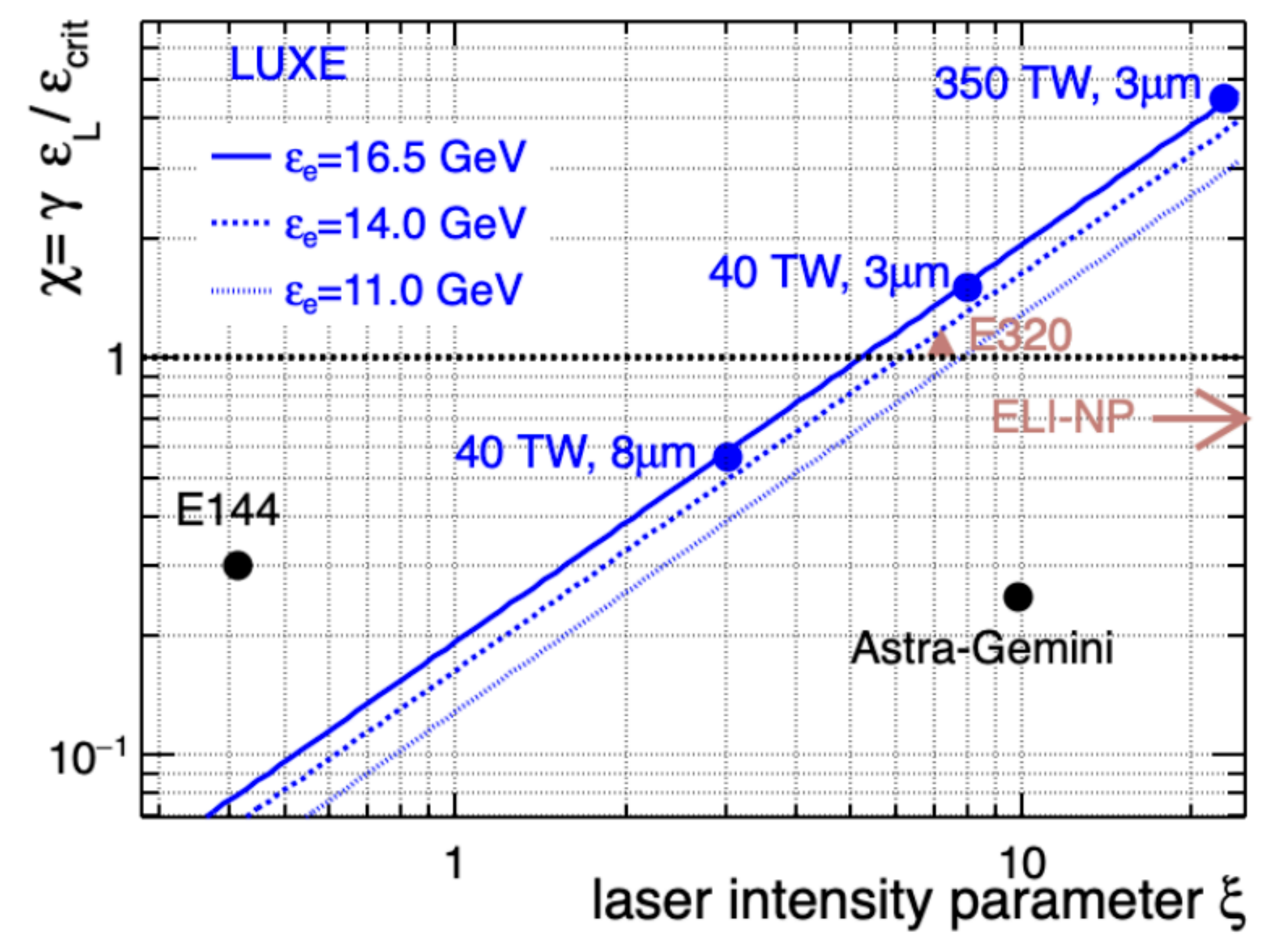
E_e up to 16.5 GeV, $N_e = 1.5\times10^9$ e^-/ bunch



Compton process followed by Breit-Wheeler process

The rate of laser assisted one photon pair production asymptotically resembles to that of the spontaneous pair production in vacuum.

Hartin et.al. Phys. Rev. D 99, 036008 (2019)



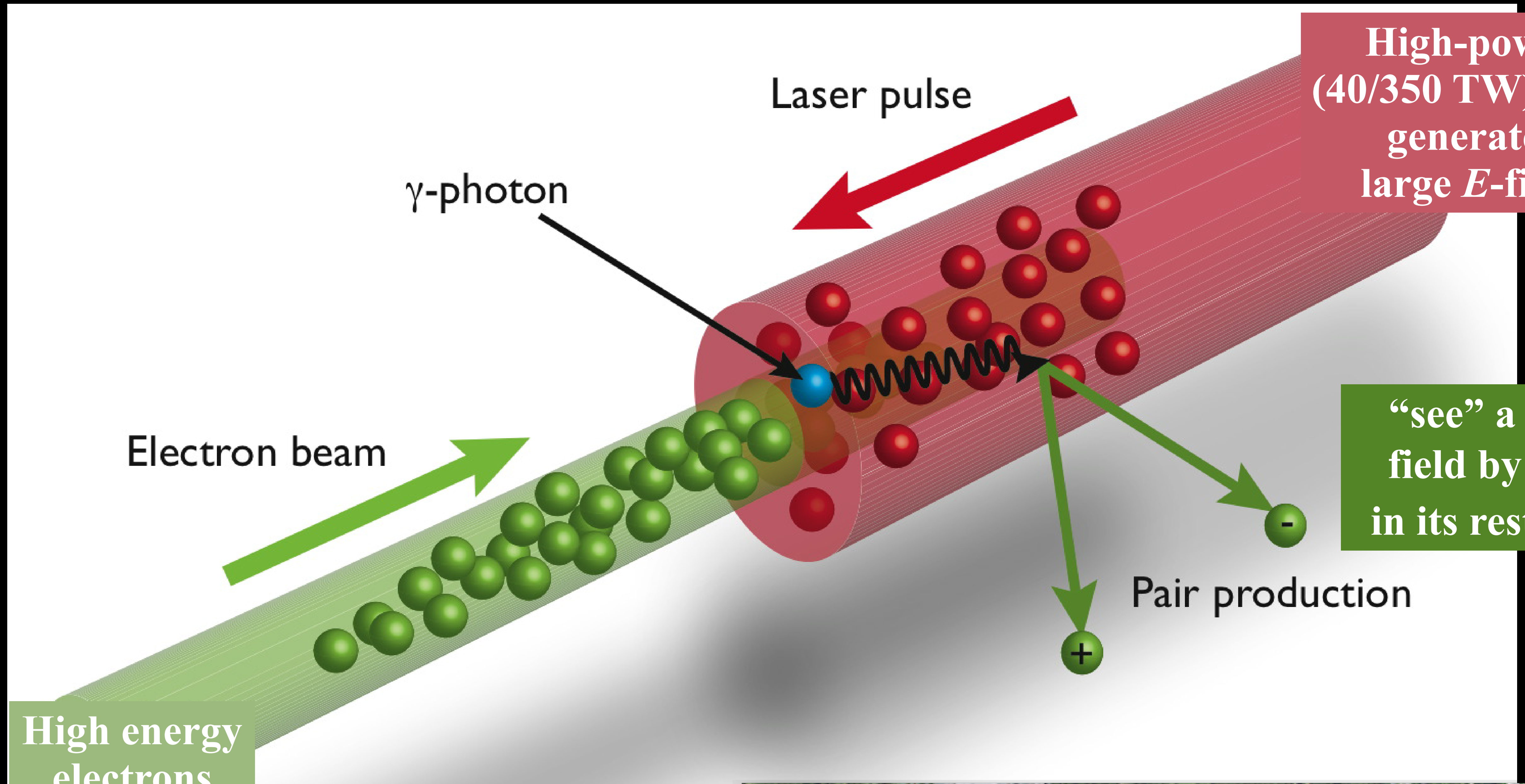
Laser intensity parameter: $\xi = (m_e\epsilon_L)/(\omega_L\epsilon_s)$.

Quantum parameter: $\chi_{e,\gamma} \propto (E_{e,\gamma}/m_e)\xi$, describes the interaction.

Non-perturbative when $\xi > 1$

A Brief Idea about the LUXE physics

Laser Und XFEL Experiment



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Con

Breit-Wheeler process

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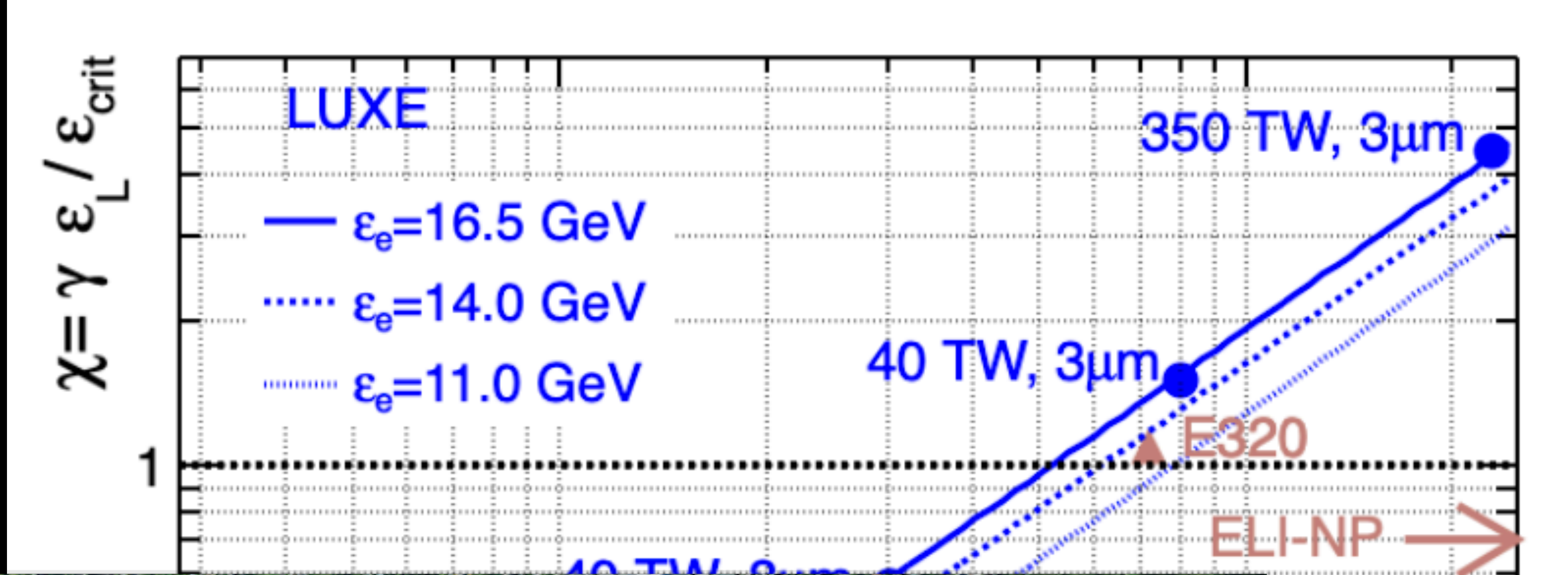
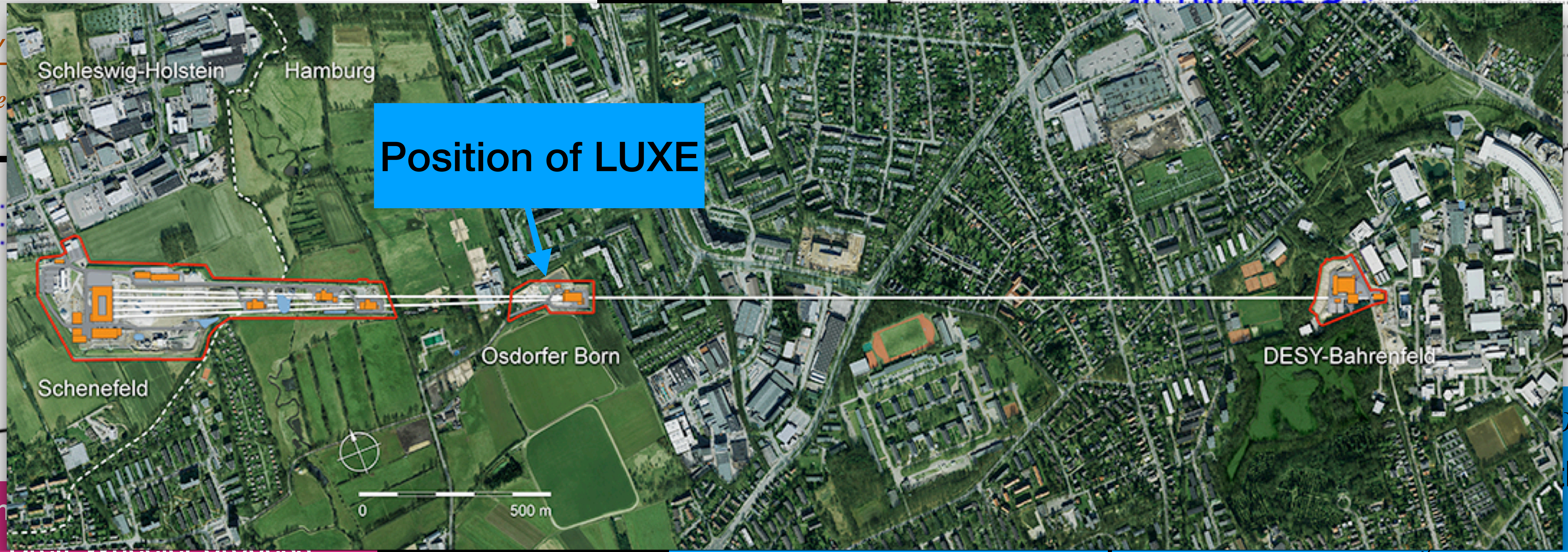
Hartin et.al. Phys. Rev. D 99, 036008 (2019)





Position of LUXE

$\omega_L\epsilon_s$).

he interaction.

LUXE

e + laser mode

BSM detector
$a \rightarrow \gamma\gamma$

Forward detectors
Γ_{γ_C}, ξ

IP detectors
$\Gamma_{e^+}, \Gamma_{e_C}$

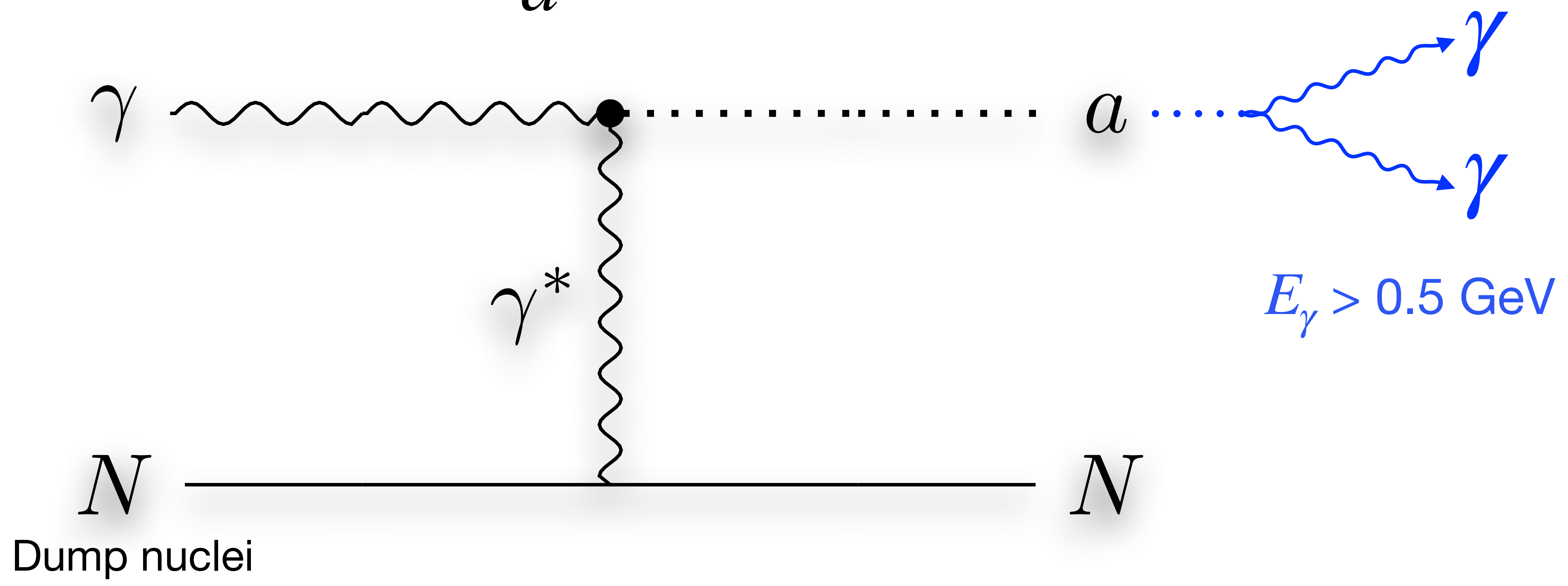
e+laser mode
(not to scale)

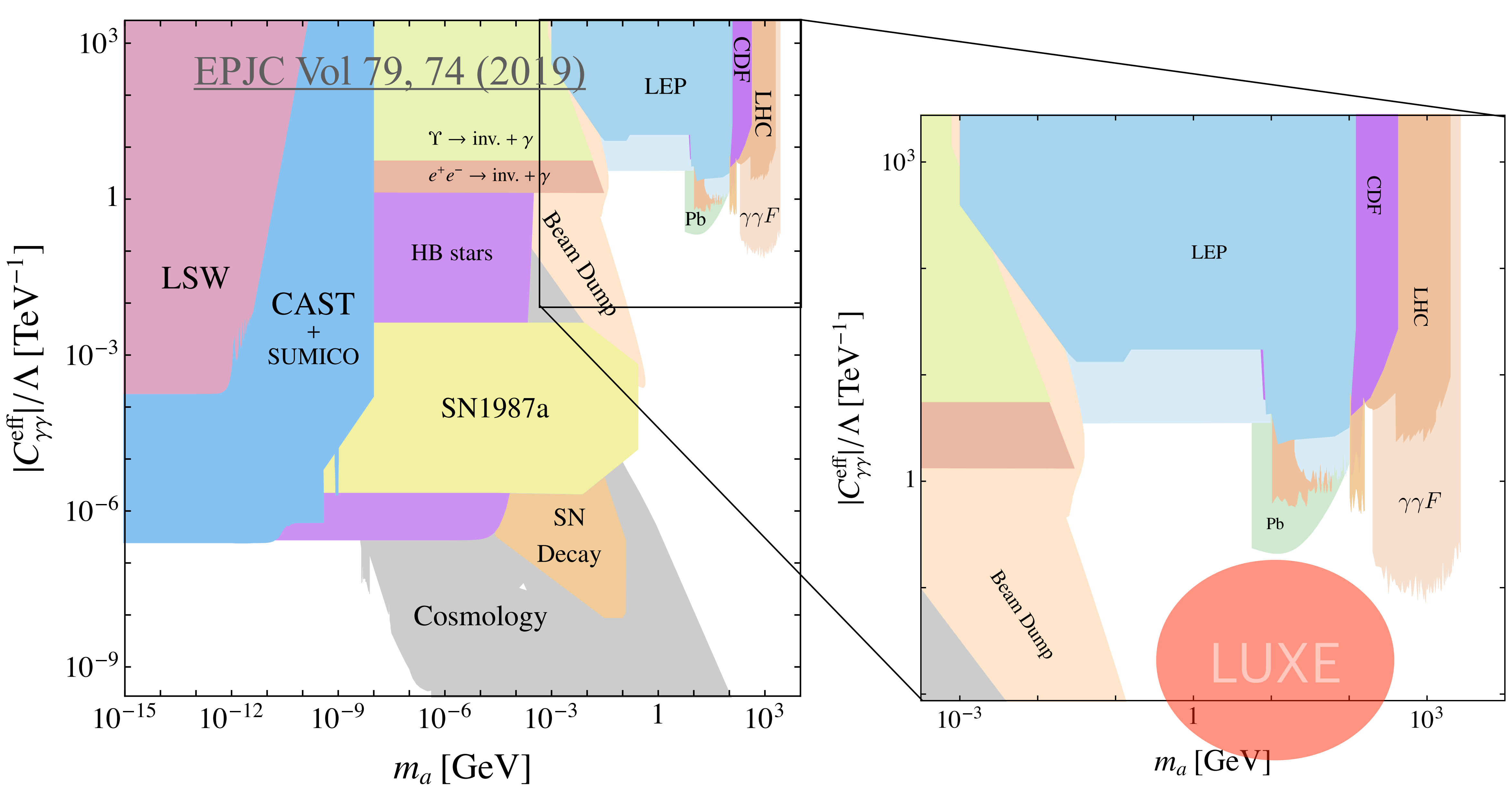
New Physics @ LUXE

Focus on axion-like-particles (ALP)

- Well motivated BSM scenario
  - The axions originally proposed as a solution to strong CP problem.
  - If very light, it is a dark matter candidate.
  - Light ALPs arise in variety of models motivated by Goldstone theorem.
- Focussing on the Primakoff production
  - Displaced decay of ALPs to 2 hard photons
- Everything applies to scalar with:
  - $a \to \phi,\ \tilde{F}_{\mu\nu} \to F_{\mu\nu},\ i\gamma^5 \to 1$

$$\mathscr{L}_a = \frac{a}{4\Lambda_a} F_{\mu\nu}\tilde{F}^{\mu\nu} + i\cancelto{\text{ignore today}}{g_{ae}}\, a\bar{e}\gamma^5 e$$

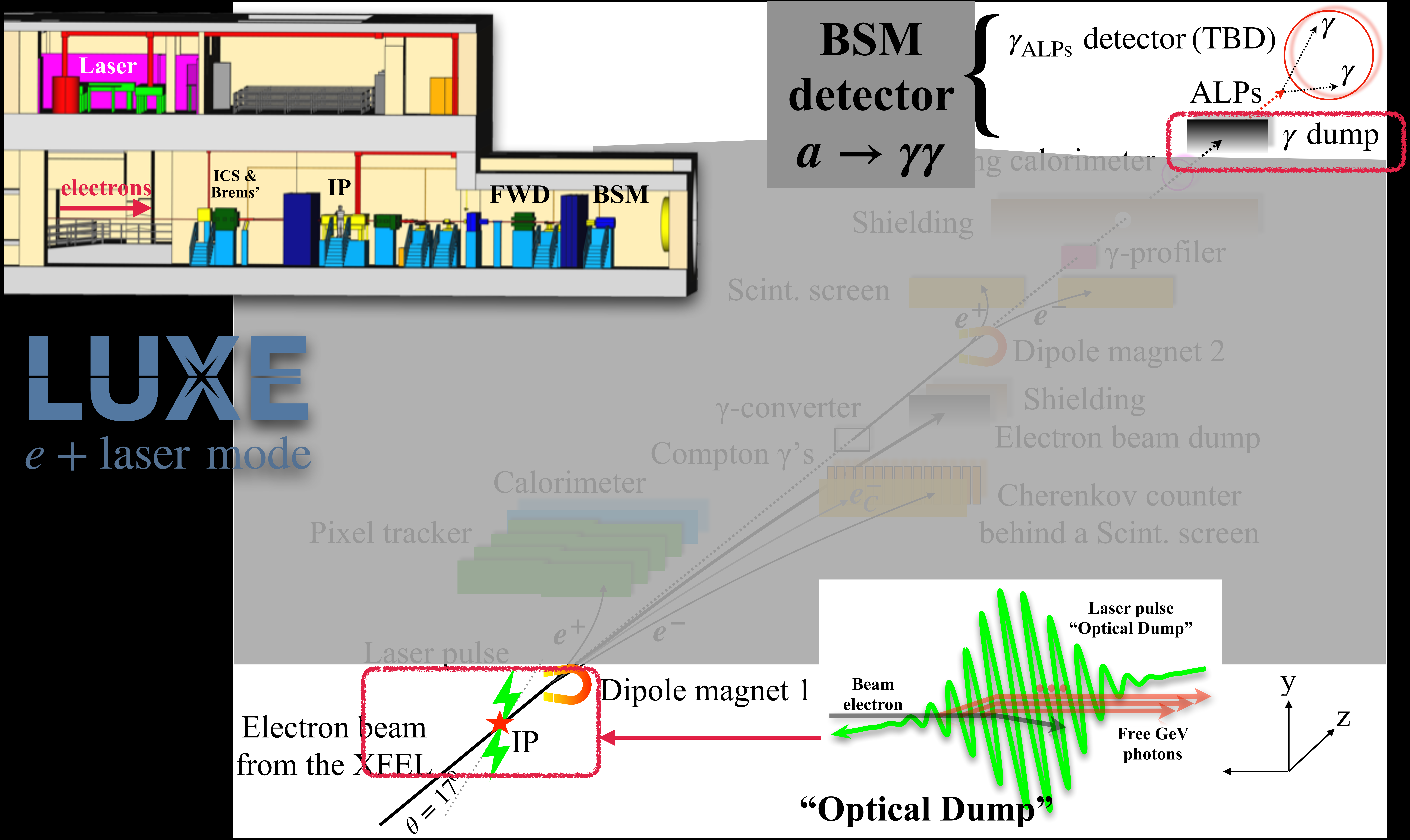




EPJC Vol 79, 74 (2019)

BSM detector
$a \rightarrow \gamma\gamma$

LUXE
e + laser mode



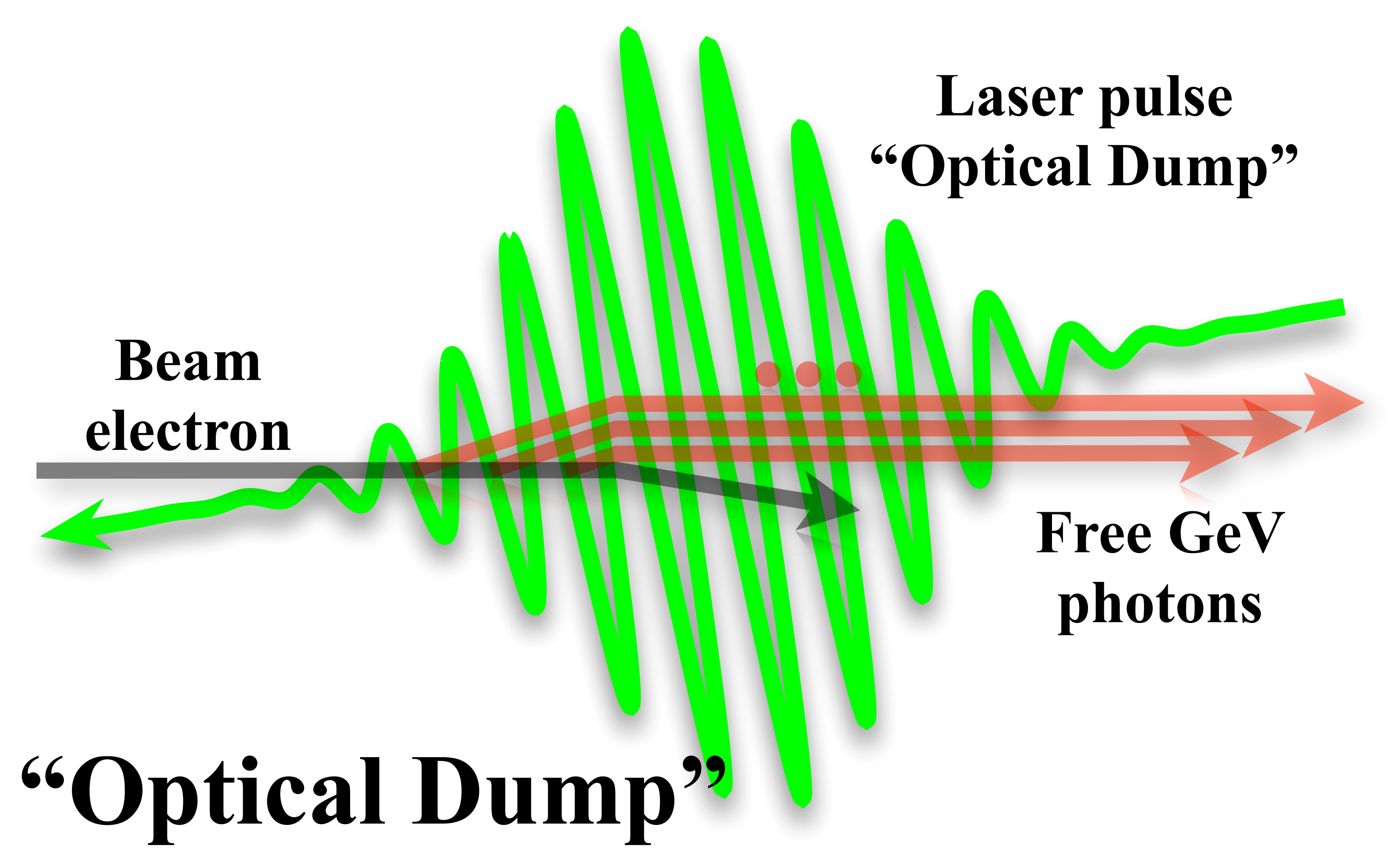
Concept of Optical Dump

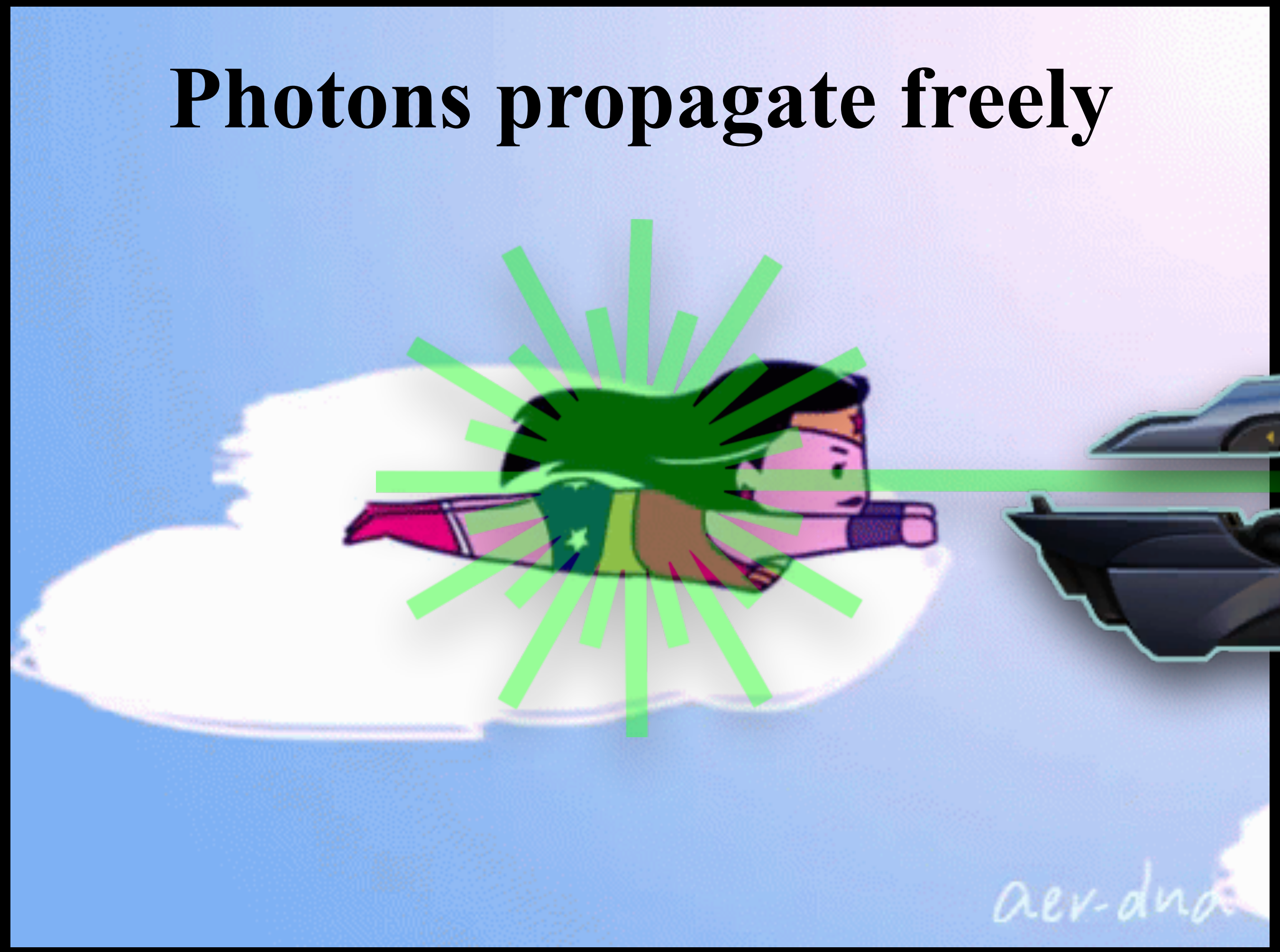
- The LUXE 800 nm laser timescale is……..….$\omega_L^{-1} \sim 0.4\ \text{fs}$: good to use laser as a background field to a leading order.
- The laser pulse duration is……………….…..….$t_L \sim \mathcal{O}(30-200)\ \text{fs}$
- The (Compton) photon production time is.….$\tau_\gamma \sim \mathcal{O}(10)\ \text{fs}$

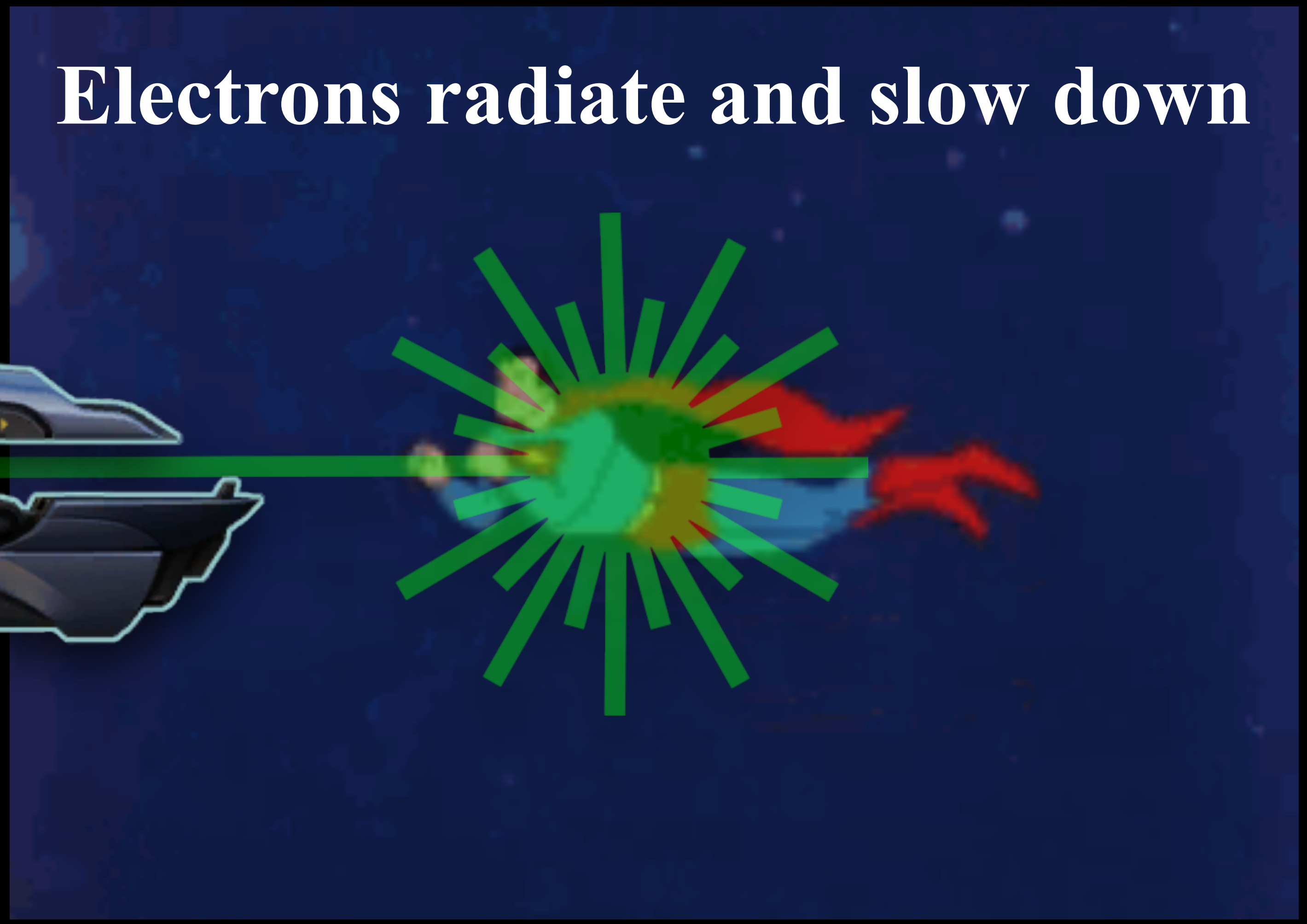
$\Big\}$ ✶laser behaves as a thick target for electrons.

- The (BW) pair production timescale is……...$\tau_{ee} \sim \mathcal{O}(10^4-10^6)\ \text{fs}$: treat the photons in the laser as free streaming.

Time scales: $\omega_L^{-1} \ll \tau_\gamma \lesssim t_L \ll \tau_{ee}$







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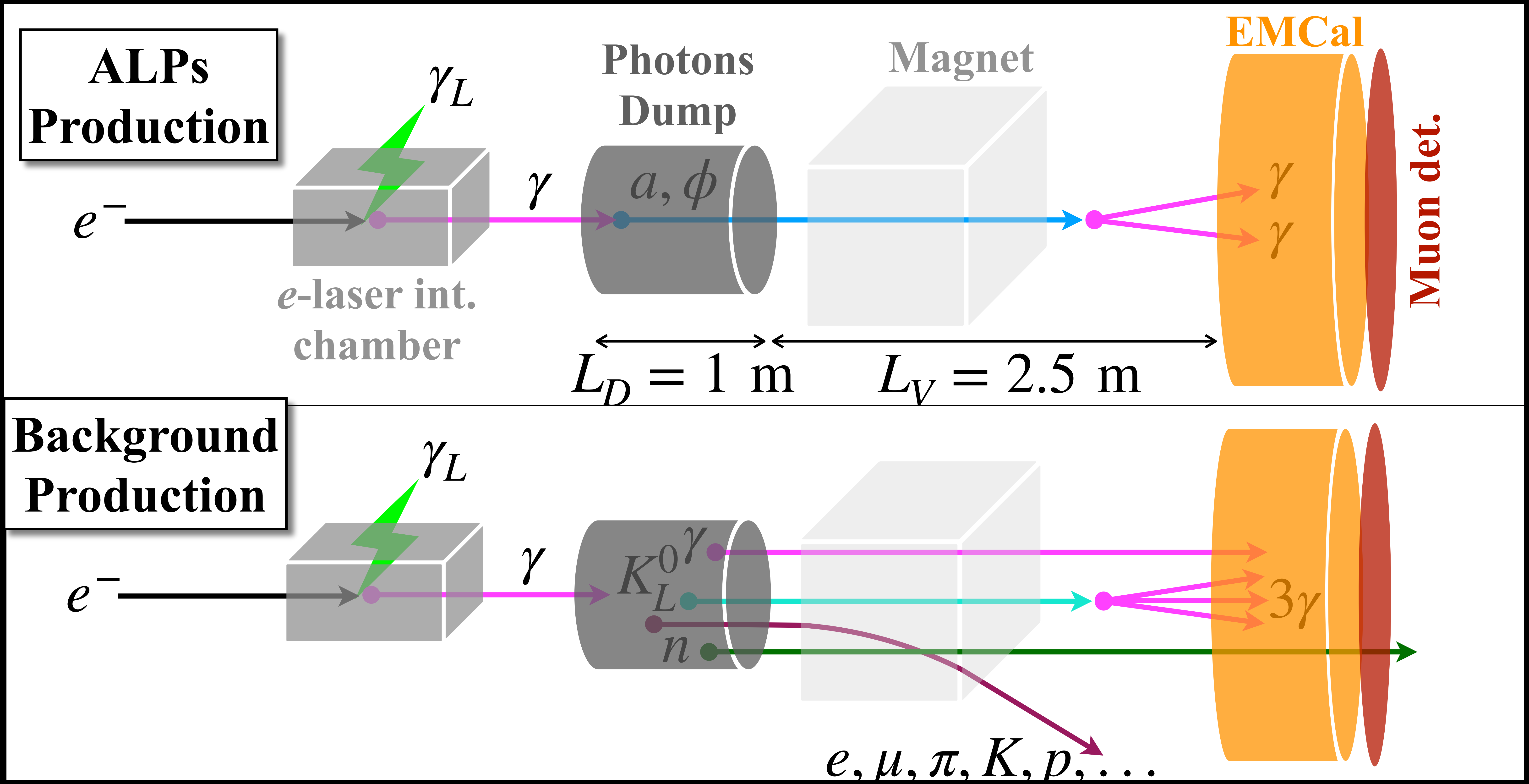


Background Estimation:

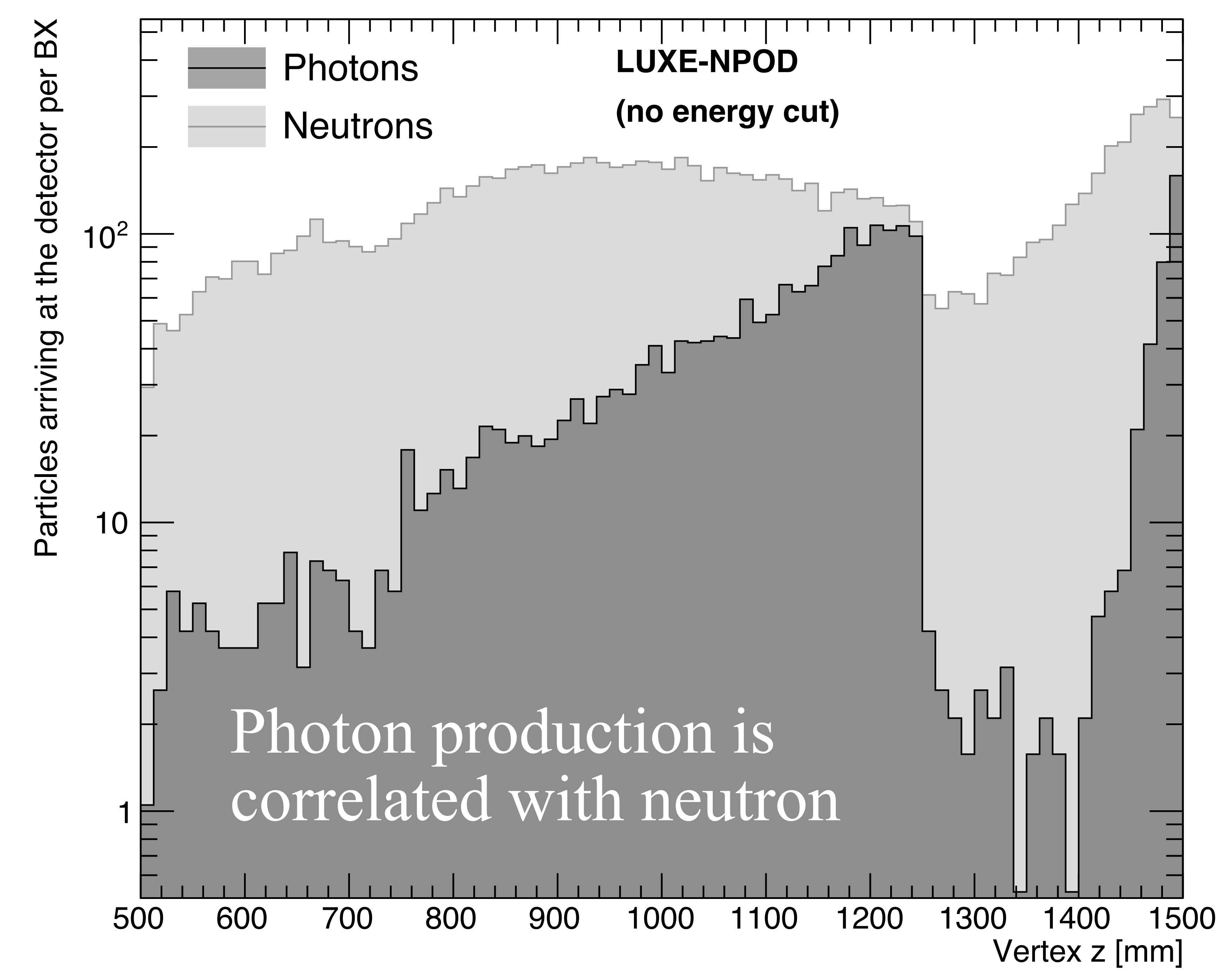
- ◉ SM particles produced in the dump during the shower
  - ◉ Charged particles: electrons, muons and hadrons.
    - ◉ Can be bent away from the detector surface by a magnetic field.
  - ◉ Fake photons: mostly neutrons.
  - ◉ Real photons: EM/hadronic interactions from the close to the end of the dump or from meson decay.

- ✳Background estimated from the Geant4 simulation
  - ✳Got 0 photons and 10 neutrons (with $E > 0.5$ GeV) in the 2 BX simulated for the 1 m long dump.
  - ✳Photons can be statistically limited here.
  - ✳Unfortunately simulation is computationally expensive.

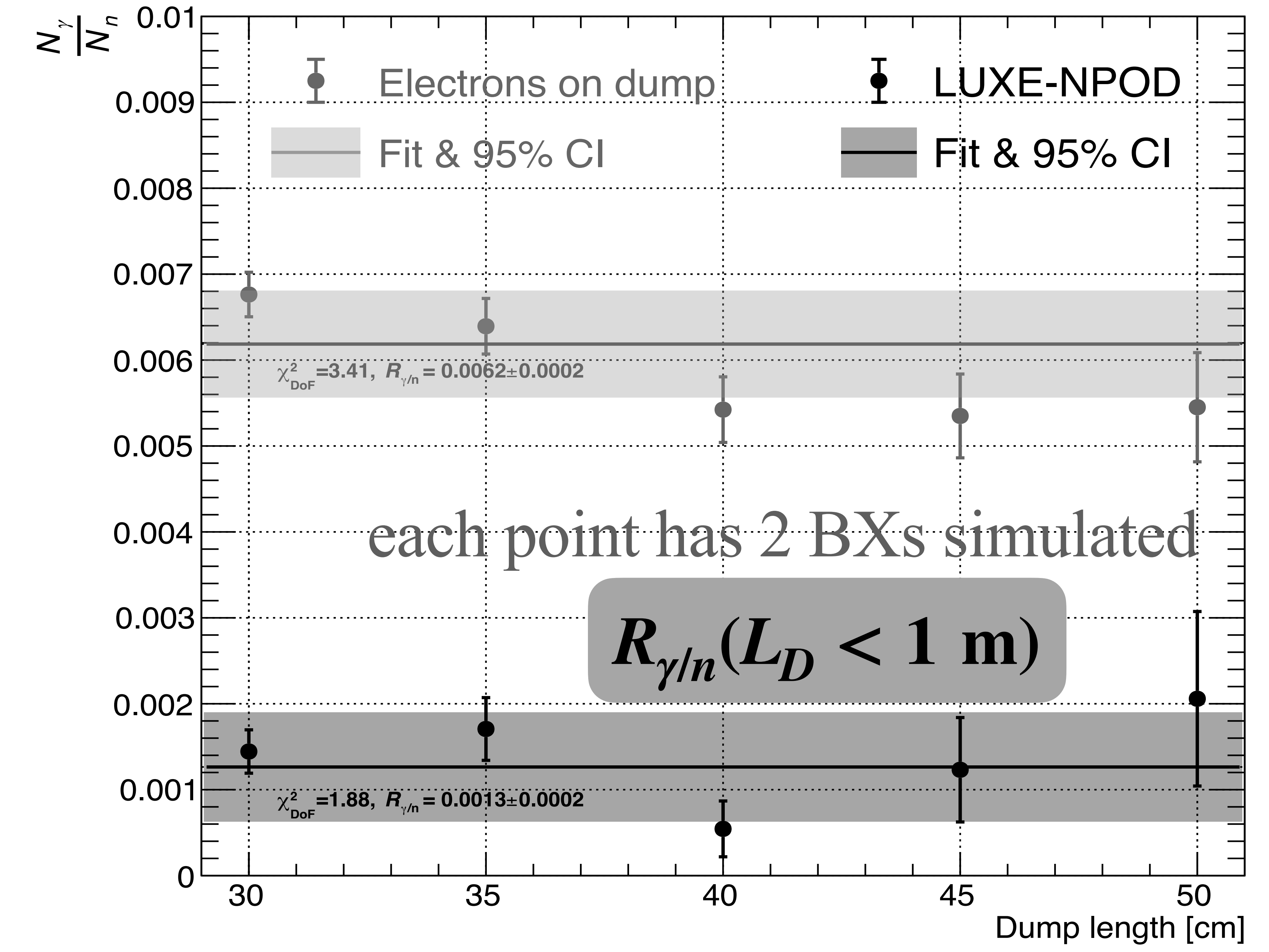
★ Way out: photon production is correlated with neutron production in hadronic processes

★ The number of photons can be estimated from the photons to neutron ratio at the shorter dump where there are more number of photons.

★$N_\gamma \sim N_n(L_D = 1m) \times R_{\gamma/n}(L_D < 1m)$



Photon production is correlated with neutron



each point has 2 BXs simulated

$R_{\gamma/n}(L_D < 1\ \text{m})$

Total background count

Parameter	LUXE NPOD	Electrons on dump
$R_{\gamma/n}$ (fit)	0.0013	0.0062
μ_n (count)	9.8	42.6
μ_γ (extrap.)	0.013	0.264

- **Benchmark assumptions**
  - one year of phase-1 running with $T \sim 10^7$ live seconds (BXs)
  - rejection from kinematics & timing is $R_{\text{sel}} \lesssim 10^{-3} - 10^{-4}$
  - neutron-to-photon fake rate is $f_{n\to\gamma} \lesssim 10^{-3} - 10^{-4}$

- Number of bkg two-photon events is $\boldsymbol{N_{\text{bkg}} = T_{\text{operation}} R_{\text{sel}} P_{\text{bkg}}}$

$\text{bkg} = 2\gamma$

$\text{bkg} = 2n \to 2\gamma$

$\text{bkg} = \gamma + n \to 2\gamma$

- The probabilities are given by Poisson and Binomial laws:

$$P_{N_\gamma} = \frac{\mu_\gamma^{N_\gamma} e^{-\mu_\gamma}}{N_\gamma!}$$

$$P_{N_n \to N_\gamma} = \sum_{k_n = N_n}^{\infty} \frac{\mu_n^{k_n} e^{-\mu_n}}{k_n!} \mathrm{B}(N_n, k_n, f_{n\to\gamma})$$

$$P_{n+\gamma\to 2\gamma} = P_{1n\to 1\gamma} \cdot P_{1\gamma}$$

Max N_{bkg}	LUXE NPOD	Electrons on dump
$N_{2\gamma}$	0.4	133.9
N_{2n}	0.1	1.1
N_γ	0.3	21.1

$N_{\text{bkg}}^{\text{tot}} < 1$ $N_{\text{bkg}}^{\text{tot}} > 156$

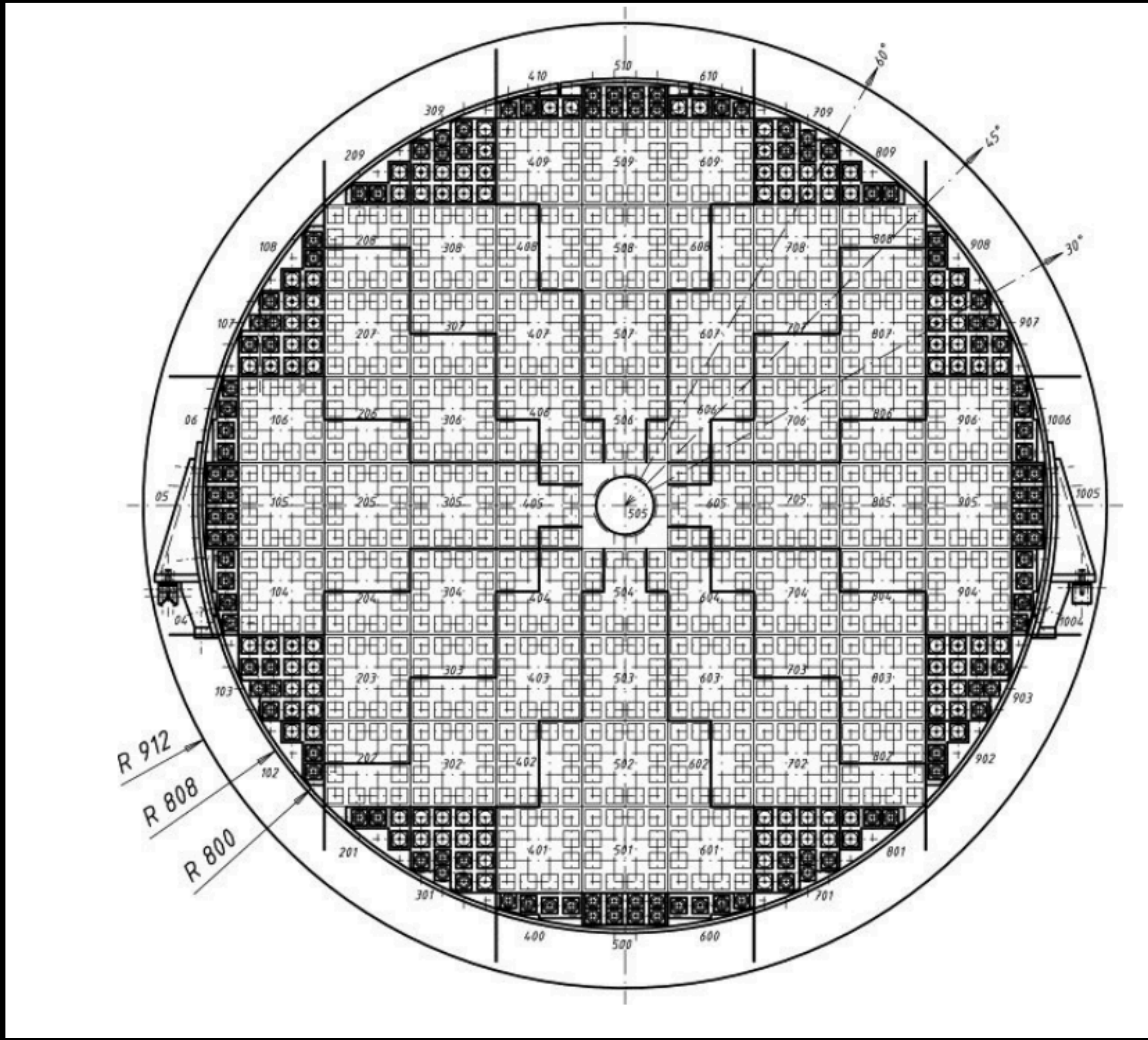
Detector proposal

- Physics goal of the detector:
  - Signal efficiency
    - Photon shower separation (~2 cm)
  - Precise reconstruction of ALP invariant mass
    - Good resolution of photon direction and energy
  - Background suppression
    - Vertex resolution to reject non-resonant photons
    - Shower shape determination
    - Good time resolution (<1 ns) to reject neutrons
- Proposal:
  - Phase-0:
    - H1 lead-scintillating-fiber calorimeter.
    - 4x4x25 cm^3 cells
    - Energy resolution $7.5\,\%/\sqrt{E} + 2\,\%$
    - Time resolution < 1 ns.
  - Phase-1:
    - Tracking calorimeter like HGCAL followed by an existing crystal or SpaCal ECAL to get the full energy.

"Ideal" EMCal req.:

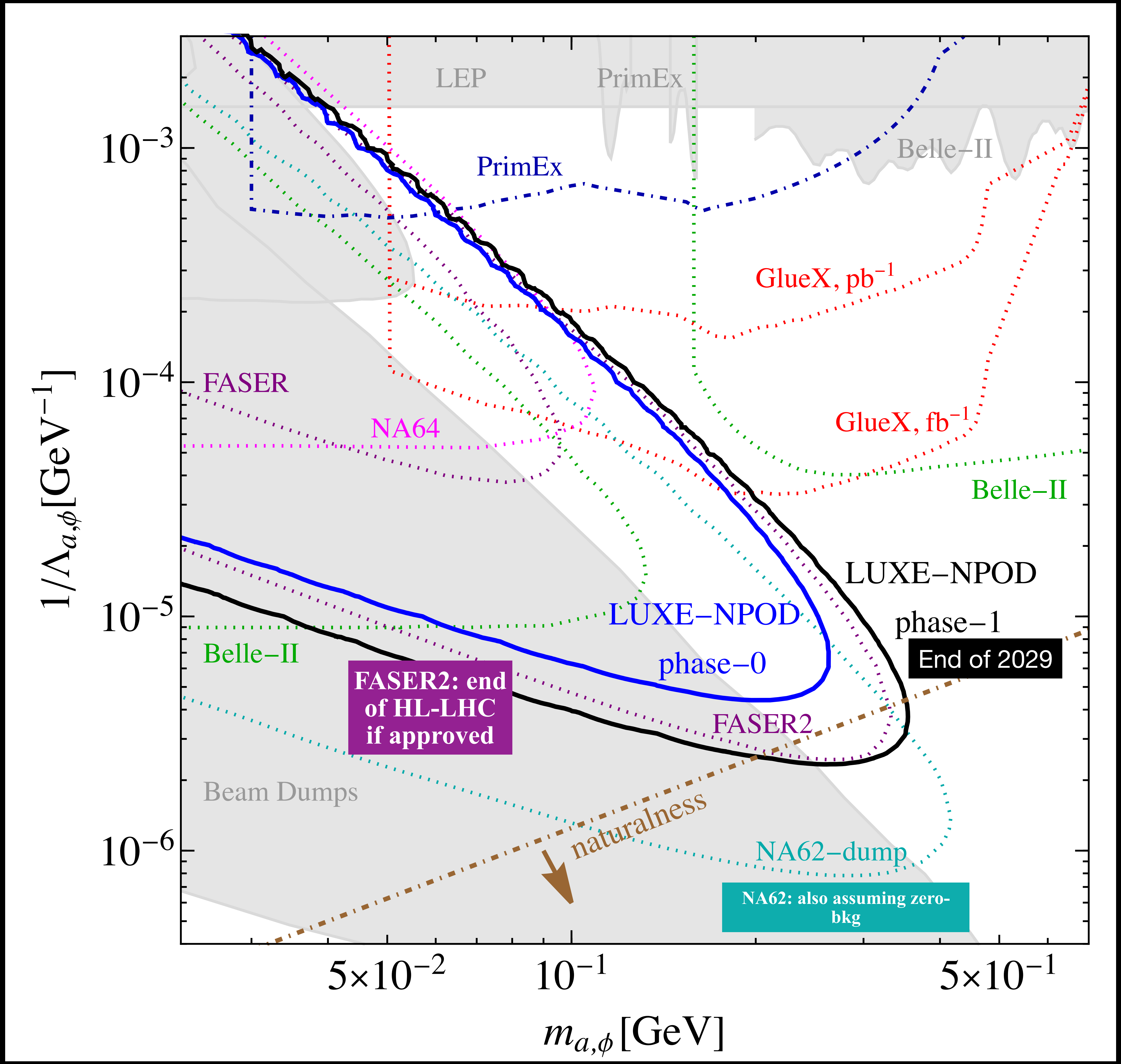
- $E_\gamma > 0.5$ GeV
- $\sigma_t \sim \mathcal{O}(100\text{ ps})$
- $\sigma_r \sim \mathcal{O}(100\ \mu\text{m})$
- $\sigma_\theta \sim \mathcal{O}(10\text{ mrad})$

10.1016/j.cpc.2010.02.004



Summary

- LUXE is a new experiment with baseline plan of testing strong field QED.
    - Regions never been explored in a clean environment.
    - Plan to start taking data by 2026.
- Search for new physics
    - Using optical dump feature of this experiment
    - Proposal is easily added to the experiment with essential background free search.
- The reach of LUXE is comparable with NA62 and FASER2.
    - LUXE reach in the mass 40 MeV to 350 MeV above $1/\Lambda > 10^{-6}$ GeV^{-1}.



Setting the number of observed signal-like events to $N_a = 3$, the 95 % CL equivalent for background free search

9 countries
22 institutes

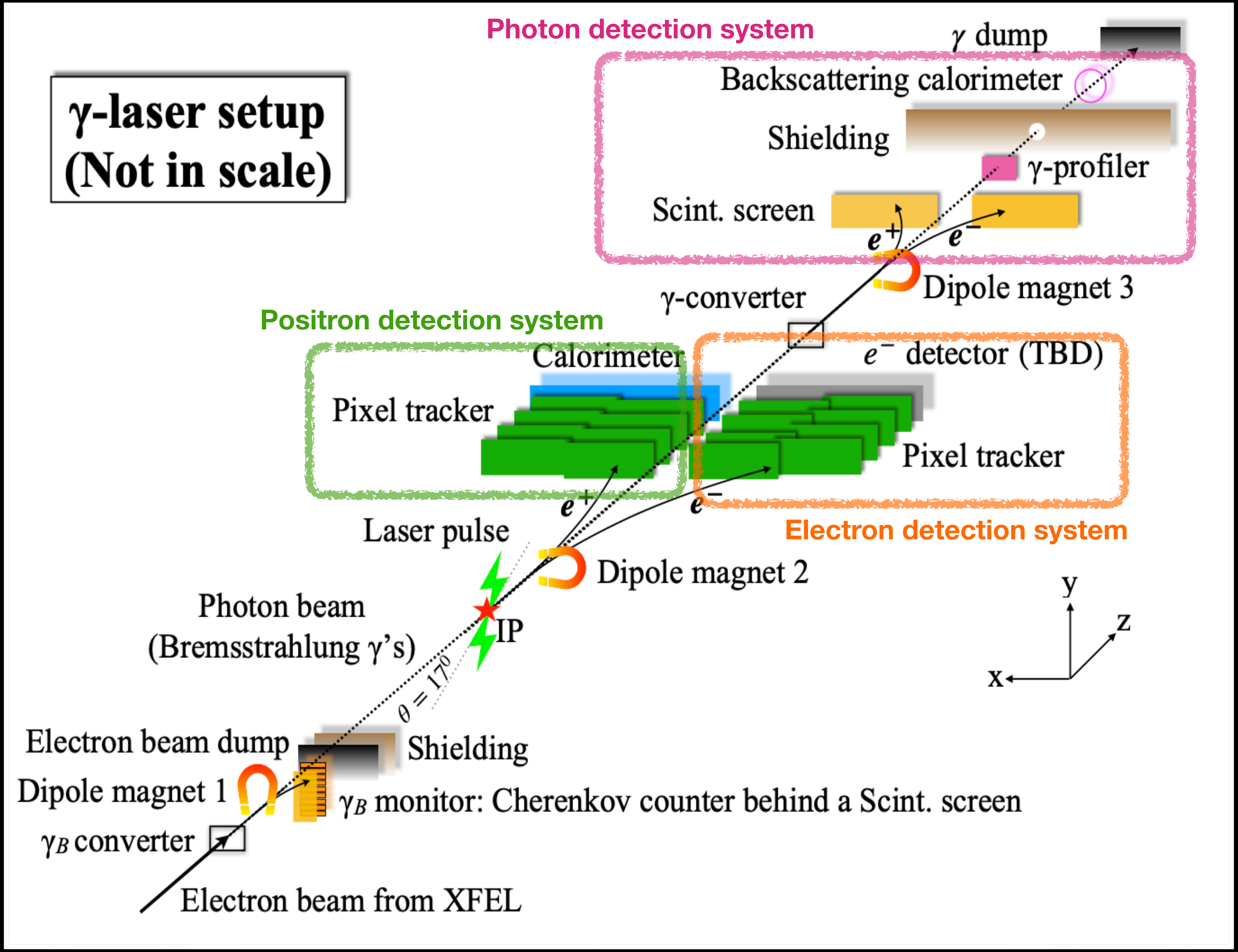
	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
LUXE	Design & Approval		Installation (in EuXFEL shutdowns)			Operation				

Thank you!

Back up

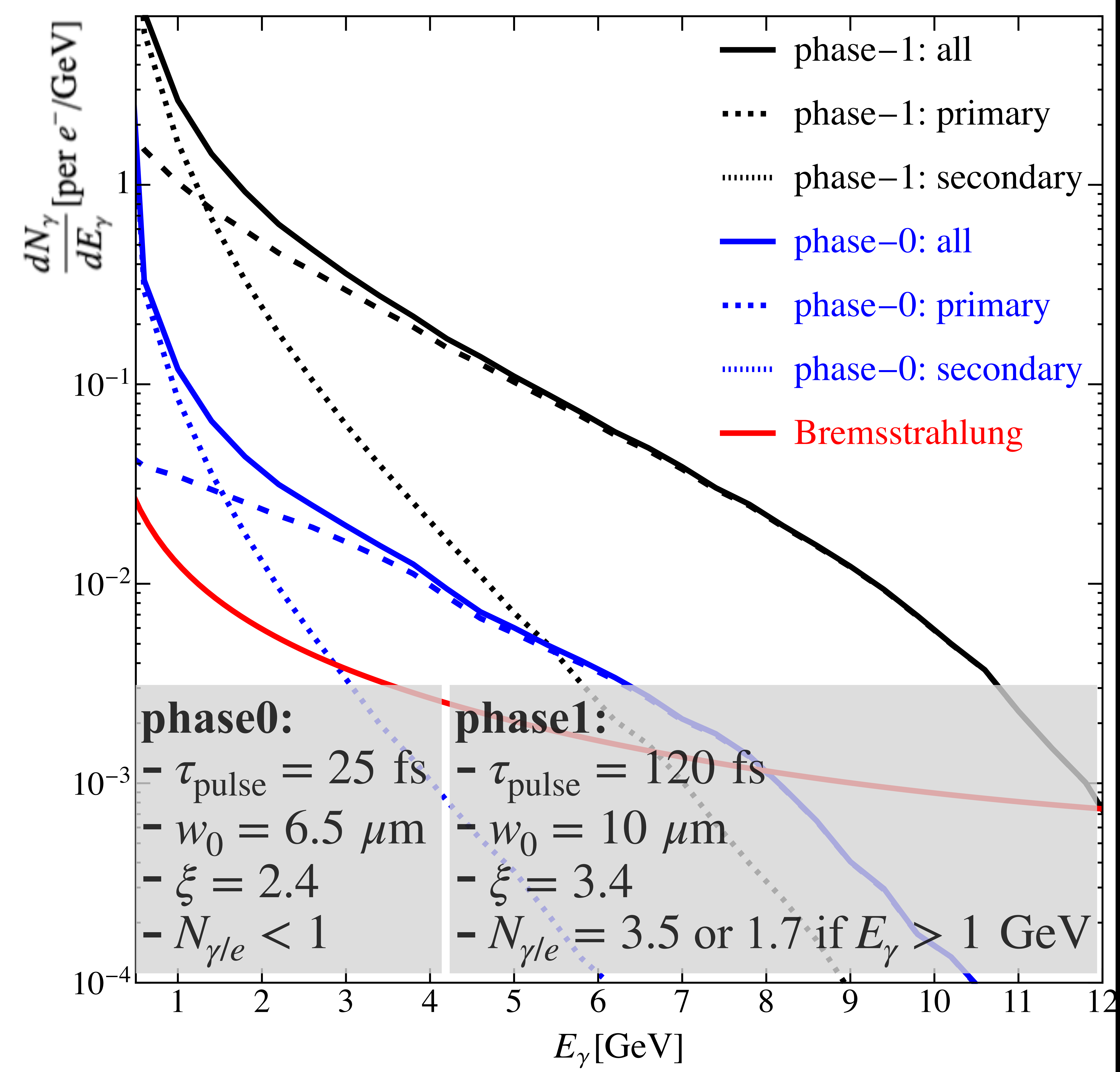
LUXE

γ+laser setup



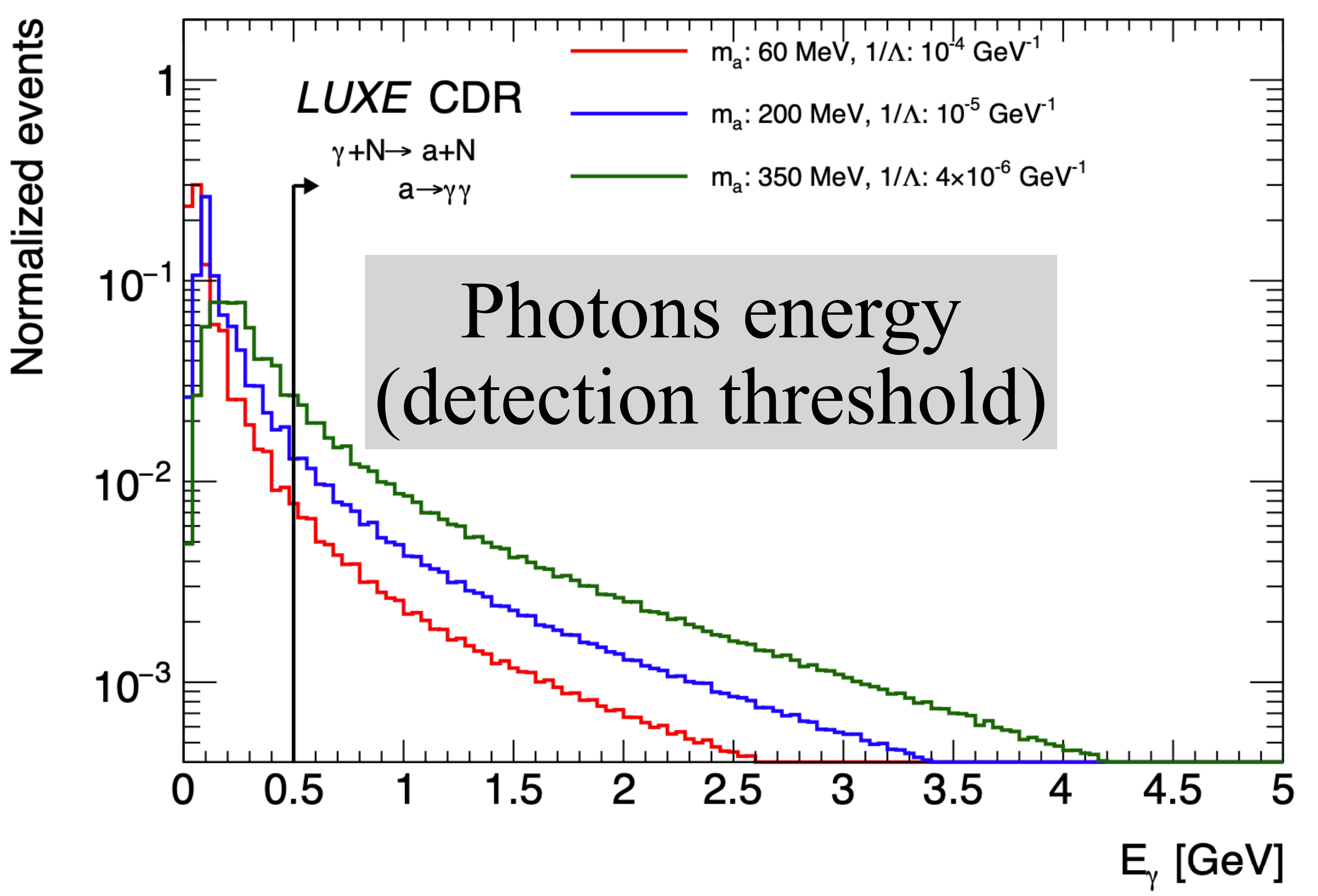
Photon spectra for ALPs production

- Spectra of photons per initial electrons
  - Primary photons from the interaction point
  - Secondary photons from the shower in the dump
- For phase I, there are many photons per initial electron
  - ~3.5 photons for $E_\gamma > 0$ GeV
  - ~1.7 photons for $E_\gamma > 1$ GeV
- More photons if the electron beam is sent directly to the dump
  - More signal, but at the cost of much more background.

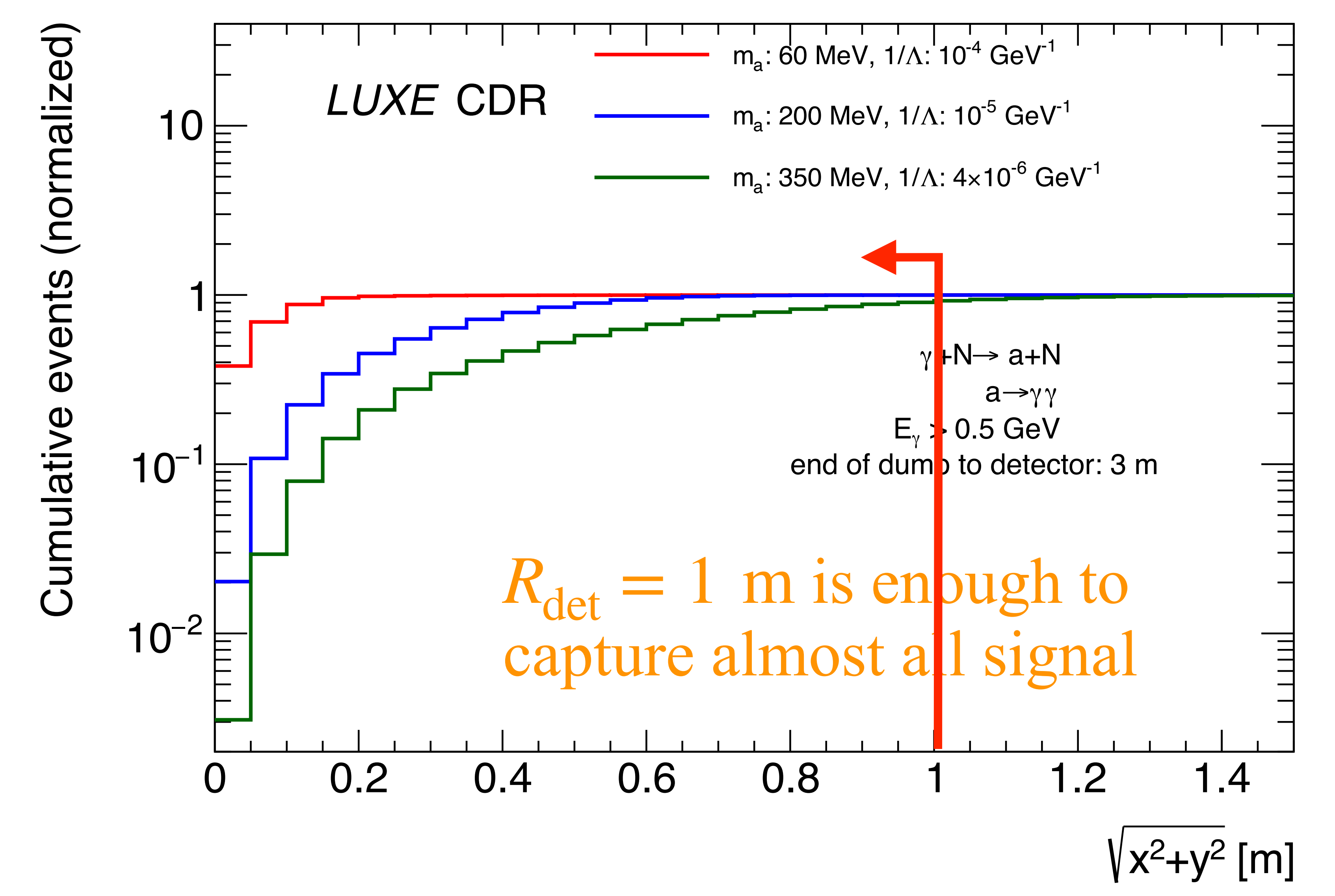


Kinematics: Signal

(Full MadGraph sim different colored curves showing different signals)



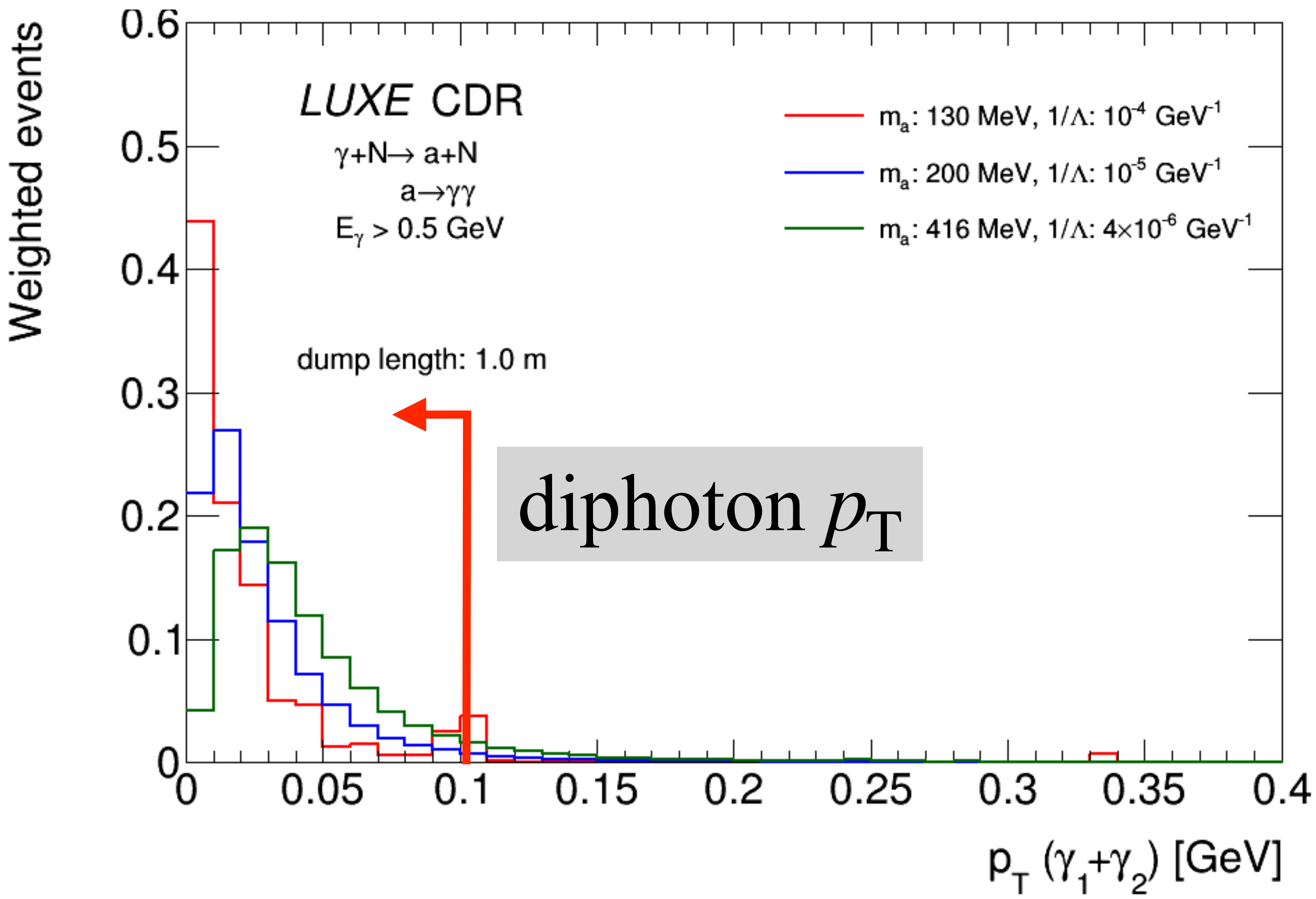
Photons energy (detection threshold)



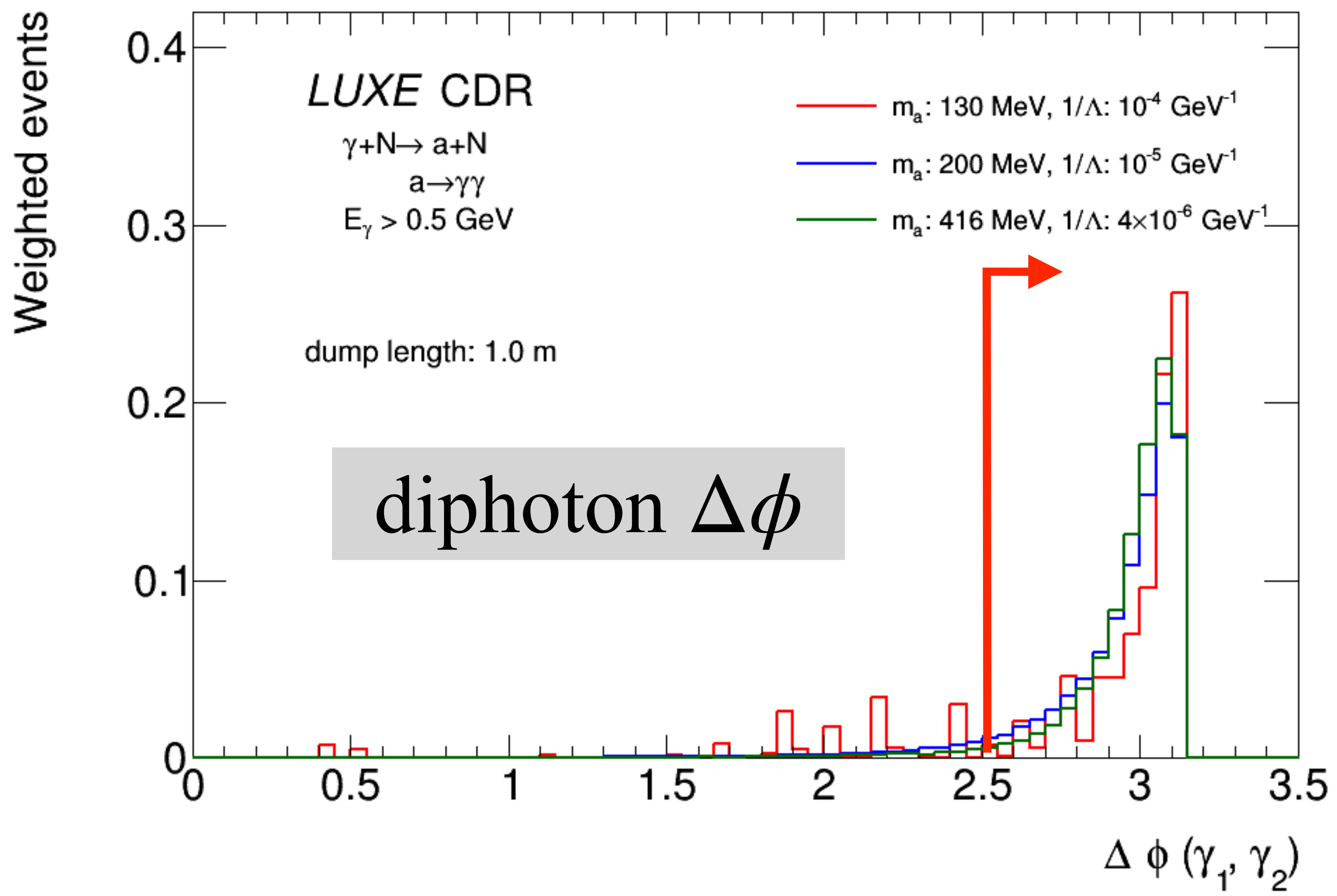
$R_{\text{det}} = 1$ m is enough to capture almost all signal

Cuts to improve significance?

- back-to back in x-y
- low diphoton p_T
- common vertex
- diphoton mass



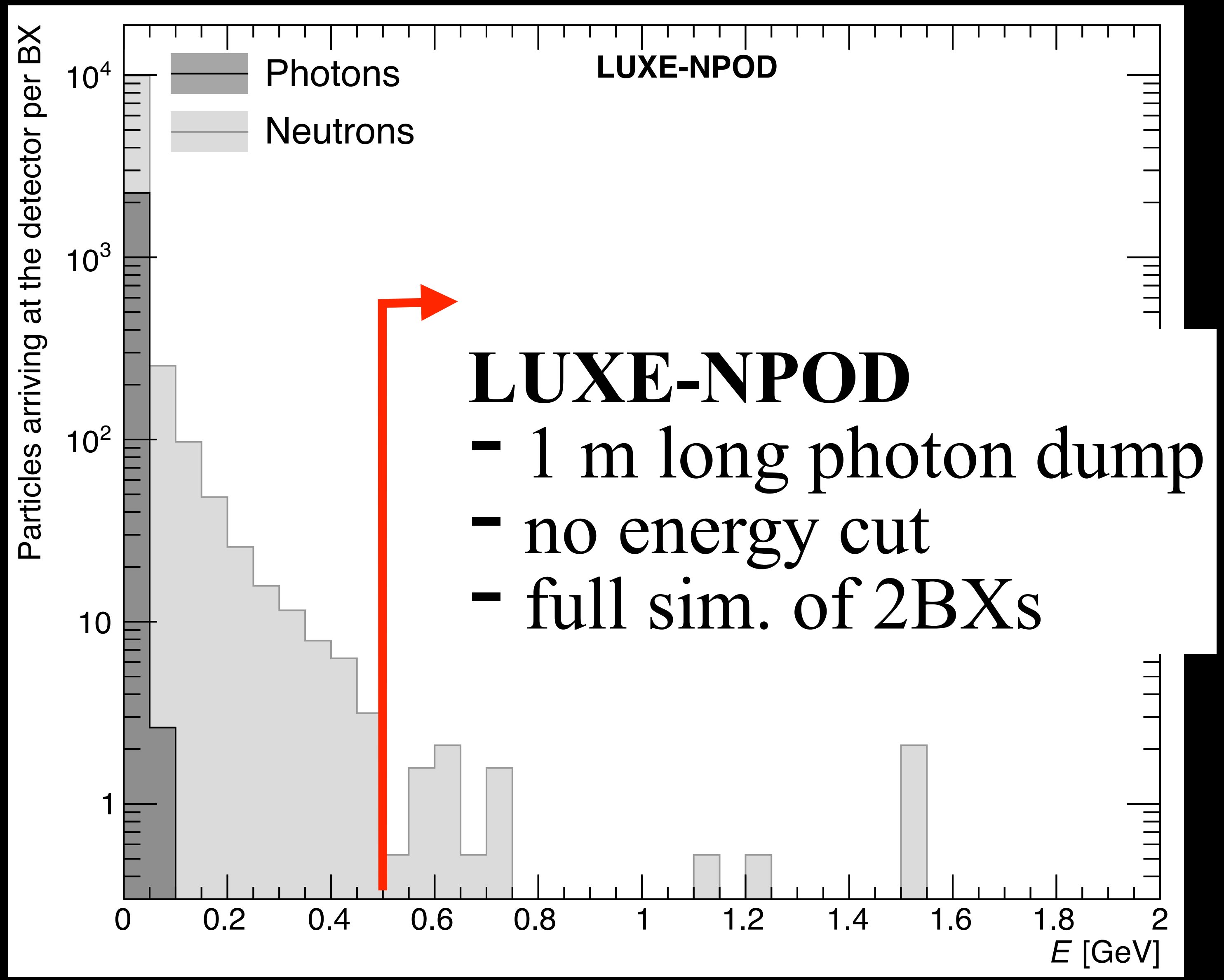
diphoton p_T



diphoton $\Delta\phi$

Fake photons from neutrons

- Most neutrons are very soft: one needs a few ~GeV neutron to fake a 0.5 GeV photon

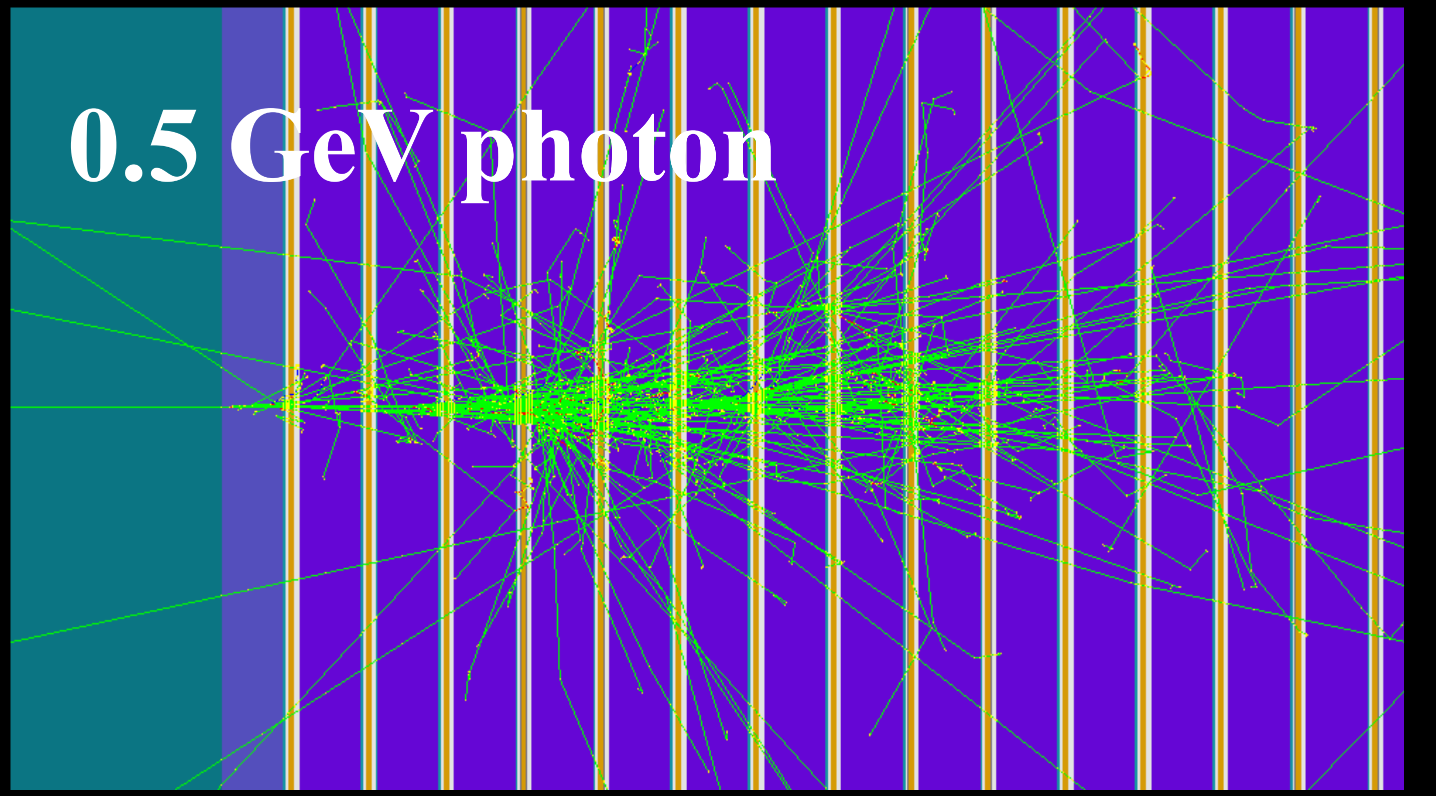


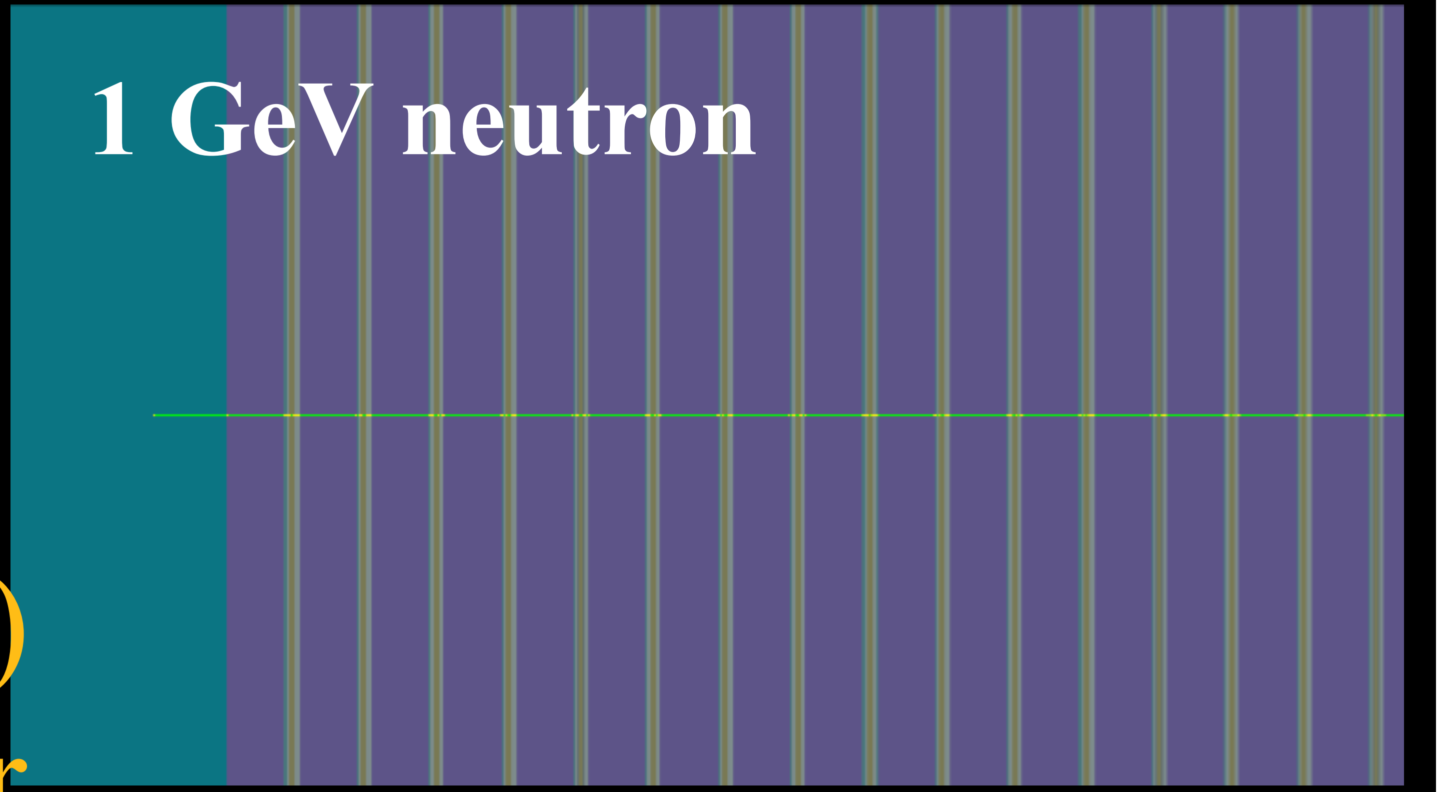
LUXE-NPOD
- 1 m long photon dump
- no energy cut
- full sim. of 2BXs

- Very different shower shapes (γ vs n)
  - hard neutrons become more similar

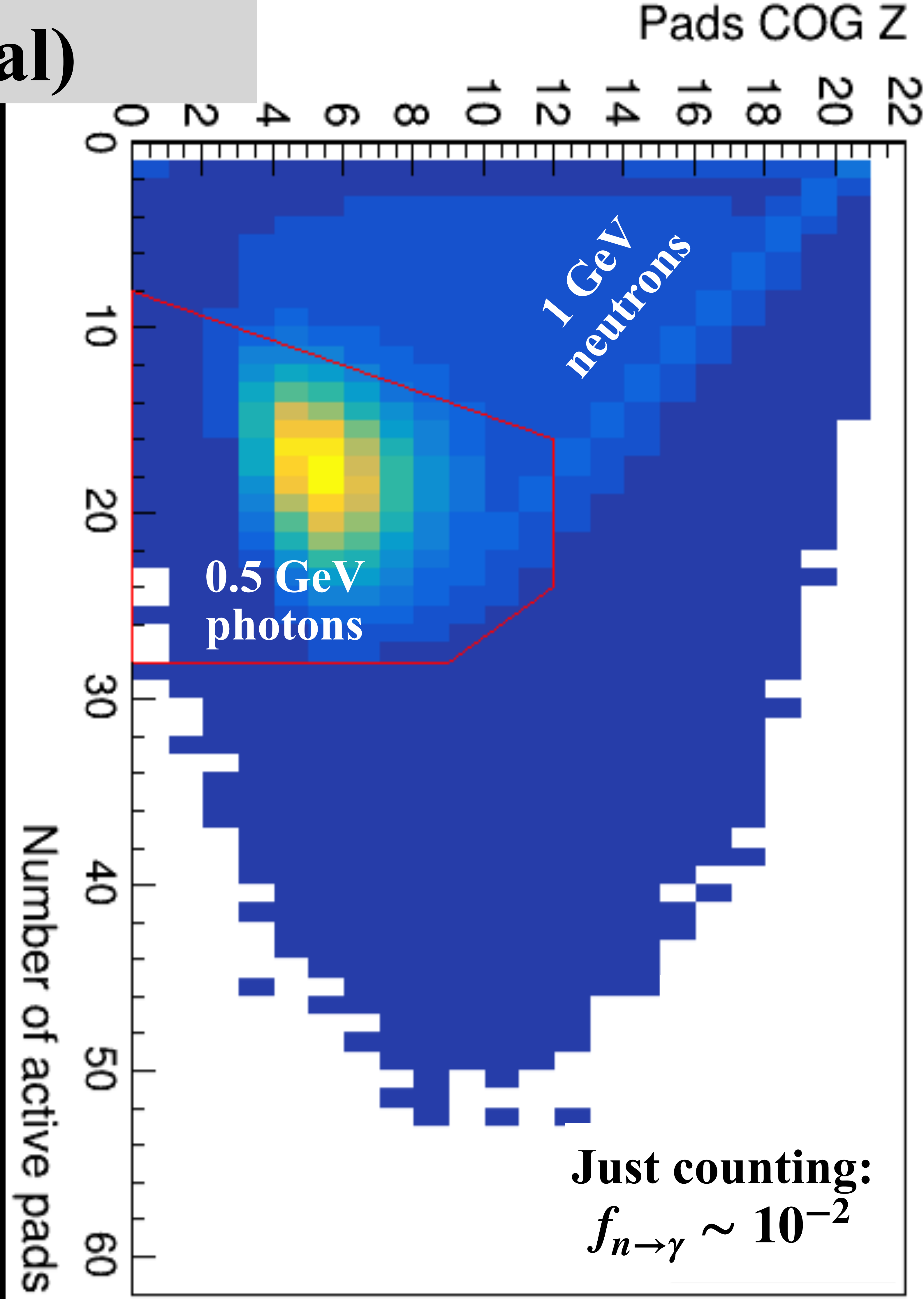
- Study done by **Sasha Borysov**

sampling calorimeter (A proposal)



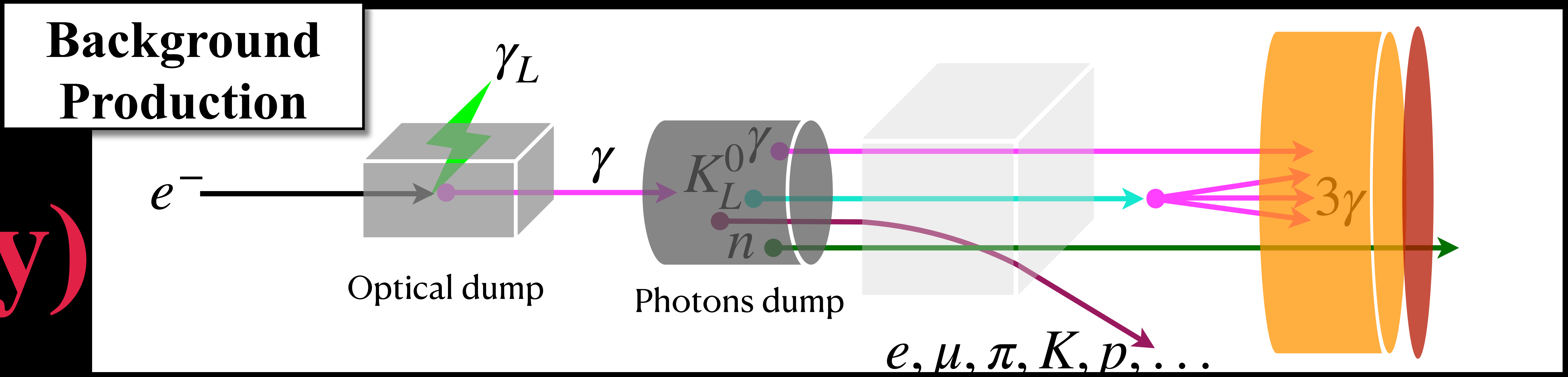


~20 layers of silicon sensors with $\sim 5 \times 5$ mm^2 pads, between tungsten plates

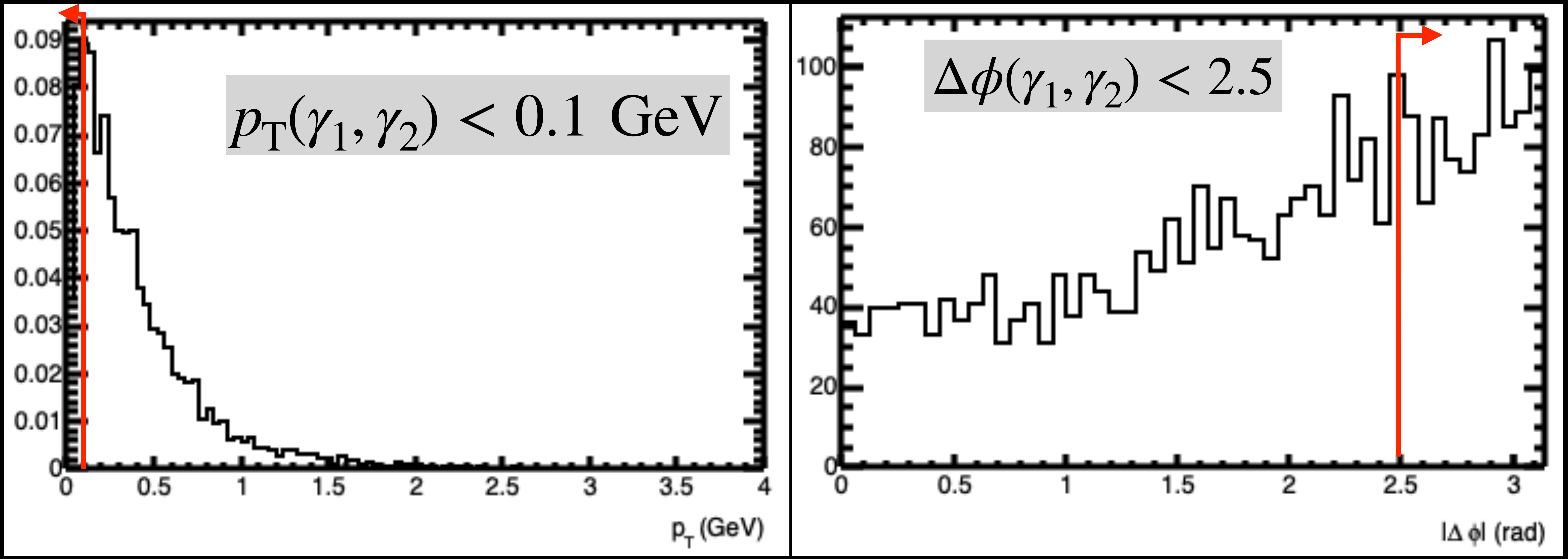


Just counting: $f_{n\to\gamma} \sim 10^{-2}$

Kinematics: Background (Toy)



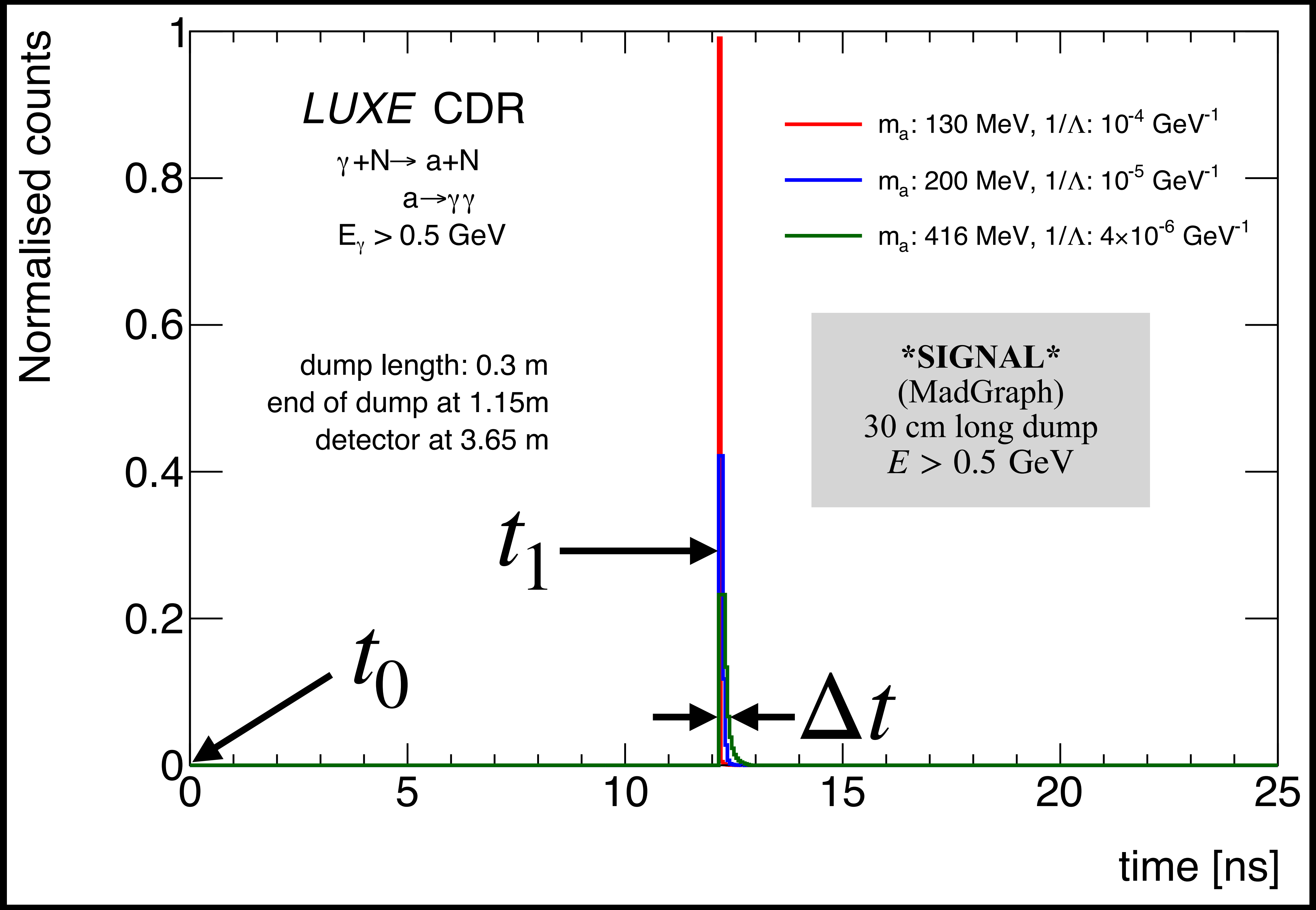
- Two-photon toy background
- Exponentially falling energy distribution (good approximation)
- Flat R distributions and ϕ (good approximation)
- Polar angle (θ) calculated from R, and smeared by ±20 mrad (SplitCal of SHiP)

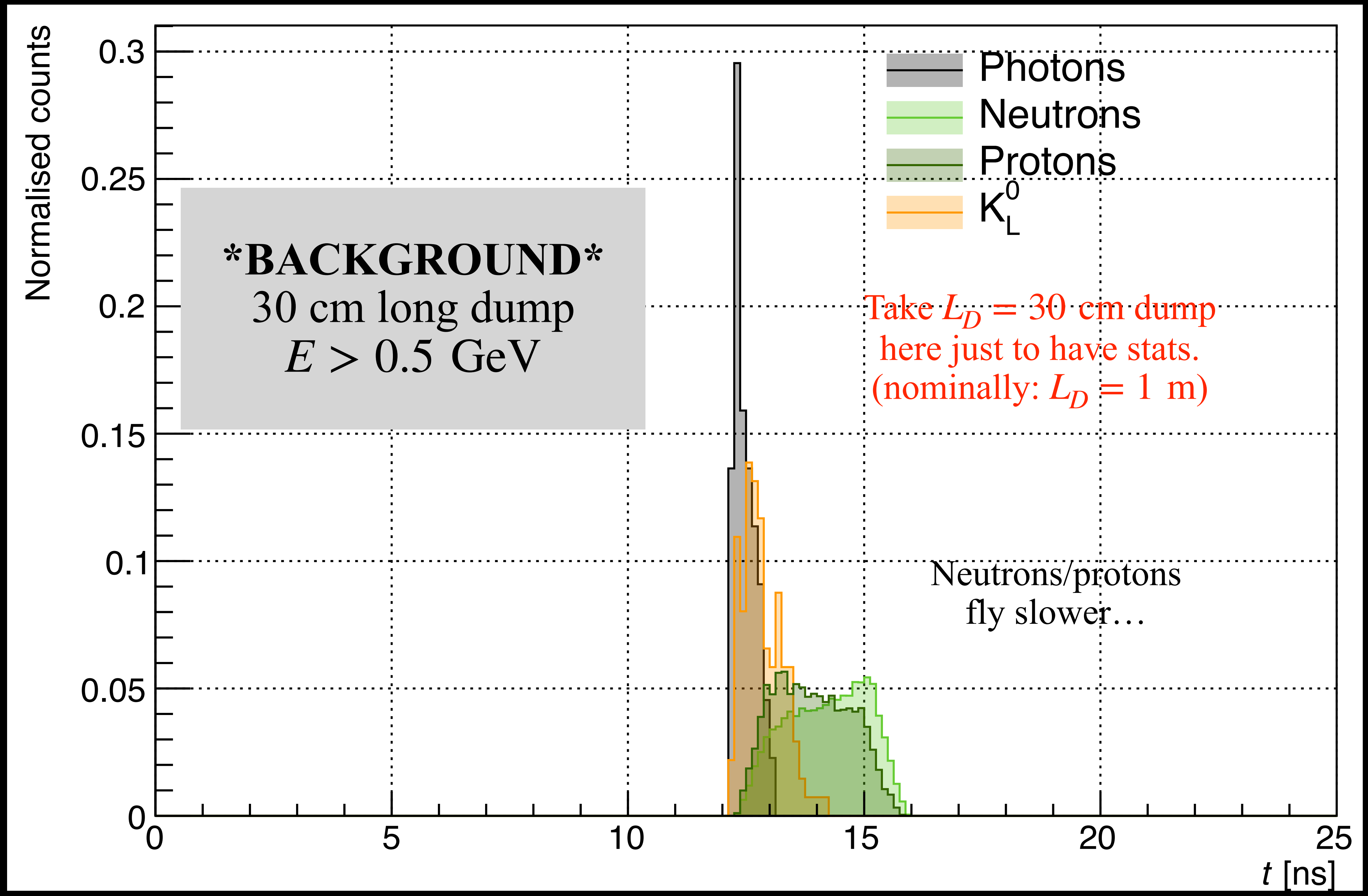


- Rejection better than 10^{-3} is well achievable

Plots by Beate Heinemann

Use of timing information



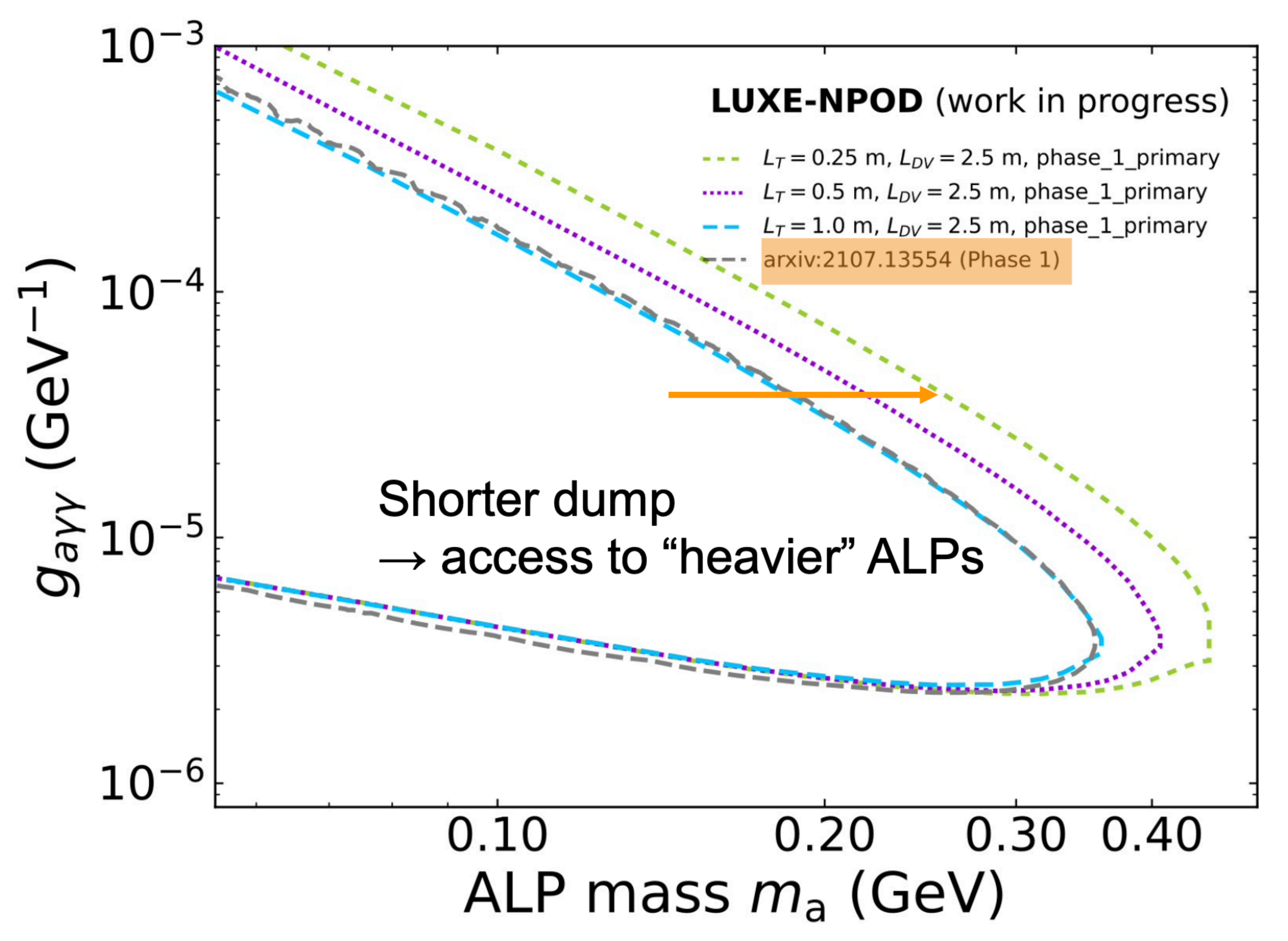


- ★Signal and background particles take different time to travel the distance between the dump and the detector face.
  - ★Signal ALPs are faster than background neutrons/protons.
- ★Trigger at t_0 (Eu.XFEL clock) and then open a short time window Δt.
  - ★Most signal and background photons will arrive within $\Delta t \sim 0.5$ ns
  - ★Almost all hadrons will arrive after that.

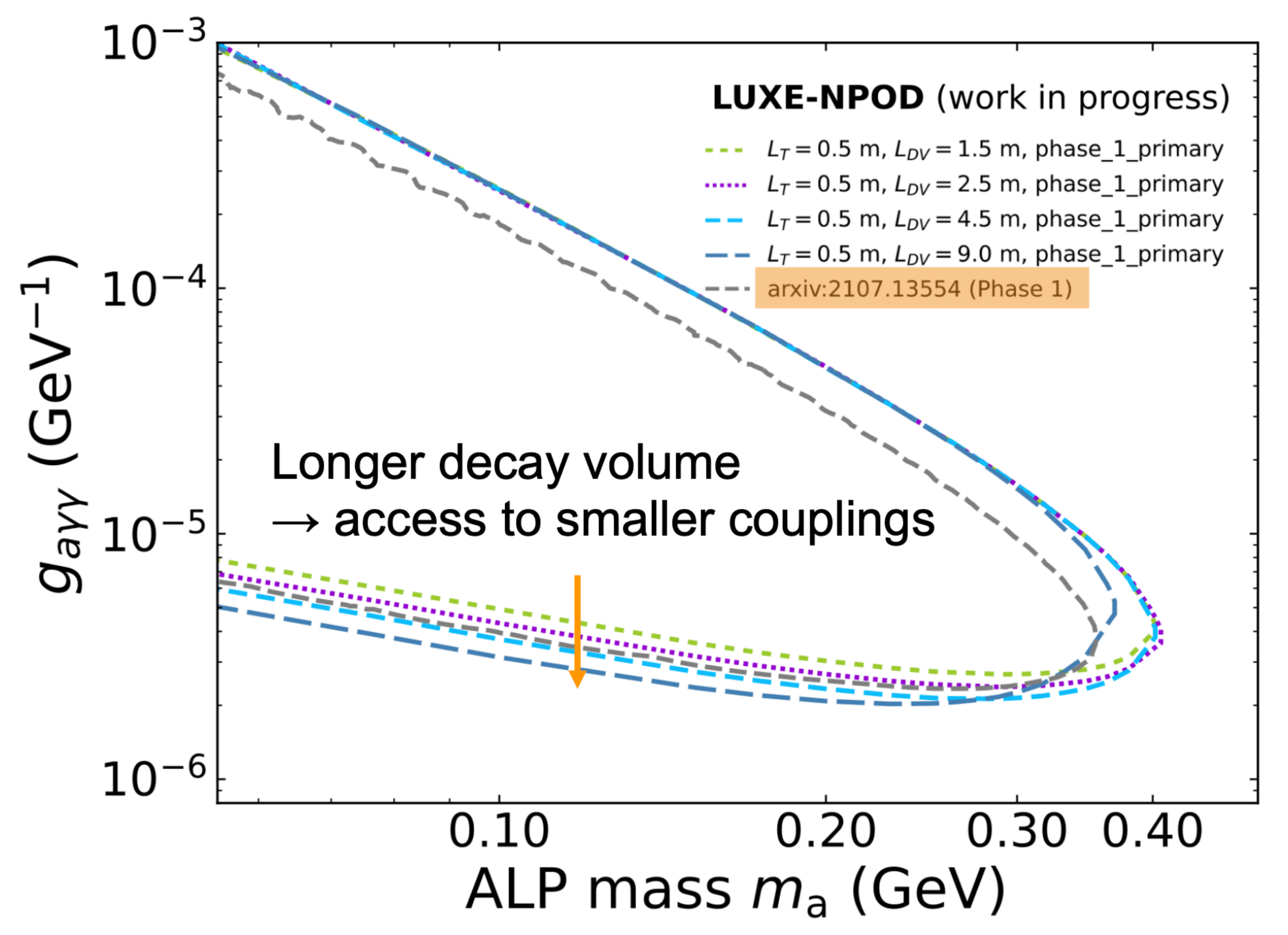
	Background rejection ~[%]				**Signal efficiency [%] for m_a:1/Λ_a**		
Δt [ns]	**γ**	**n**	**p**	**K_L**	**130:1e-4**	**200:e-5**	**416:e-5**
0.1	57	99.9	99.9	87	99.6	84	46
0.5	16	96	94	52	100	100	99
1.0	0	80	70	13	100	100	100

$R_{\mathrm{sel}}^{\mathrm{neutrons}} \sim 10^{-3}$

Effect of dump length and decay volume:



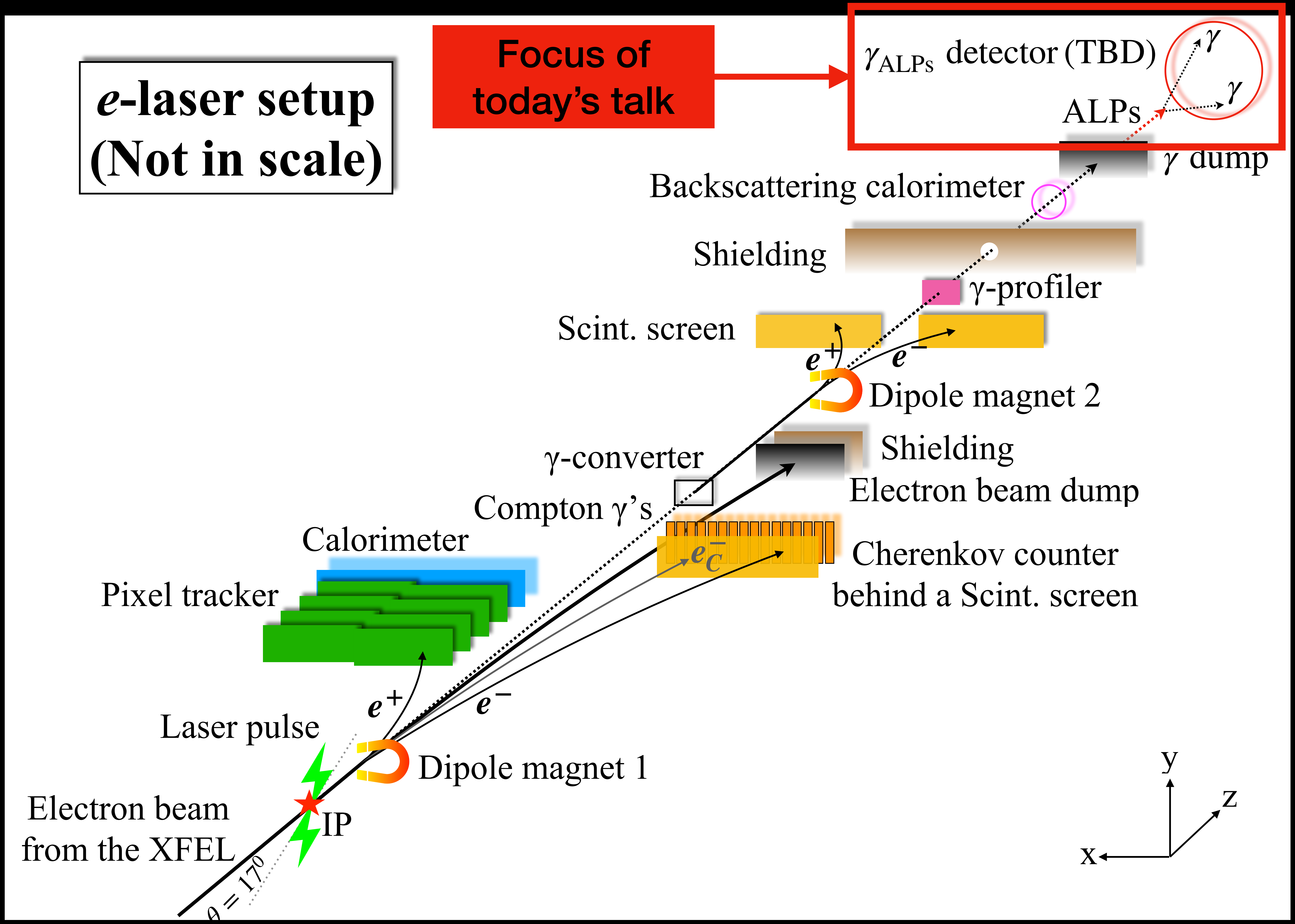
Shorter dump
→ access to “heavier” ALPs



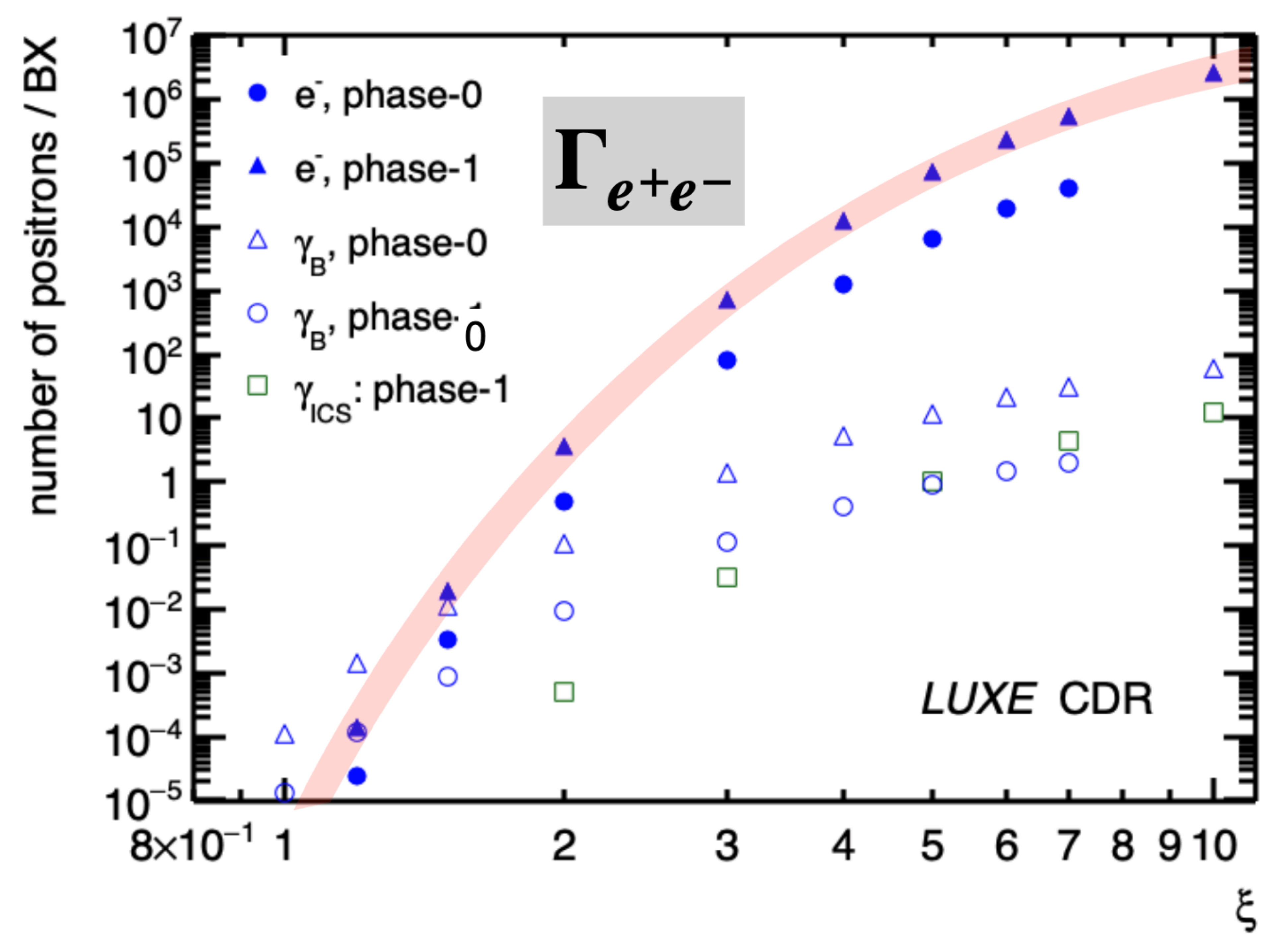
Longer decay volume
→ access to smaller couplings

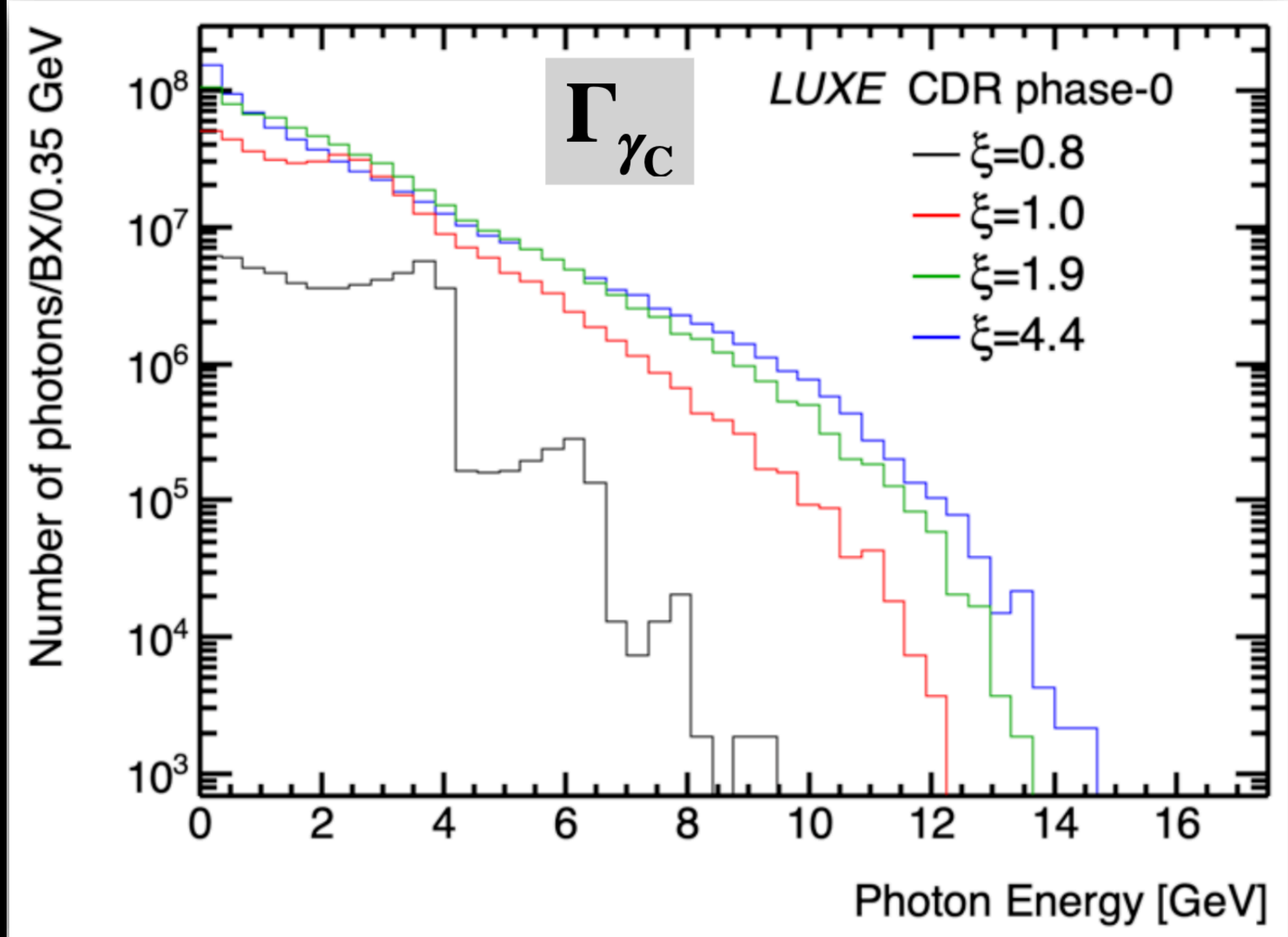
Assuming no background events.

Experimental setup

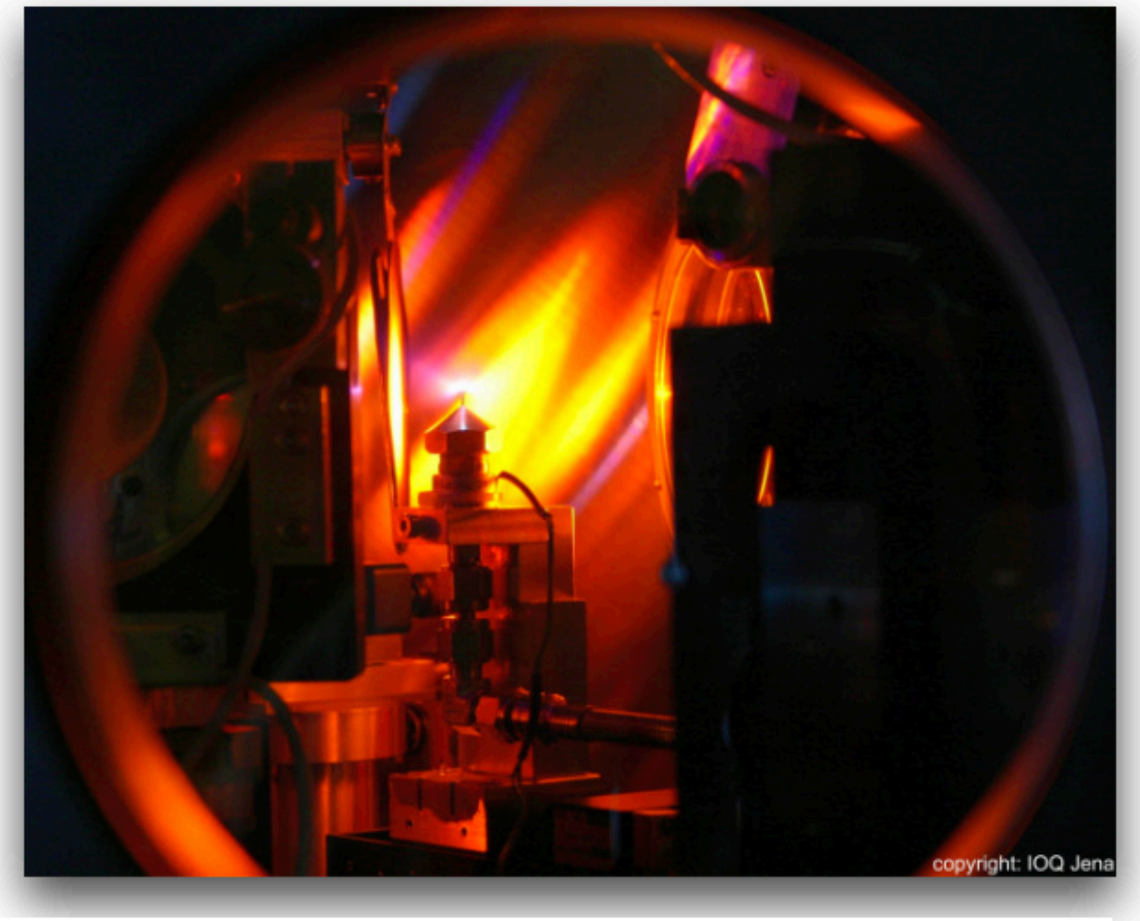


Focus of today's talk

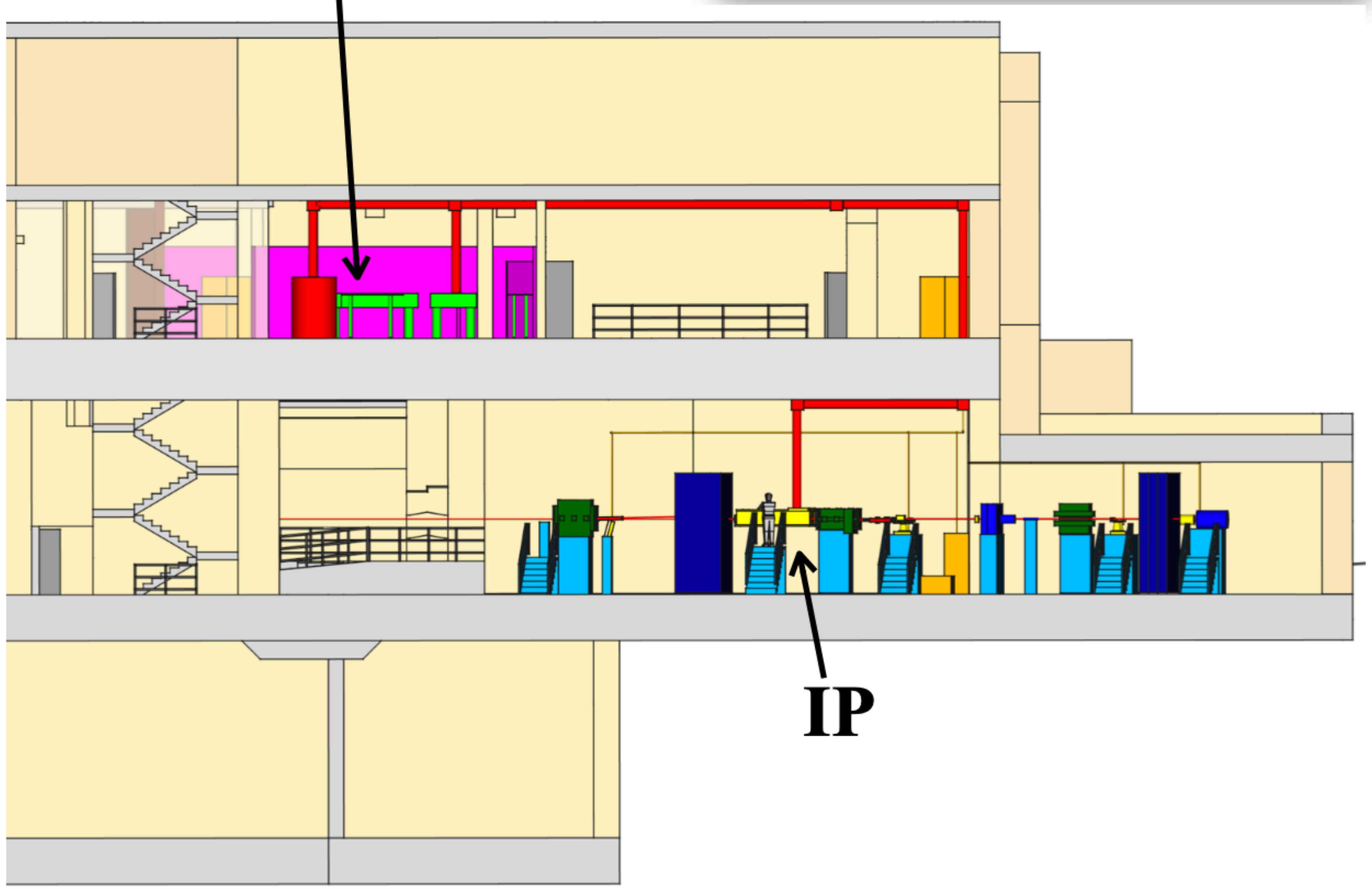




Laser


copyright: IOQ Jena

- Phase-I: the JETi40 40 TW laser loaned to LUXE by Helmholtz Institute Jena
- Phase-II: looking up towards a 350 TW laser with as small as $3\times3\ \mu\text{m}^2$ spot size
- Challenge: exact knowledge of the intensity at the IP
  - with the laser being ~10's of meters away from it
  - and with a remote diagnostics system



Laser diagnostics

- Measure laser parameters to infer the intensity, *I*
  - can be indirect and direct, relative and absolute

- Small fluctuations in *I* lead to large rate fluctuations
  - air movement, vibrations, temp-drift, pump discharge variations, etc.

- The laser beam will be attenuated and imaged on the return path to the diagnostics 10s of meters away from the IP

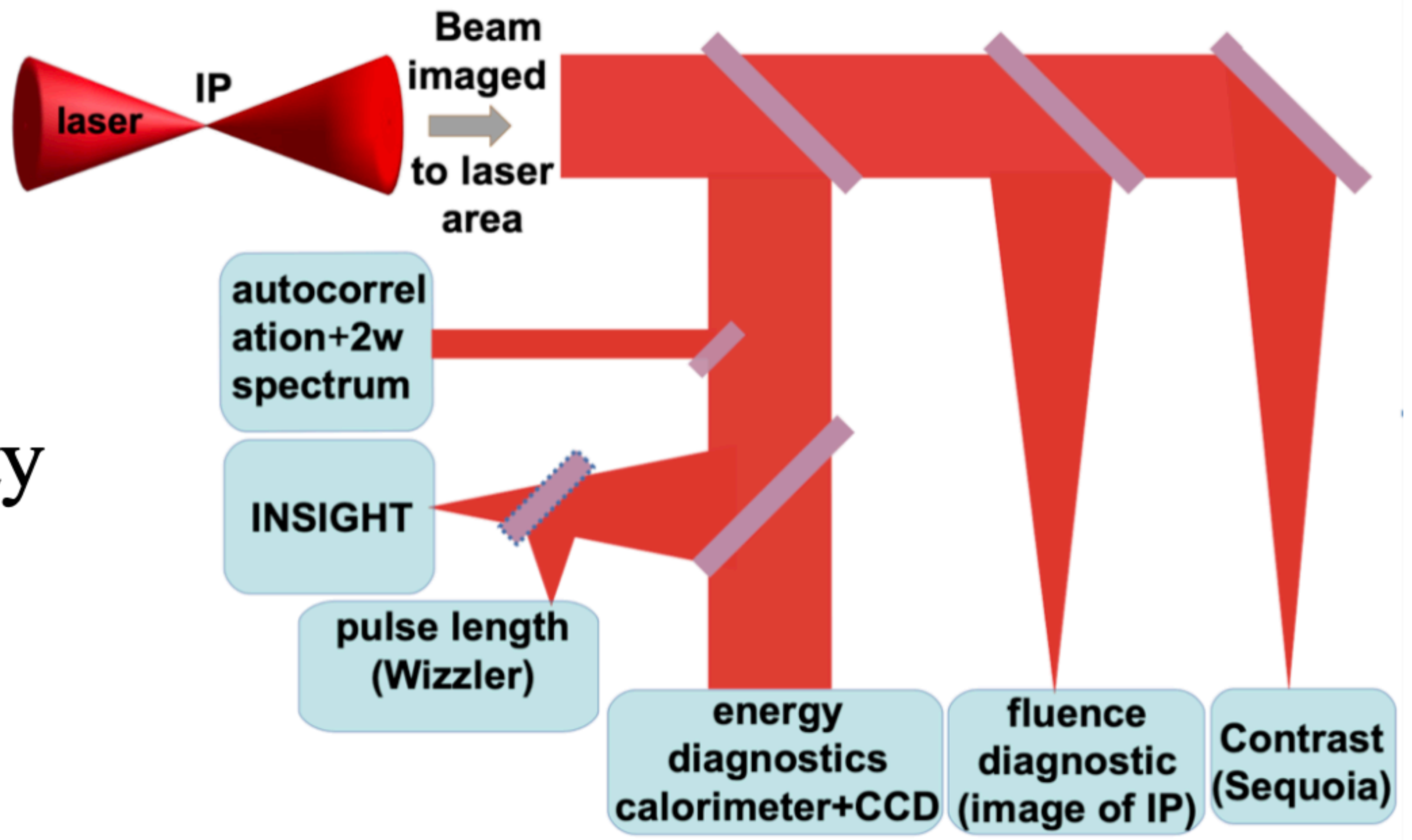
$$I = \frac{E}{A \times \tau}$$

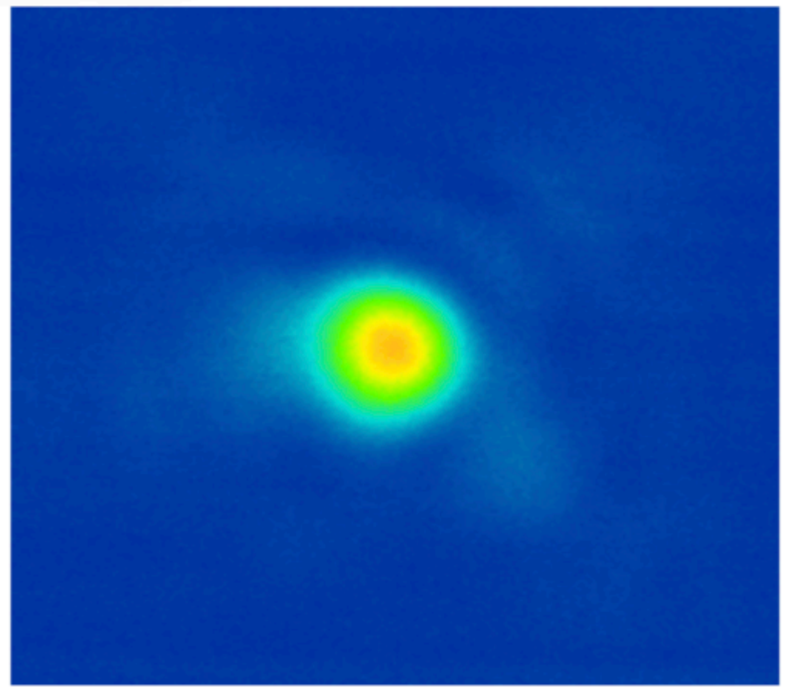
← pulse energy

← pulse spot size × duration

Diagnostics

- relative intensity
- pulse duration
- beam size





ALPs production

$$N_a \approx \mathscr{L}_{\text{eff}} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \sigma_a(E_\gamma, Z) \left(e^{-\frac{L_D}{L_a}} - e^{-\frac{L_V + L_D}{L_a}} \right) \mathscr{A} \qquad \mathscr{L}_{\text{eff}} = N_e N_{\text{BX}} \frac{9\rho_W X_0}{7A_W m_0}$$

$$L_a = c\tau_a \frac{p_a}{m_a}$$

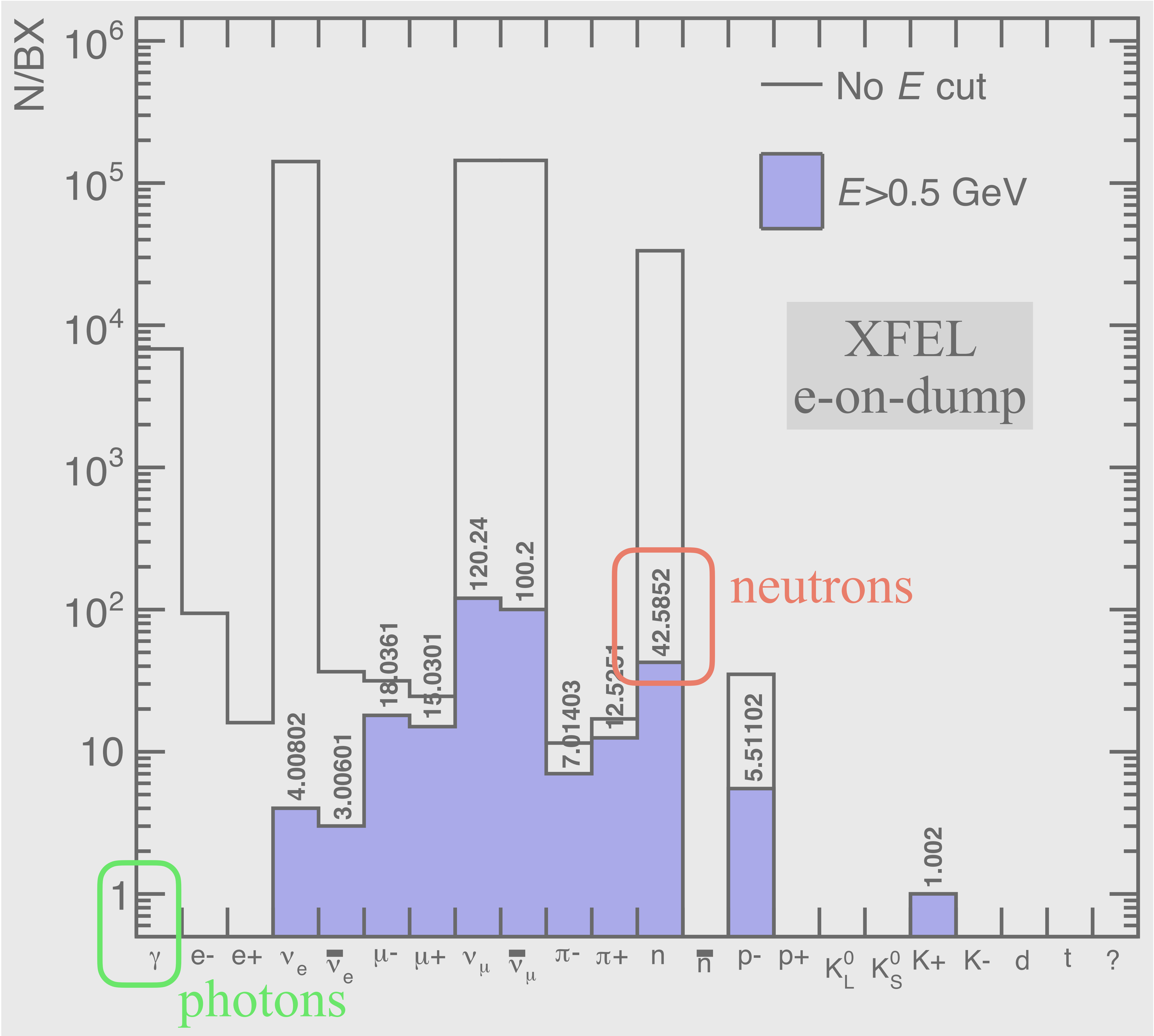
$$p_a \approx \sqrt{E_\gamma^2 - m_a^2}$$

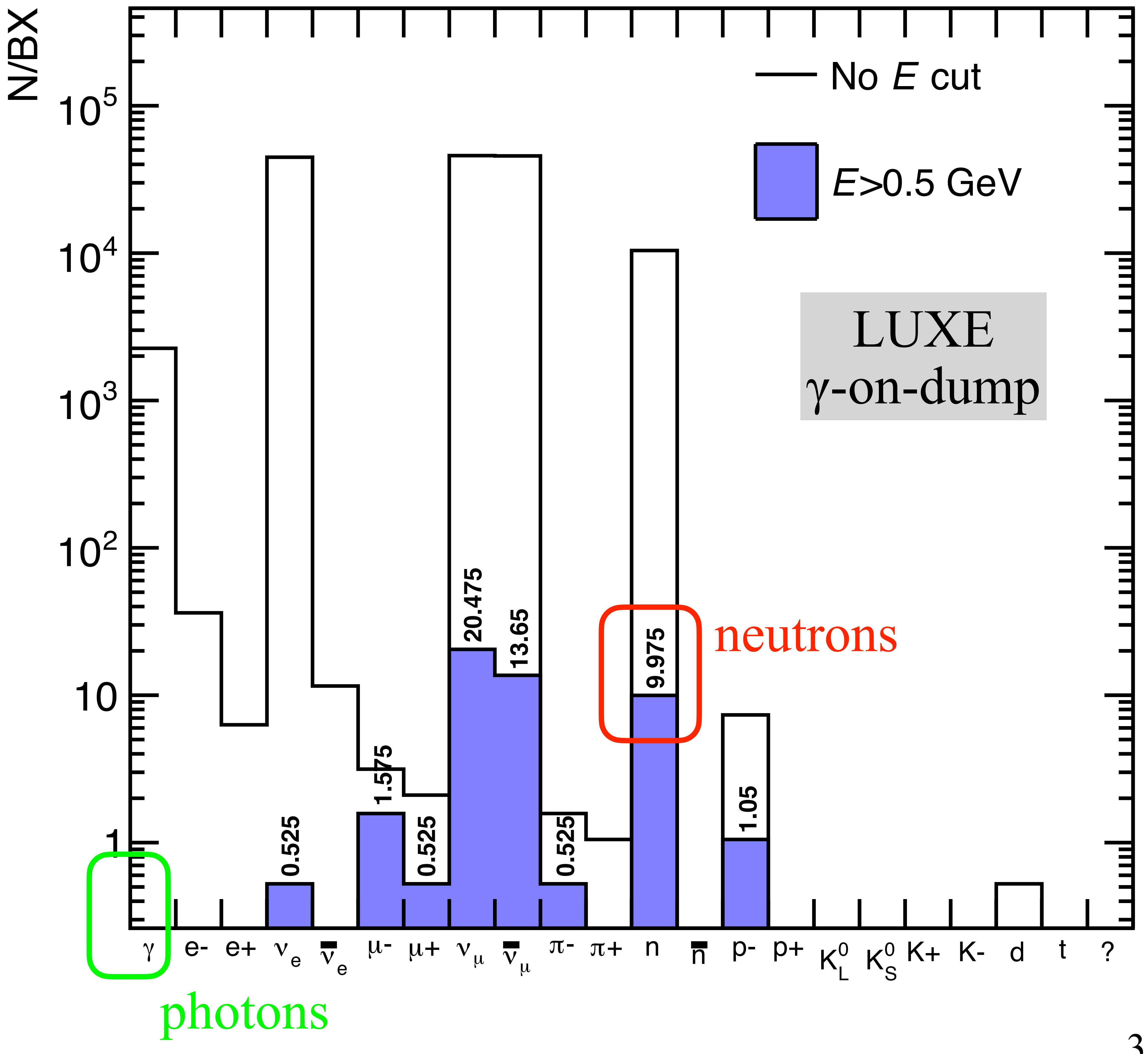
- $N_e = 1.5 \times 10^9$ is the number of electron per bunch and $N_{\text{BX}}(=10^7)$ is the number of BXs assumed
- E_γ is the incoming photon energy
- $\mathscr{L}_{\text{eff}}$ is the effective luminosity, where ρ_W is the Tungsten density, A_W is its mass number and X_0 is its radiation length. $m_0 \sim 930$ MeV is the nucleon mass
- L_a is the ALP propagation length, where τ_a is its proper lifetime and p_a is its momentum
- $\sigma_a(E_\gamma, Z)$ is the Primakoff production cross section of the ALP in the dump
- $\mathscr{A}$ is the angular acceptance times efficiency of the detector
- dN_γ/dE_γ is the differential photon flux per initial electron, includes photons from the electron-laser interaction, as well as secondary photons produced in the EM shower which develops in the dump
- $L_D = 1$ m is the dump's length. The dump is positioned ~13 m away from the electron-laser interaction region
- $L_V = 2.5$ m is the length of the decay volume
- The decay rate of the ALP into two photons is $\Gamma_{a\to\gamma\gamma} = m_a^3/(64\pi\Lambda_a^2)$

From Noam Tal Hod, WIS

Particles from e/γ-beam on 1m W dump

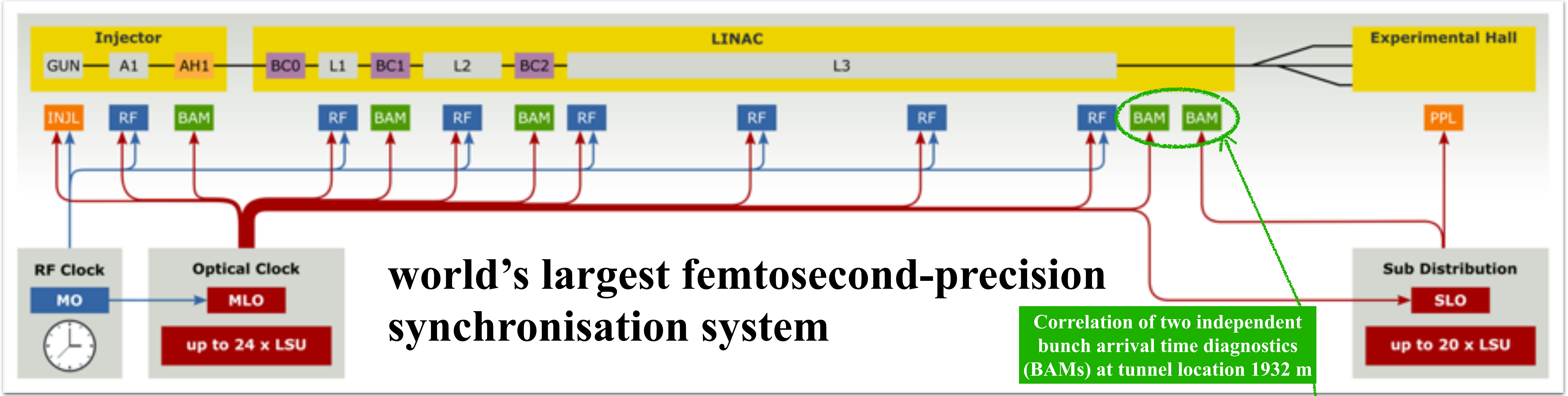
Each simulation in the following is equivalent to about 2 BXs (i.e. 3e9 primary e's)
Showing the number of particles - only those which arrive at the detector surface





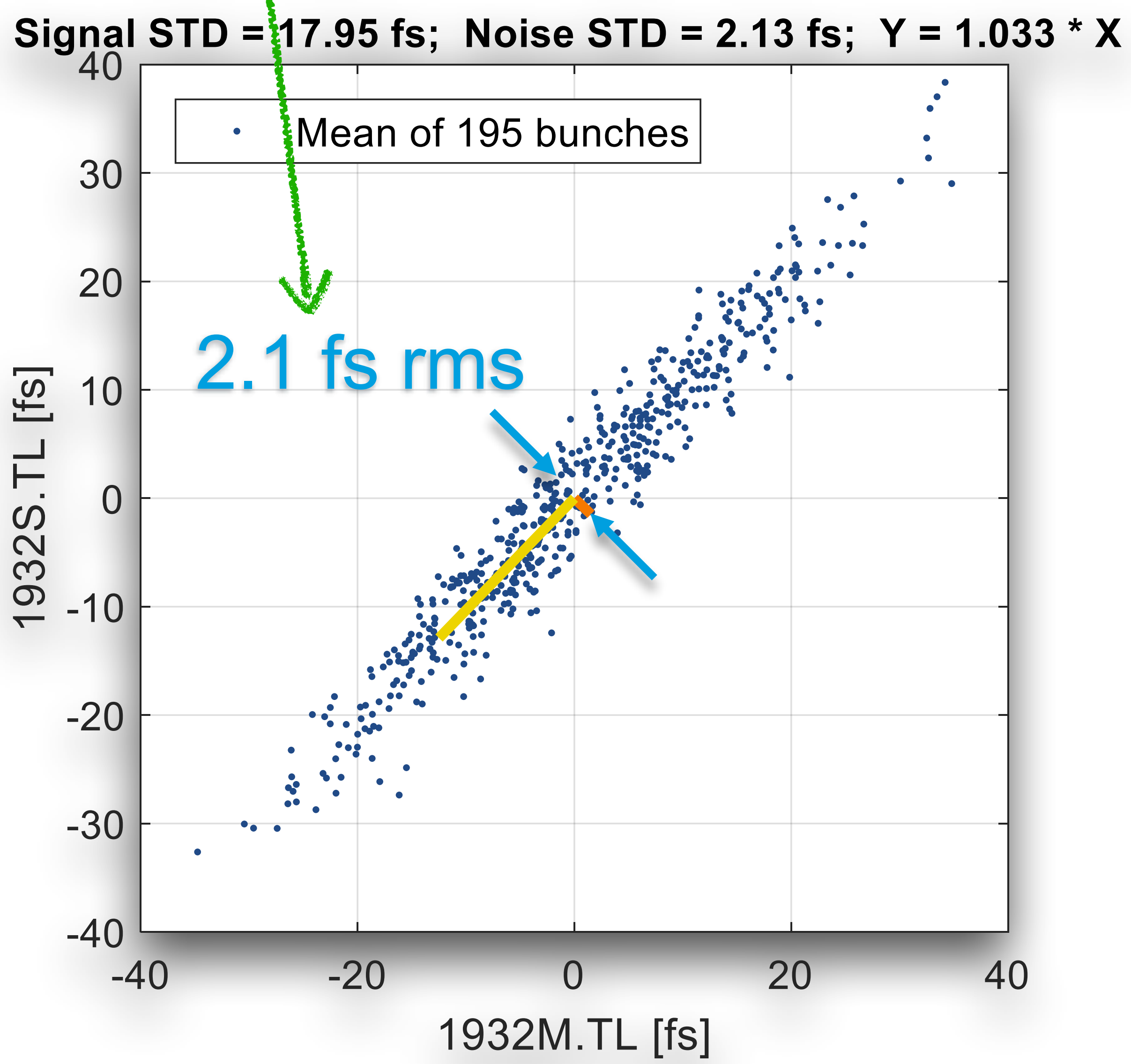
From Noam Tal Hod, WIS

Synchronisation & Trigger



world’s largest femtosecond-precision synchronisation system

Correlation of two independent bunch arrival time diagnostics (BAMs) at tunnel location 1932 m



Synchronisation of the XFEL:

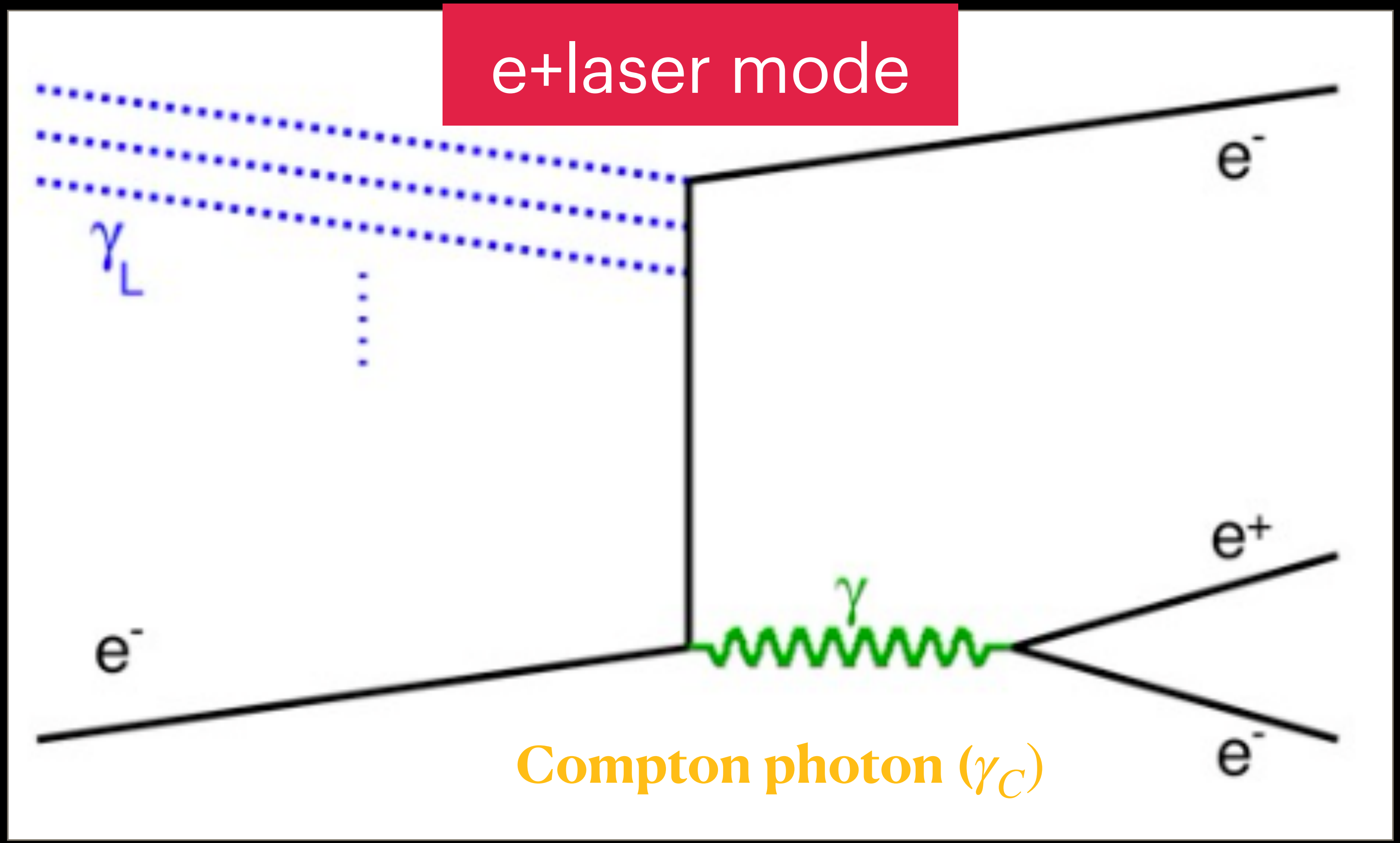
- Optical clock (master laser oscillator, MLO) provides stable pulsed optical reference (Phase-locked to radio frequency (RF) oscillator (MO))
- Optical reference distributed via length-stabilised optical fibre links for laser locking and RF re-sync

LUXE’s laser oscillator:

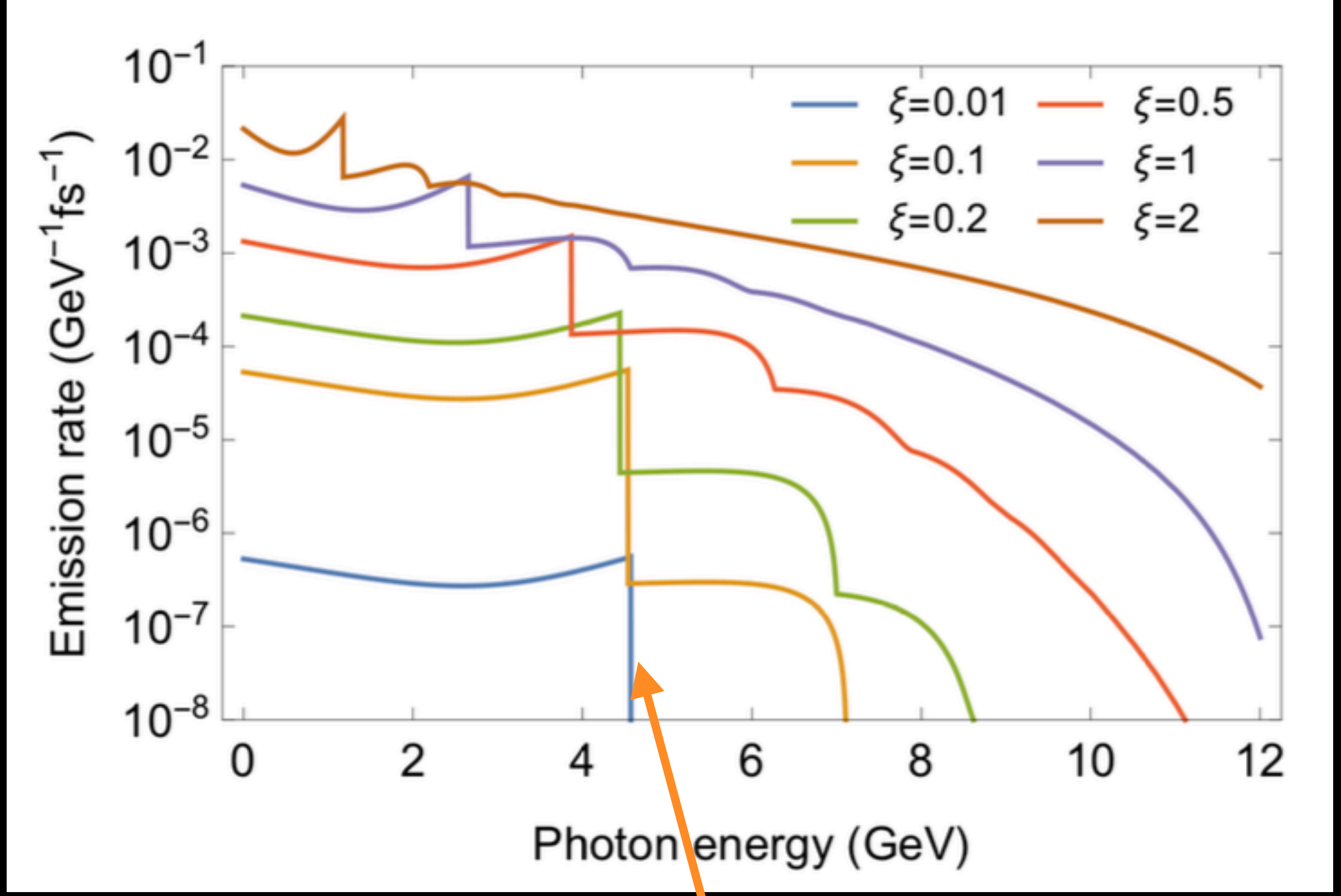
- connected to the optical sync system, which will in turn trigger the detectors

From Noam Tal Hod, WIS

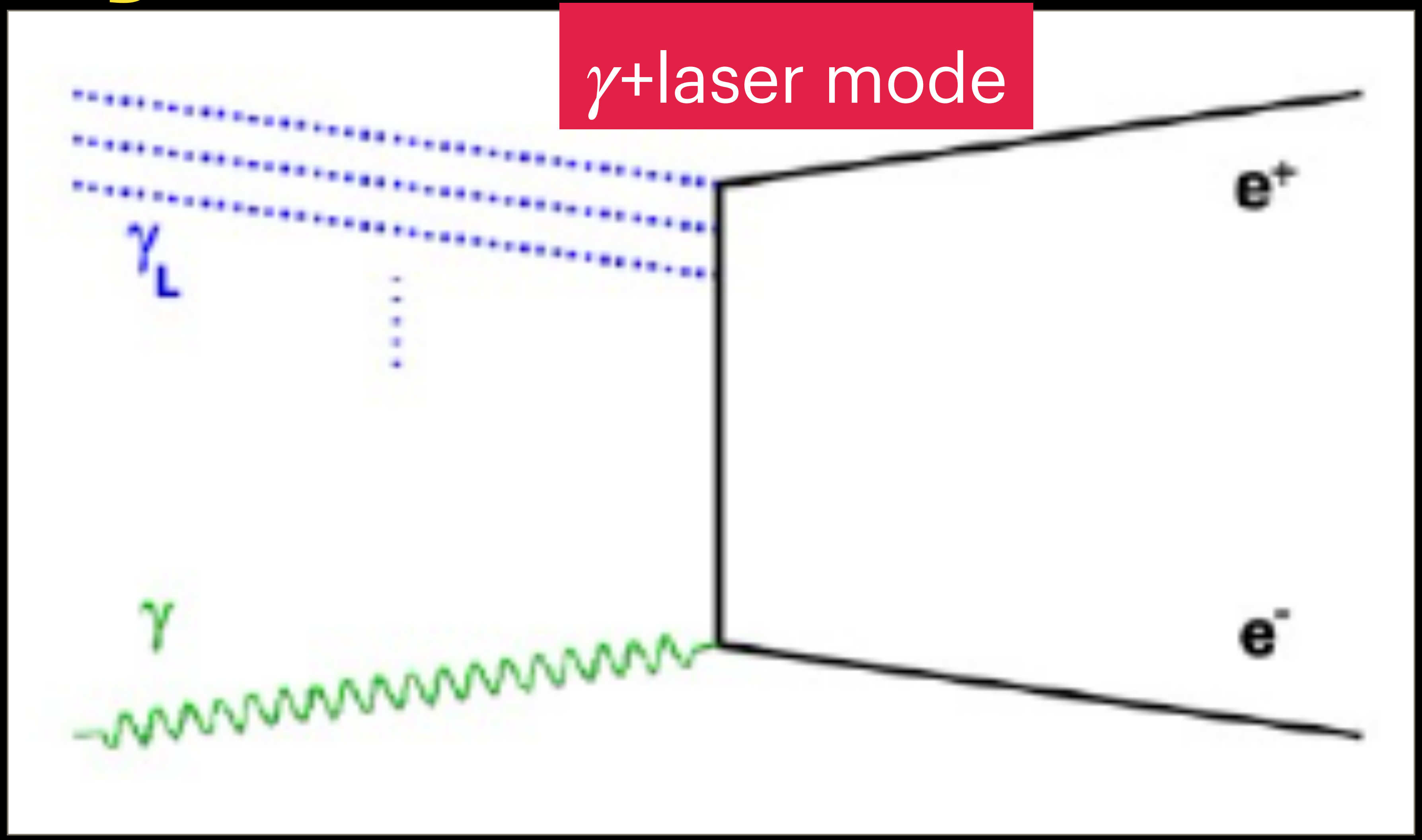
A Brief Idea about the LUXE physics



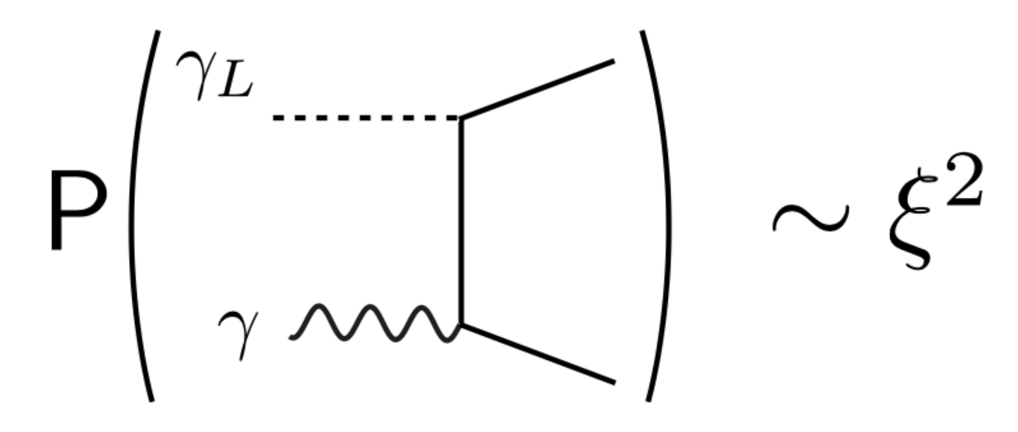
Non-linear Compton (C) scattering, followed by pair production: $e^- + n\gamma_L \rightarrow e^- + \gamma, \gamma \rightarrow e^+ + e^-$



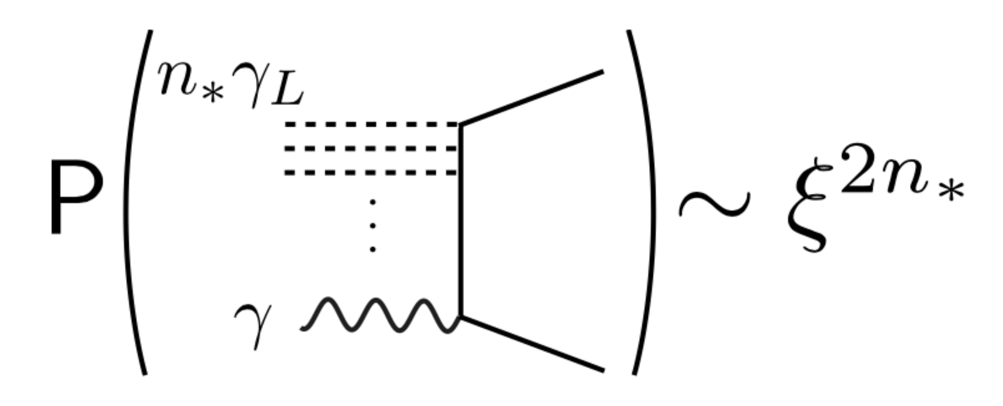
Compton Edge



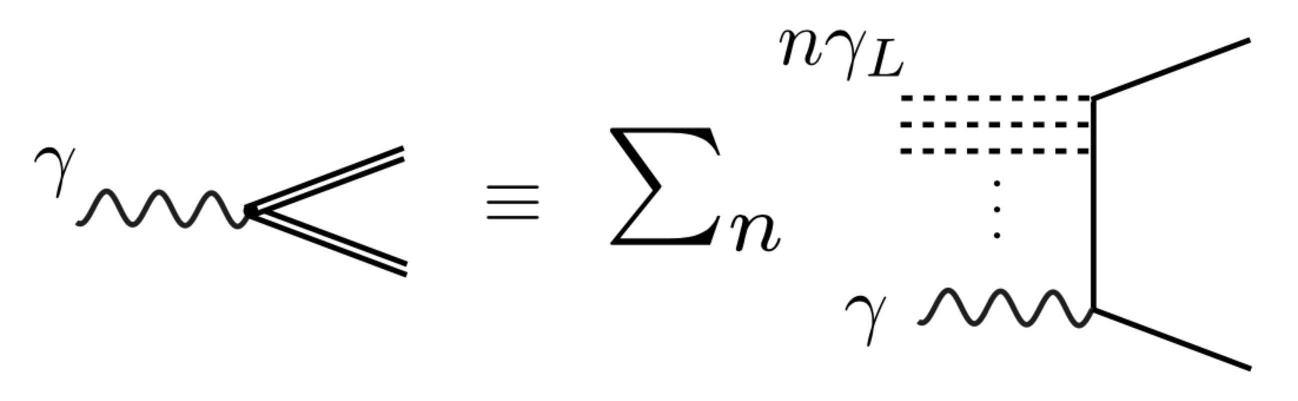
Non-linear Breit-Wheeler (BW): $n_* \gamma_L + \gamma \rightarrow e^+ + e^-$



Linear Breit-Wheeler



Perturbative non-linear Breit-Wheeler



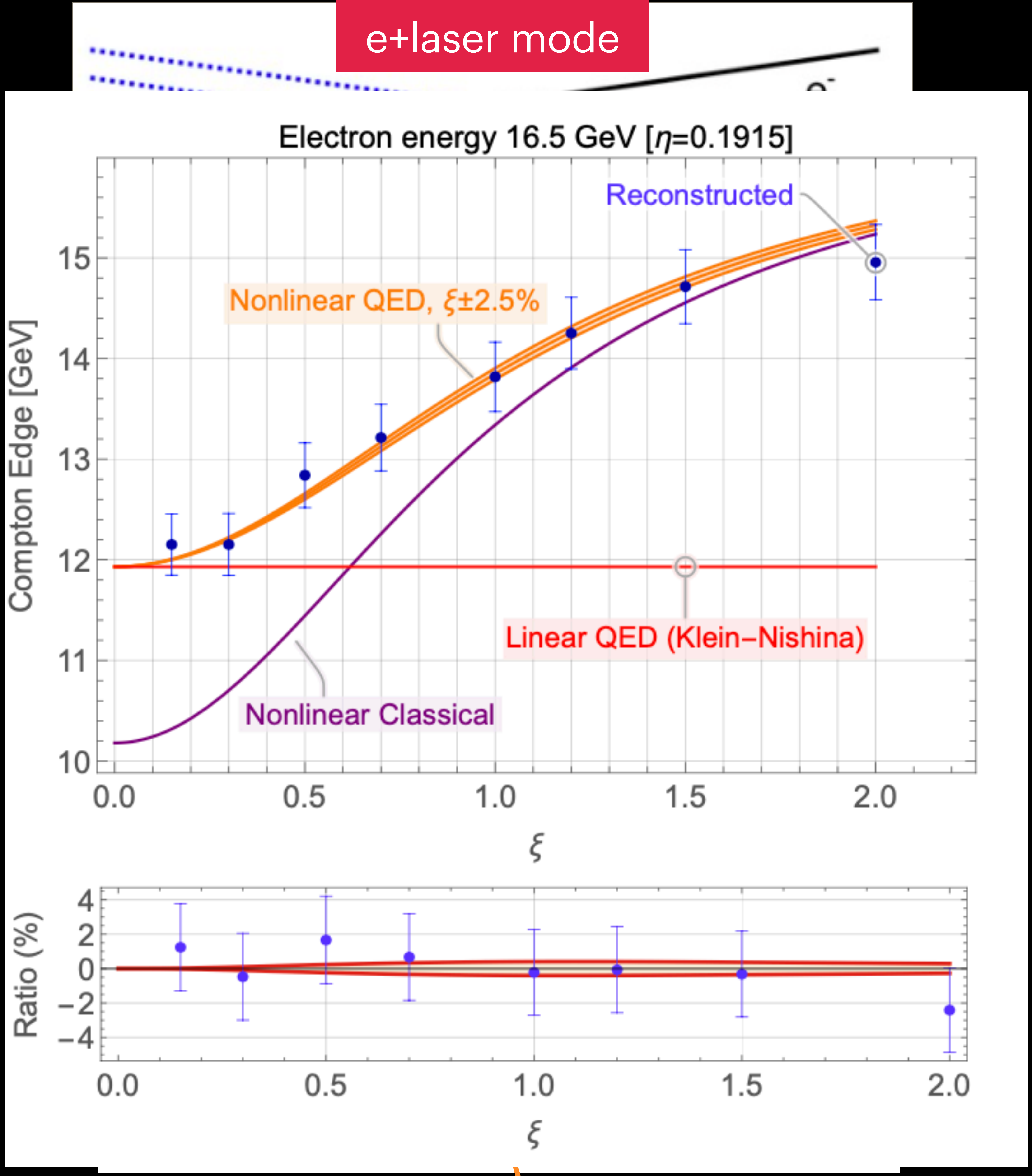
$$\Gamma_{\mathrm{BW}} \propto \exp\left[-\frac{8}{3}\frac{1}{\gamma_e(1+\cos\theta)}\frac{\mathcal{E}_{\mathrm{cr}}}{\mathcal{E}_L}\right]$$

For $\xi \ll 1$

Non-perturbative non-linear Breit-Wheeler

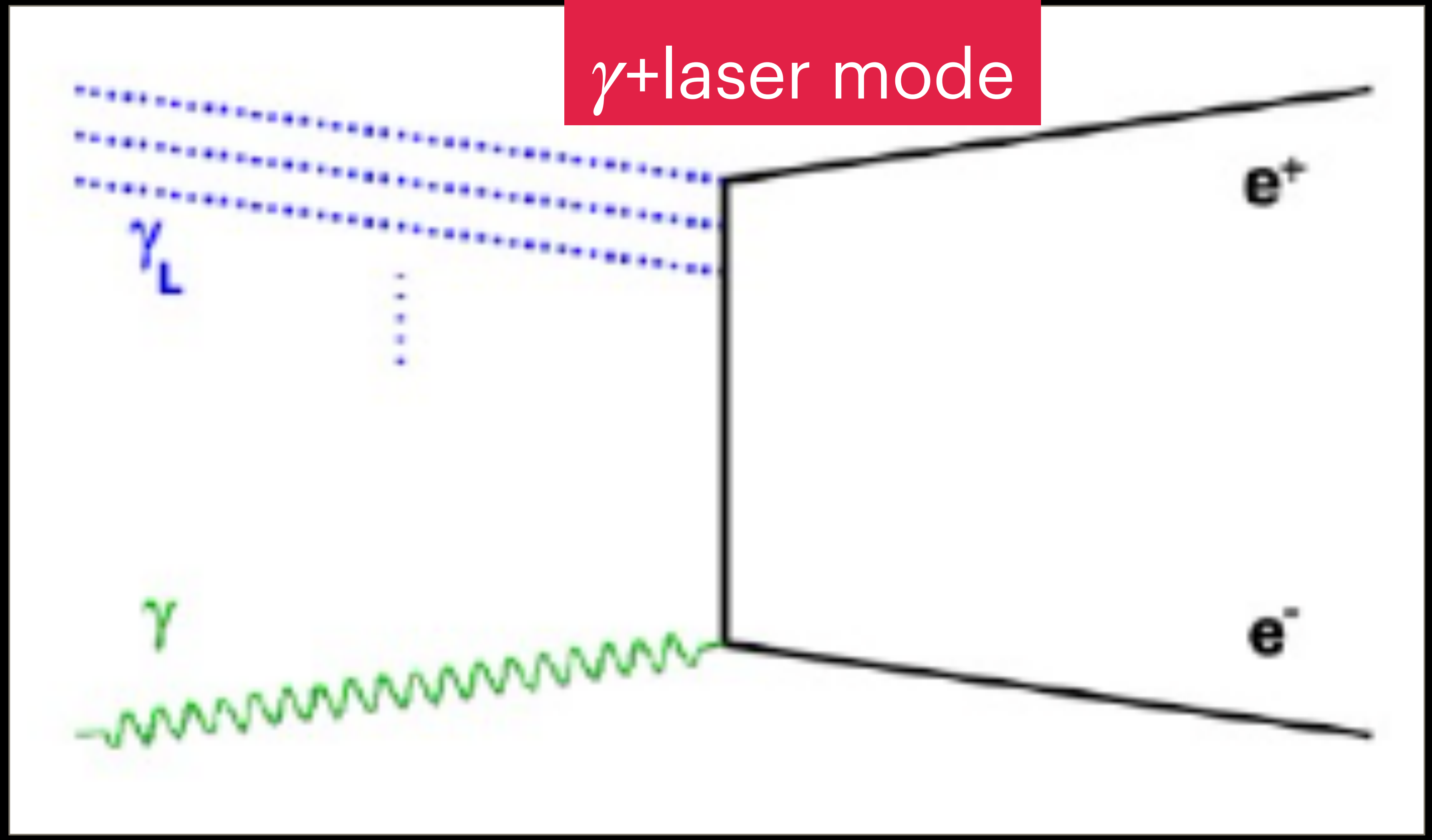
A Brief Idea about the LUXE physics

e+laser mode

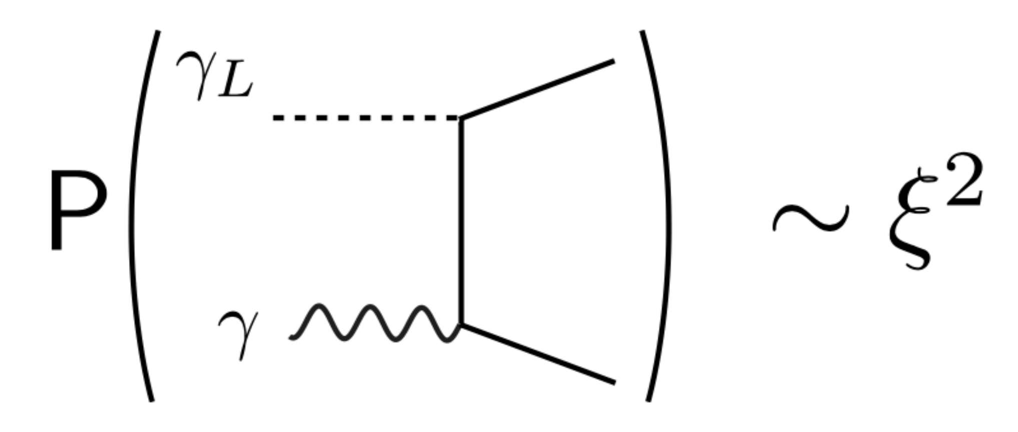


Compton Edge

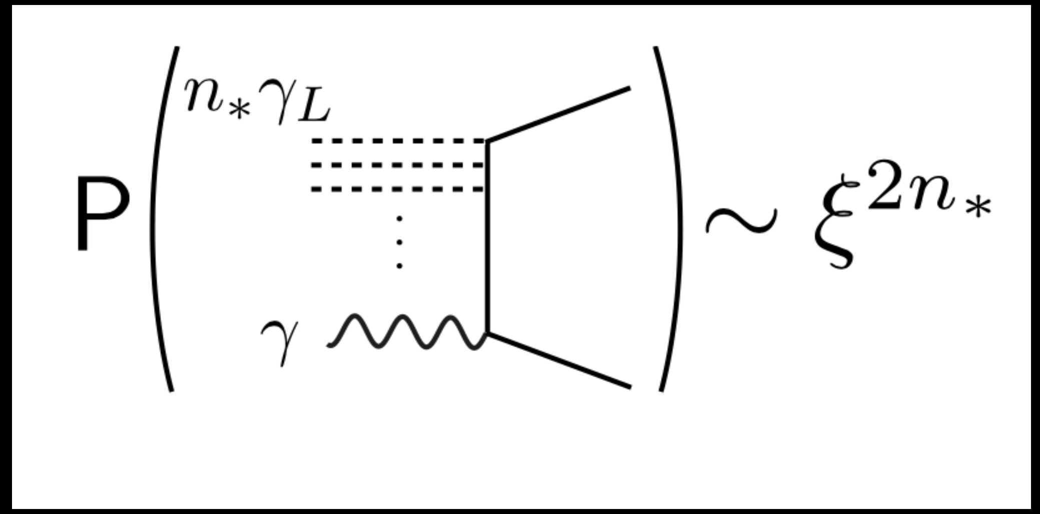
γ+laser mode



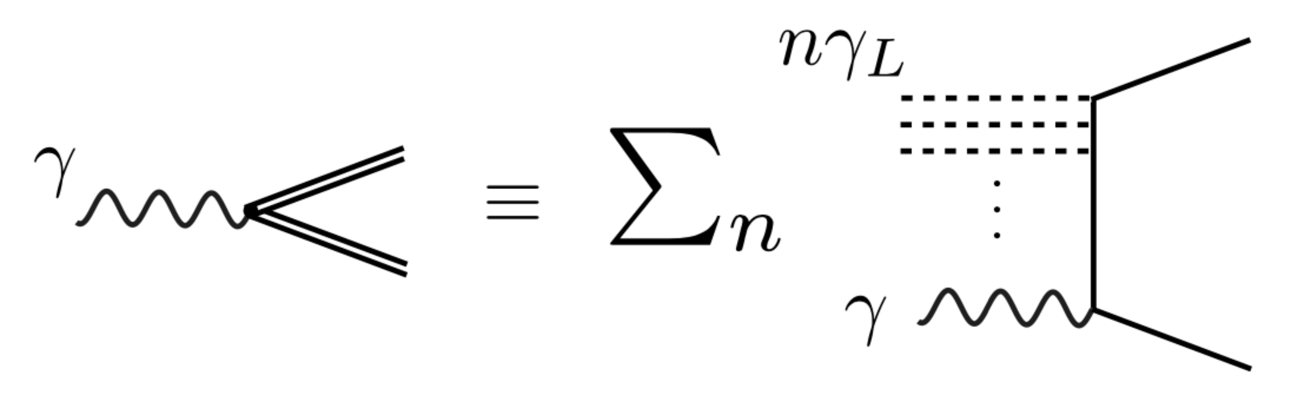
Non-linear Breit-Wheeler (BW): $n_* \gamma_L + \gamma \rightarrow e^+ + e^-$



Linear Breit-Wheeler



Perturbative non-linear Breit-Wheeler



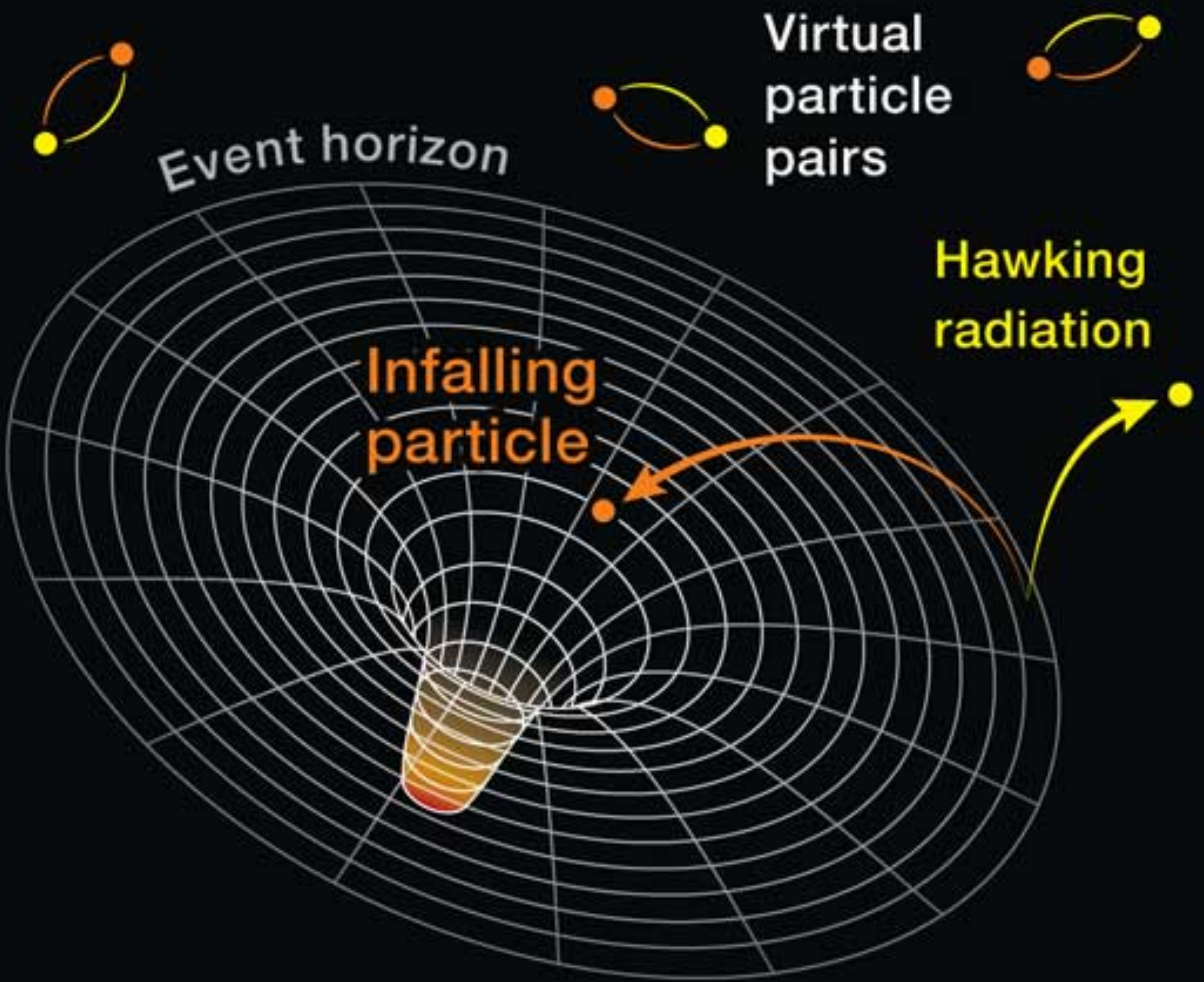
Non-perturbative non-linear Breit-Wheeler

$$\Gamma_{\mathrm{BW}} \propto \exp\left[-\frac{8}{3}\frac{1}{\gamma_e(1+\cos\theta)}\frac{\mathcal{E}_{\mathrm{cr}}}{\mathcal{E}_L}\right]$$

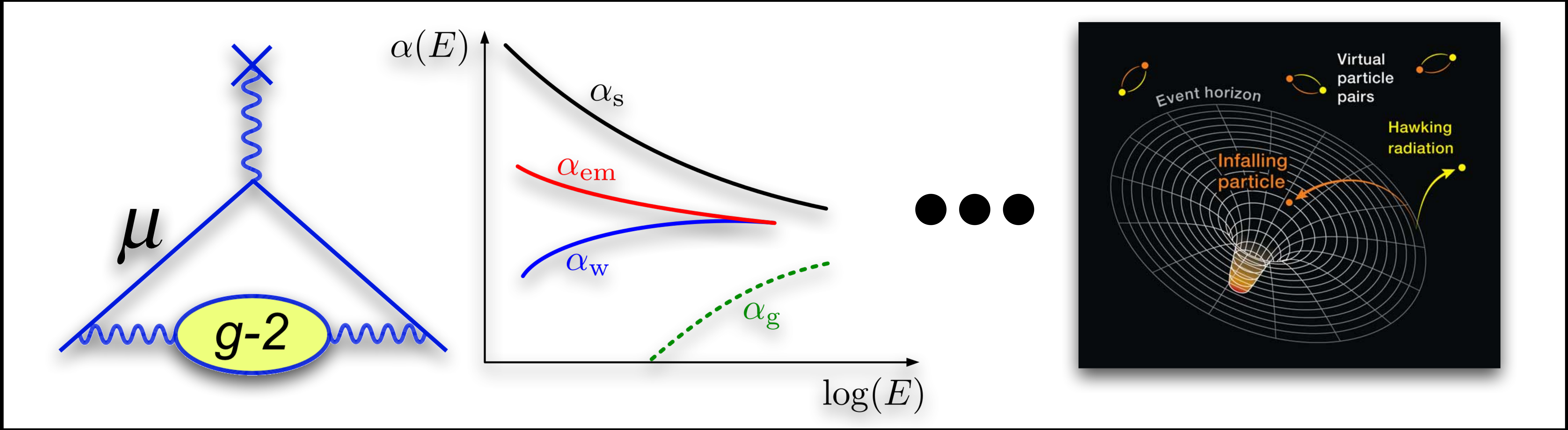
For $\xi \ll 1$

The Hawking equivalent

- **Outside observer:** the BH has radiated a particle so the energy must come from it
- **Looking at the system:** the BH energy has decreased so its mass must decrease



Why strong field physics?



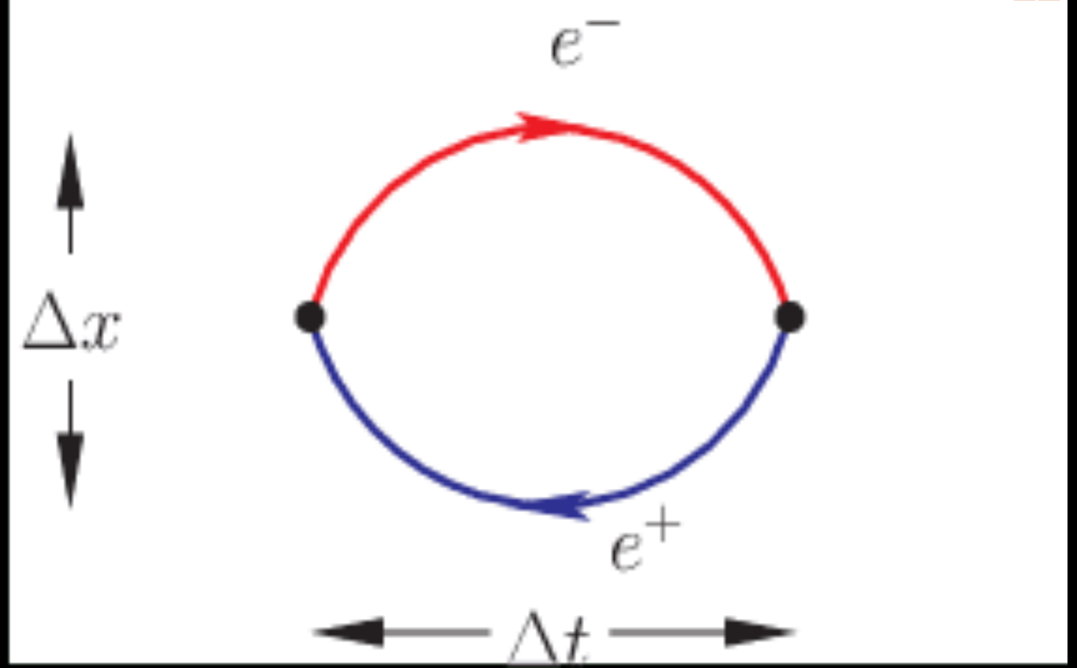
- Reaching ϵ_S is equivalent e.g. to the measurement of the anomalous magnetic moment or the coupling constant and deviations could be a hint for new physics
- Non-perturbative QFT is still being actively developed
- Can provide insight into the vacuum state / Higgs mechanism
- Schwinger effect proposed as mechanism for reheating in the early universe
- New physics opportunities with strong field (ALPs, mCPs,…)

The Schwinger mechanism simplified

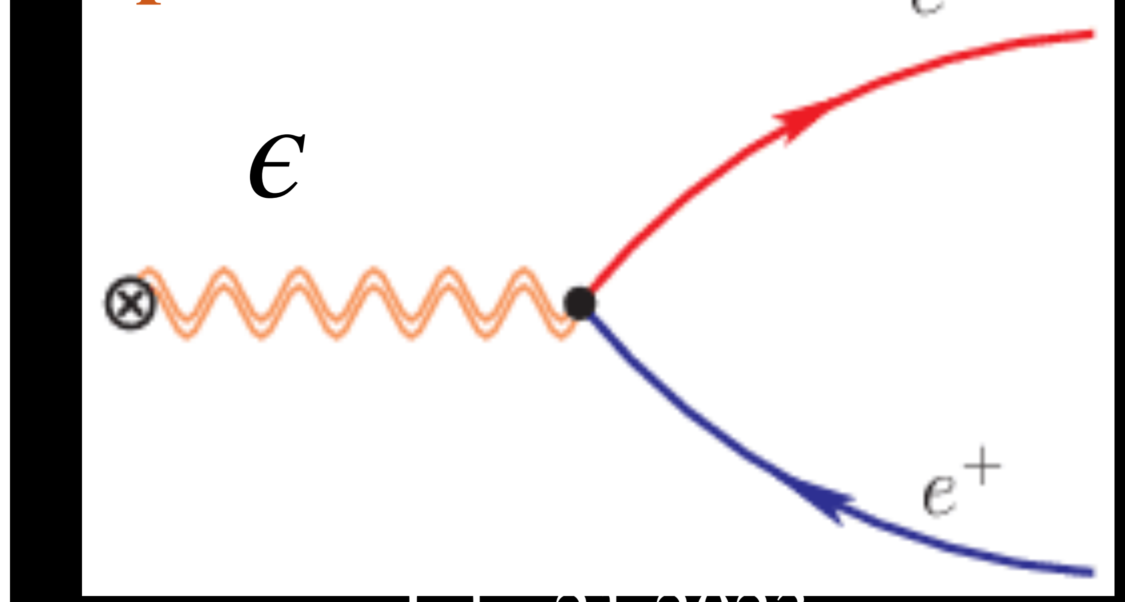
- Force of external static electric field is: $F = e\epsilon$
- Energy to separate the virtual pair in a distance d: $E = F \cdot d = e\epsilon \cdot d$
- Energy required to materialise as a real pair: $E = 2m_e c^2$
- Condition to materialise as a real pair in distance d: $e\epsilon d = 2m_e c^2$
- Compton wavelength (typical scale): $\lambda_\mathrm{C} = \hbar/(m_e c)$
- Probability for d:

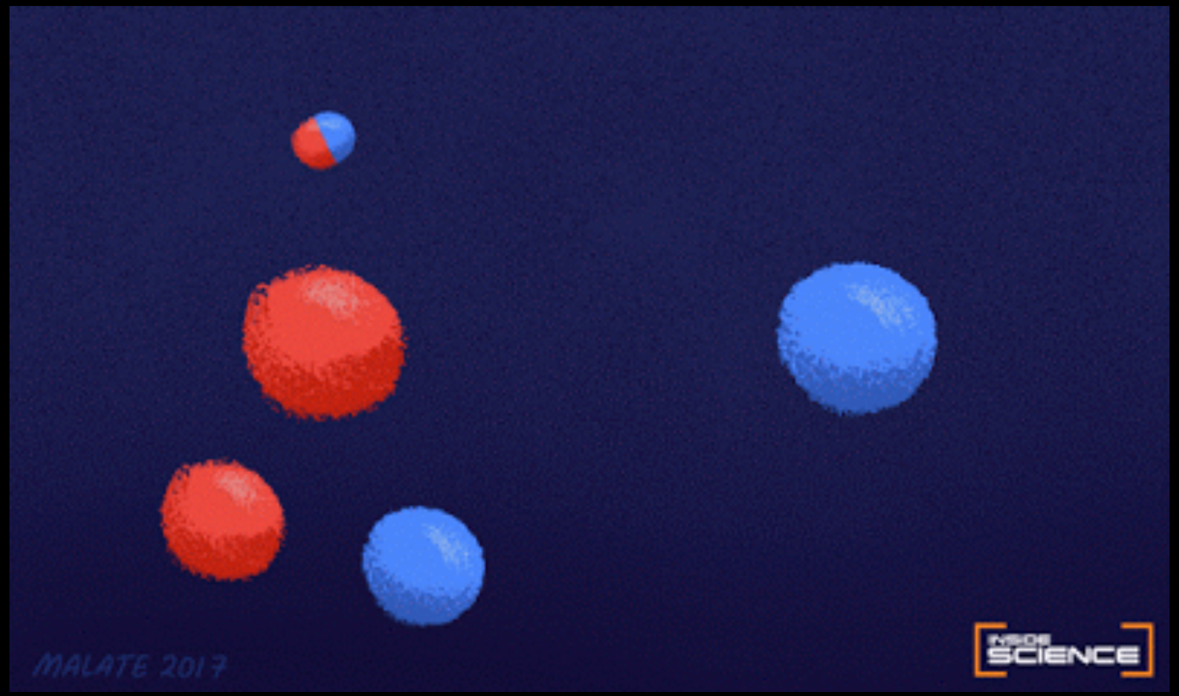
$$P \propto \exp\left(-\frac{d}{\lambda_C}\right) = \exp\left(-2\frac{m_e^2 c^3}{\hbar e \epsilon}\right) = \exp\left(-2\frac{\epsilon_\mathrm{S}}{\epsilon}\right)$$

$$\boldsymbol{\epsilon_\mathrm{S} = \frac{m_e^2 c^3}{\hbar e} \simeq 1.3 \cdot 10^{18}\ \frac{\mathrm{V}}{\mathrm{m}}}$$



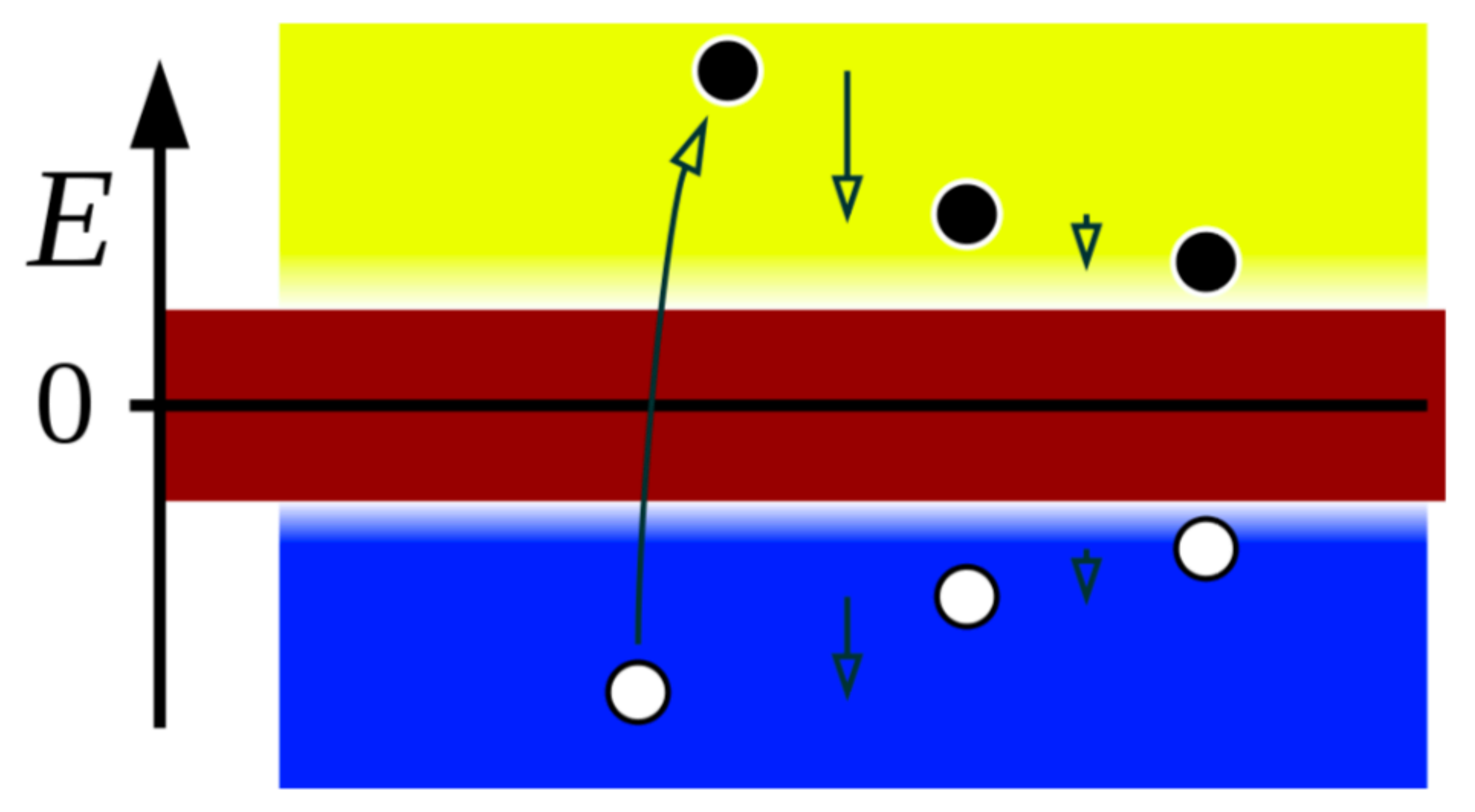
non-perturbative in *e*





The Furry Picture vacuum

The 2^{nd} quantisation of the Dirac field relies on a gap between the positive and negative energy solutions



- The external field “closes” this energy gap
- Electrons are lifted from the sea to leave the vacuum charged
- The VEV of the EM current must no longer vanish
- Separation into creation and destruction operators is problematic
- This point is the limit of the validity of the Furry picture

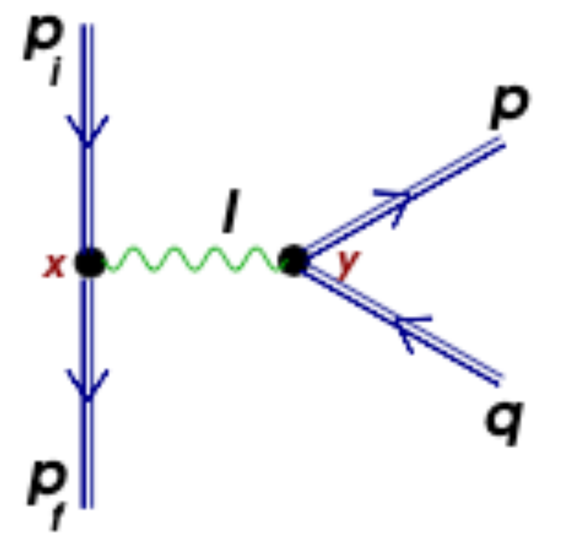
The Furry Picture

IJMP A, Vol. 33, No. 13 (2018) 1830011

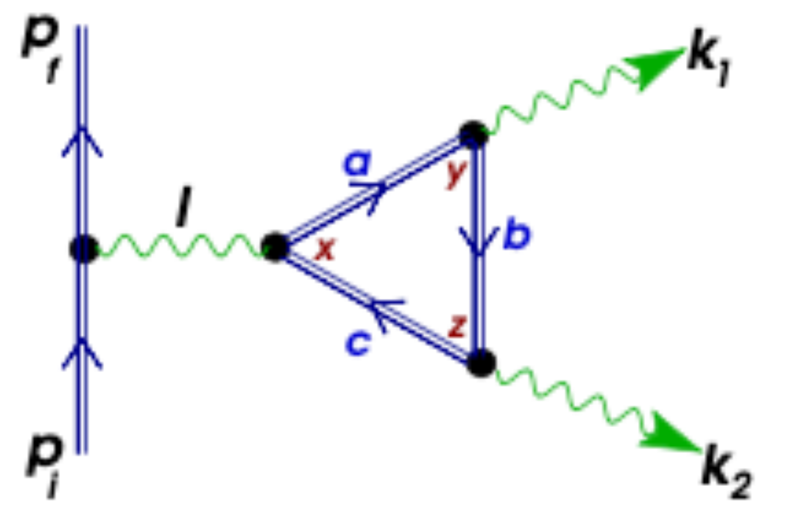
- If the external field is sufficiently strong: quantum interactions with it leave it essentially unchanged and it can be considered to be a classical background field
- Separate the gauge field to external and quantum parts: $\mathscr{L}_{\text{Int}} = \bar{\psi}(i\not{\partial} - m)\psi - \frac{1}{4}F_{\mu\nu}^2 - e\bar{\psi}(\not{A}_{\text{ext}} + \not{A})\psi$ and shift $\not{A}_{\text{ext}}$ to the Dirac component: $\mathscr{L}_{\text{FP}} = \bar{\psi}^{\text{FP}}(i\not{\partial} - e\not{A}_{\text{ext}} - m)\psi^{\text{FP}} - \frac{1}{4}F_{\mu\nu}^2 - e\bar{\psi}^{\text{FP}}\not{A}\psi^{\text{FP}}$

- The FP Lagrangian satisfies the Euler-Lagrange equation.
- New equation of motion for the non-perturbative (bound) Dirac field (wrt $\not{A}_{\text{ext}}$) and new solutions ψ^{FP}: $(i\not{\partial} - e\not{A}_{\text{ext}} - m)\psi^{\text{FP}} = 0$

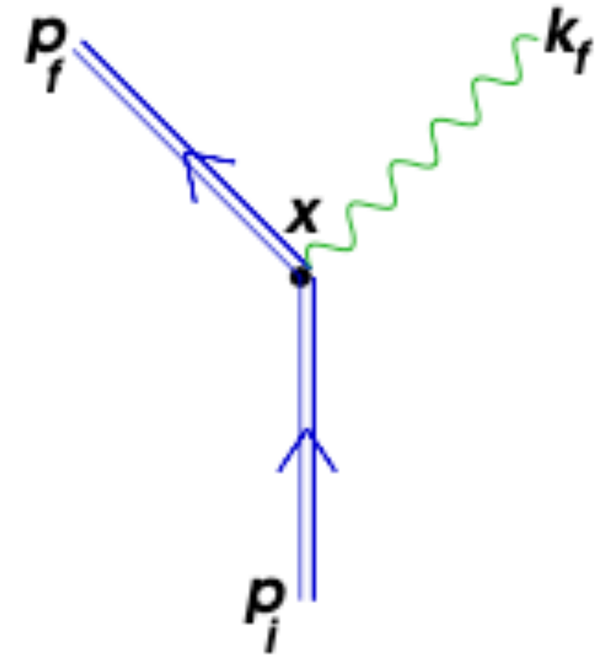
- Exact solutions exist for a certain classes of external fields (plane waves, Coloumb fields and combinations) [Volkov Z Physik 94 250 (1935), Bagrov & Gitman 1990]: $\psi^{\text{FP}} = \mathbf{E}_p e^{-ipx} u_p$ with $\mathbf{E}_p = \text{Exp}\left[-\frac{1}{2k\cdot p}\left(e\not{A}_{\text{ext}}\not{k} + i2e(A_{\text{ext}}\cdot p) - ie^2 A_{\text{ext}}^2\right)\right]$



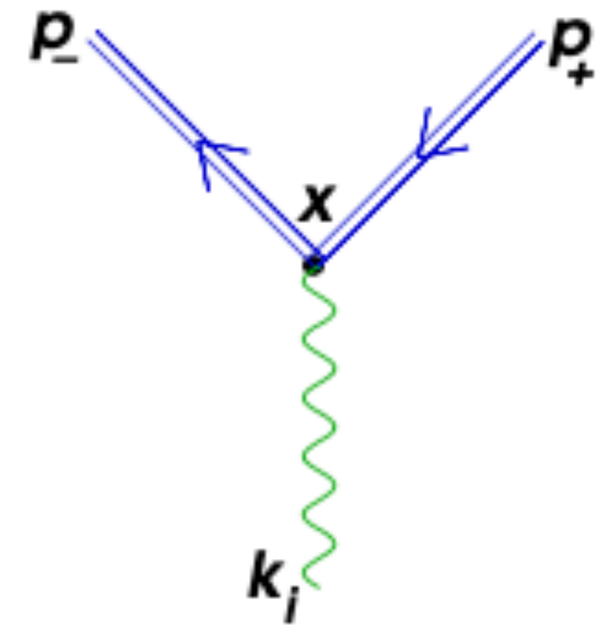
Trident process (vacuum resonance)



Photon splitting (vacuum birefringence)



High intensity Compton scatter (HICS)



One photon pair production (OPPP)

Boiling point of QED

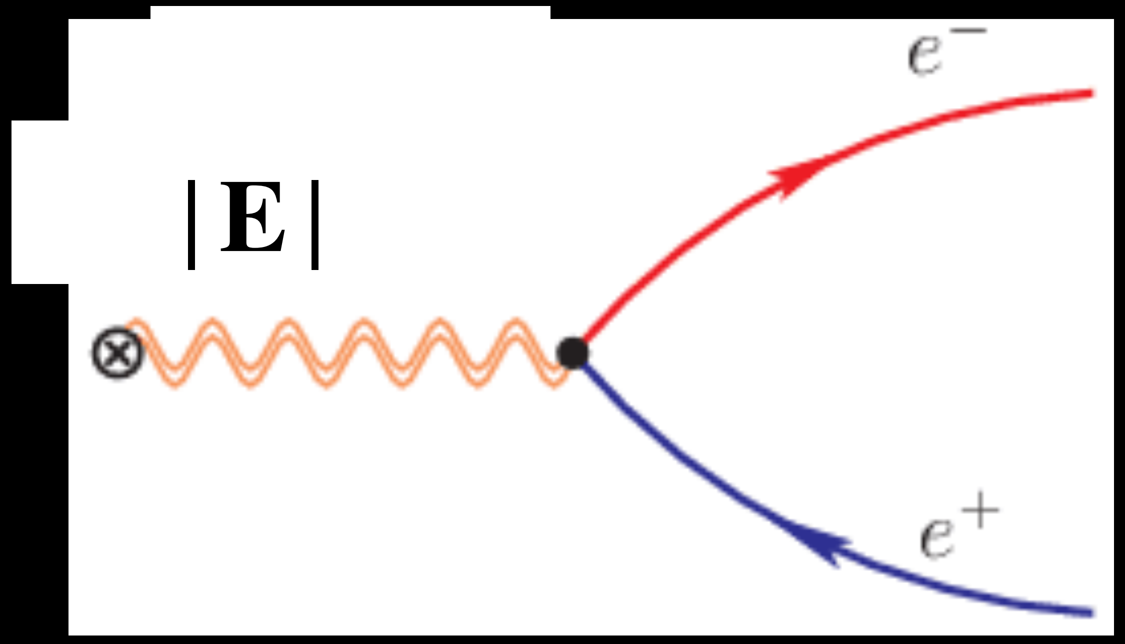
- **Weak fields:** many accurate predictions of observables through ordinary perturbative expansion in the EM coupling (α_{EM})

- **Strong fields:** observables become inaccessible through ordinary perturbative expansion and there's no experimental verification

- **For example:** the spontaneous e^+e^- pair production (SPP) rate per unit volume in strong static E-field is:

$$\frac{\Gamma_{\text{SPP}}}{V} = \frac{m_e^4}{(2\pi)^3}\left(\frac{|\mathbf{E}|}{\text{E}_\text{c}}\right)^2 \sum_{n=1}^{\infty}\frac{1}{n^2}e^{-n\pi\frac{\text{E}_\text{c}}{|\mathbf{E}|}} \sim e^{-\frac{\pi m_e^2}{\underset{\uparrow}{e}|\mathbf{E}|}}$$

non-perturbative in α_{EM}



But how to produce static E-field of the order of ~1.3×10^{18} V/m ???

Phys. Rev. D 99, 036008 (2019)

Lasers strong field “how-to”

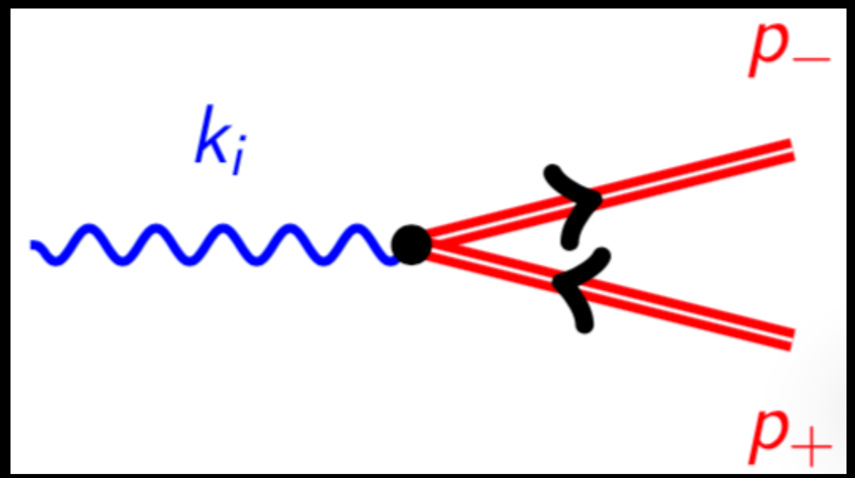
- Laser-assisted one photon pair production, OPPP (SPP ⟶OPPP)
  - the laser’s E-field frequency is ω, with momentum $k = (\omega, \mathbf{k})$
  - the laser’s E-field strength is $|\epsilon|$, with $I \sim |\epsilon|^2$
  - The e^+e^- pair picks up momentum from the laser photons

- OPPP rate is a function of the laser intensity ξ and the photon recoil χ:

Dimensionless and
Lorentz-invariant

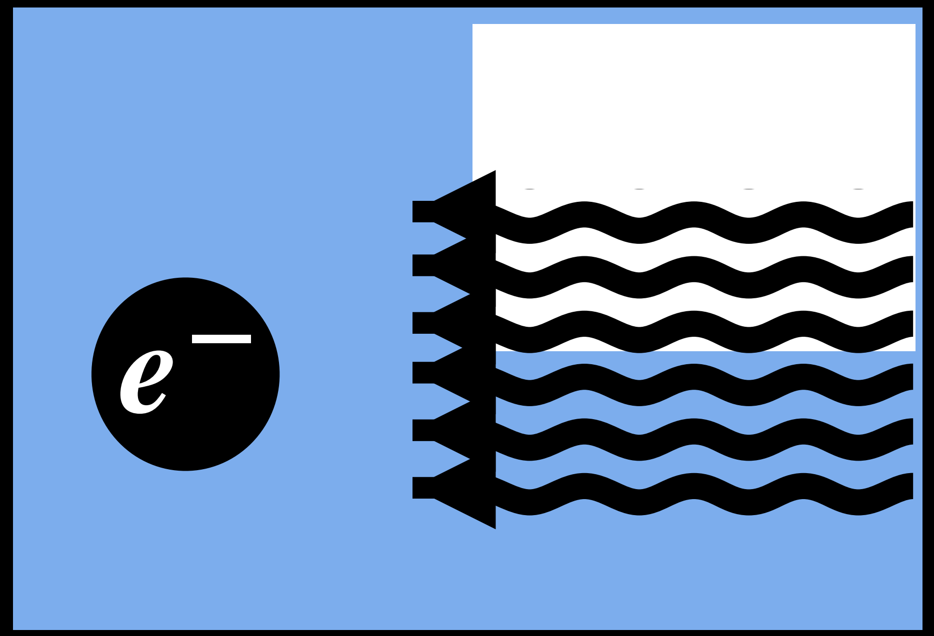
$$\begin{cases} \text{Laser intensity}: \ \xi = \dfrac{e|\epsilon|}{\omega m_e} = \dfrac{m_e}{\omega}\dfrac{|\epsilon|}{\epsilon_S} \\ \text{Photon recoil}: \ \chi_\gamma = \dfrac{k \cdot k_i}{m_e^2}\xi = (1+\cos\theta)\dfrac{\omega_i}{m_e}\dfrac{|\epsilon|}{\epsilon_S} \end{cases}$$

Initial photon : $k_i = (\omega_i, \mathbf{k}_i)$



$$\boldsymbol{\Gamma_{\text{OPPP}} = \frac{\alpha m_e^2}{4\omega_i} F(\xi, \chi_\gamma)}$$

Understanding ξ



Electron "at rest"

Infinite E-field plane wave with frequency ω

The electron will oscillate with frequency ω and radiate in turn: $eE = m_e a$

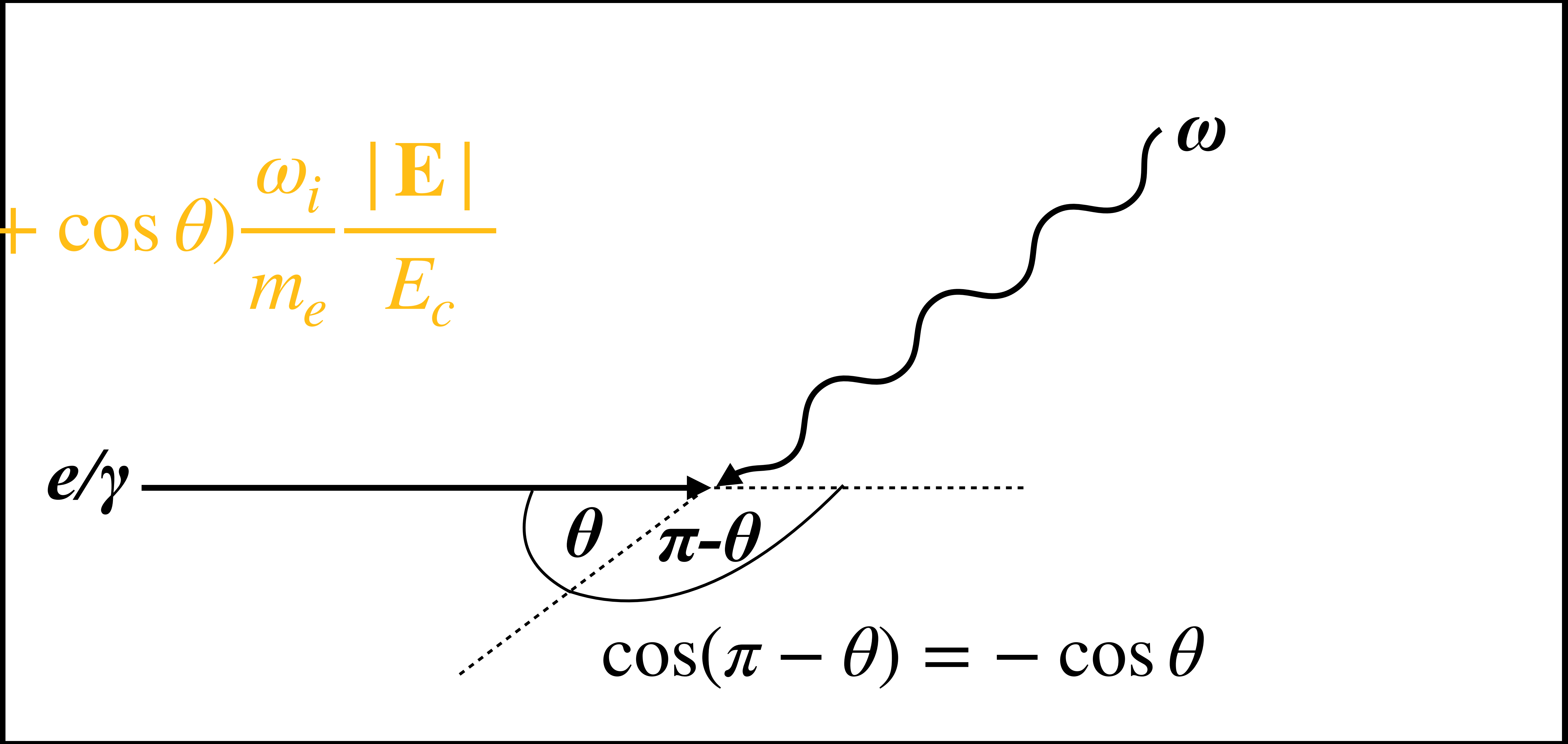
The electron's maximum velocity is: $v_{\max} = a \cdot \Delta t = \frac{eE}{m_e} \cdot \frac{1}{\omega}$

Normalise to c: $\xi \equiv \frac{v_{\max}}{c} = \frac{eE}{\omega m_e c}$ (dimensionless & Lorentz-invariant)

ξ reaches unity for e.g. a $\lambda = 800$ nm laser at an intensity of $I \sim 10^{18}$ W/cm^2

Understanding χ

Recoil parameter: $\chi = \frac{k \cdot k_i}{m_e^2}\xi = (1 + \cos\theta)\frac{\omega_i}{m_e}\frac{|\mathbf{E}|}{E_c}$



Scattering geometry: $k \cdot k_i = \omega\omega_i - |\mathbf{k}||\mathbf{k}_i|\cos(\pi - \theta) = \omega\omega_i(1 + \cos\theta)$

$$\chi = \frac{k \cdot k_i}{m_e^2}\xi = \frac{\omega\omega_i(1 + \cos\theta)}{m_e^2}\frac{e\epsilon}{\omega m_e c} = (1 + \cos\theta)\frac{\omega_i}{m_e}\frac{\epsilon}{\epsilon_S}$$

$$\frac{1}{\epsilon_S} = \frac{e}{m_e^2}$$

$$\hbar = c = 1$$

OPPP rate: $\Gamma_{\mathrm{OPPP}} \propto F(\xi,\chi_\gamma)$

Sum on number of absorbed laser γ's

J_n are Bessel functions

$$F_\gamma(\xi,\chi_\gamma) = \sum_{n>n_o}^{\infty} \int_1^{v_n} \frac{\mathrm{d}v}{v\sqrt{v(v-1)}} \left[2\,J_n^2(z_v) + \xi^2(2v-1)\left(J_{n+1}^2(z_v) + J_{n\text{-}1}^2(z_v) - 2J_n^2(z_v)\right)\right]$$

threshold number of absorbed γ's

$$n_0 \equiv \frac{2\xi\left(1+\xi^2\right)}{\chi_\gamma}, \qquad z_v \equiv \frac{4\xi^2\sqrt{1+\xi^2}}{\chi_\gamma}\left[v\left(v_n - v\right)\right]^{1/2}, \qquad v_n \equiv \frac{\chi_\gamma\, n}{2\xi(1+\xi^2)}$$

As the laser intensity ξ increases

- the threshold number of absorbed photons increases
- more terms in the summation drop out of the probability

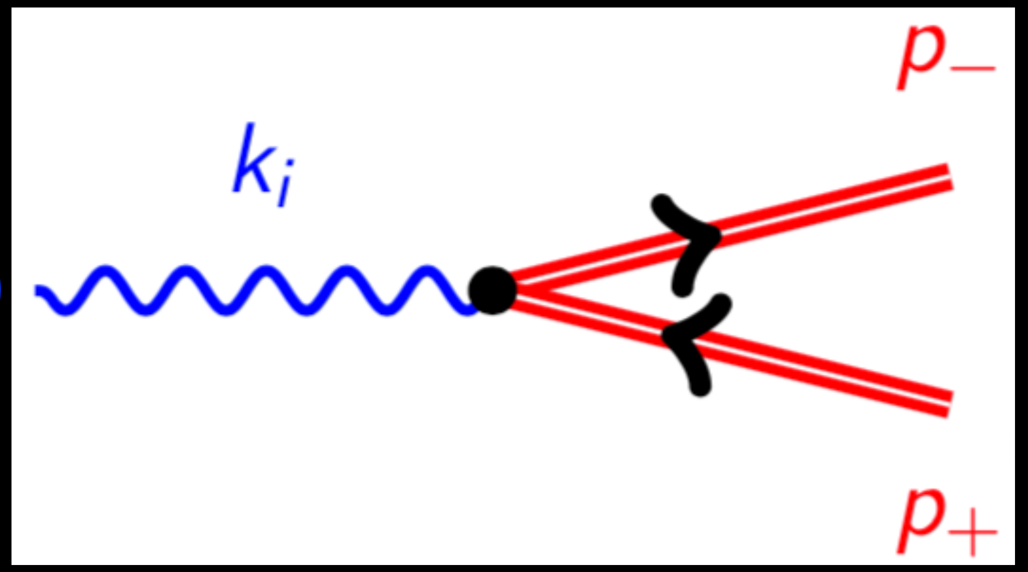
Assumption1: the laser E-field is a circularly polarised infinite plane wave

Assumption2: we can produce a mono-energetic photon beam with ~O(10 GeV)

Γ_{OPPP} asymptotically

$$\Gamma_{\mathrm{OPPP}} \longrightarrow \frac{3}{16}\sqrt{\frac{3}{2}}\alpha m_e (1+\cos\theta)\frac{|\epsilon|}{\epsilon_S}\exp\left(-\frac{8}{3}\frac{1}{1+\cos\theta}\frac{m_e}{\omega_i}\frac{\epsilon_S}{|\epsilon|}\right)$$

$\omega_i \sim \mathcal{O}(1-10\ \mathrm{GeV})$



e^+e^- pair is boosted and the E-field is enhanced

- Unlike SPP, the e^+e^- pair (in its rest frame) experiences an E-field enhanced by the relativistic boost factor: $|\epsilon| \rightarrow |\epsilon| \times \omega_i/m_e$

- However, mono-energetic photon beams with energies in the $\omega_i \sim \mathcal{O}(10\ \mathrm{GeV})$ range are not available…

Asymptotically

- For a target of thickness $X \ll X_0$, where X_0 is the radiation length:

$$\omega_i \frac{dN_\gamma}{d\omega_i} \approx \left[\frac{4}{3} - \frac{4}{3}\left(\frac{\omega_i}{E_e}\right) + \left(\frac{\omega_i}{E_e}\right)^2 \right] \frac{X}{X_0}$$

- Similarly to OPPP, replacing χ_γ with χ_e, the BPPP rate is:

$$\Gamma_{\mathrm{BPPP}} \longrightarrow \frac{\alpha m_e^2}{E_e} \frac{9}{128} \sqrt{\frac{3}{2}} \frac{X}{X_0} \chi_e^2 e^{-\frac{8}{3\chi_e}\left(1 - \frac{1}{15\xi^2}\right)}$$