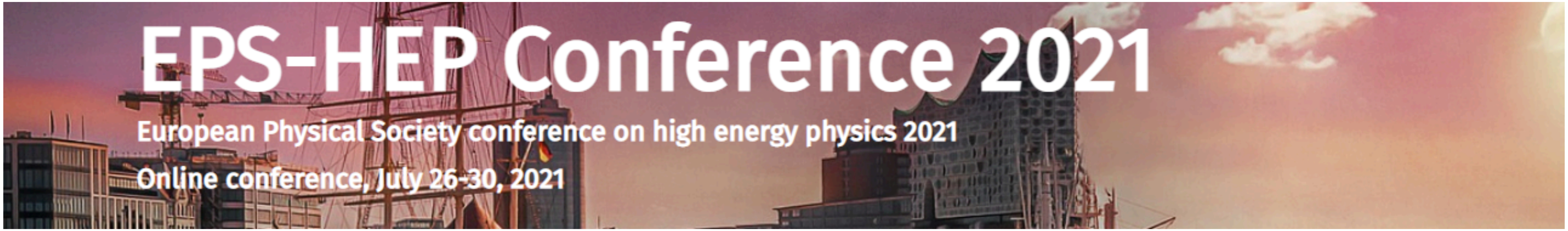


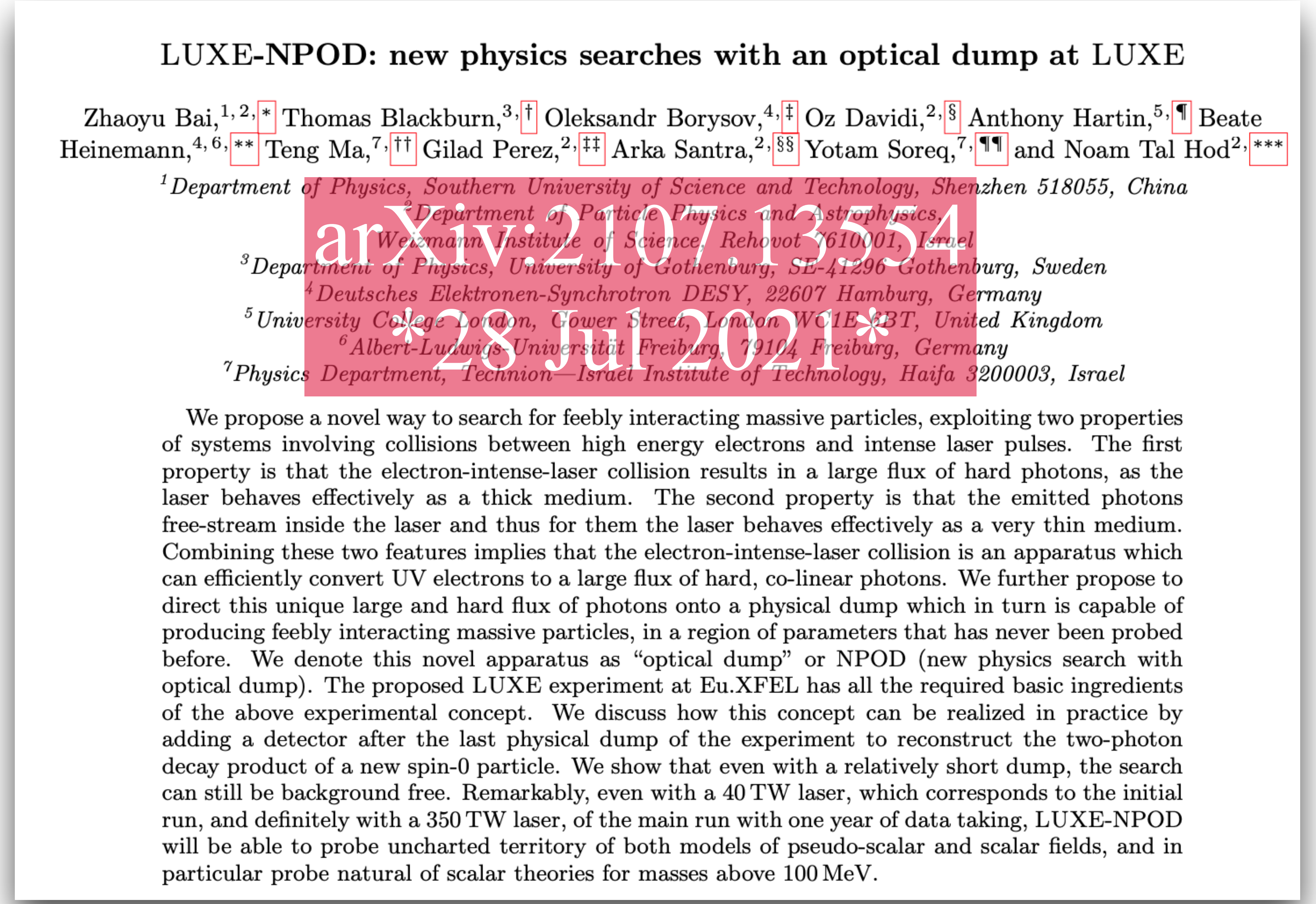
Probing new physics at the LUXE experiment

Noam Tal Hod on behalf of LUXE

July 30 2021

Outline

- Introduction and motivation
- LUXE physics and experimental setup
- New Physics @ Optical Dump with LUXE ⟶ ***LUXE-NPOD***
- For a more complete description of the non-BSM parts of LUXE, see talks by:
  - Louis Helary: Studies of high-field QED with the LUXE experiment at the European XFEL
  - Sasha Borysov: Detector Challenges of the strong-field QED experiment LUXE at the European XFEL



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

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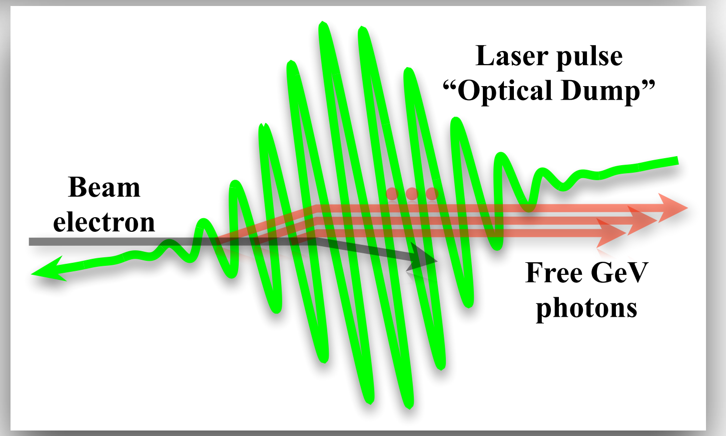
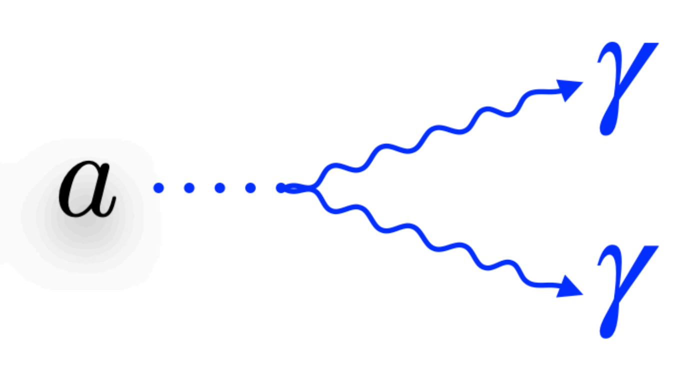
We propose a novel way to search for feebly interacting massive particles, exploiting two properties of systems involving collisions between high energy electrons and intense laser pulses. The first property is that the electron-intense-laser collision results in a large flux of hard photons, as the 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 UV electrons to a large flux of hard, co-linear photons. We further propose to direct this unique large and hard flux of photons onto a physical dump which in turn is capable of producing feebly interacting massive particles, in a region of parameters that has never been probed before. We denote this novel apparatus as "optical dump" or NPOD (new physics search with optical dump). The proposed LUXE experiment at Eu.XFEL has all the required basic ingredients of the above experimental concept. We discuss how this concept can be realized in practice by adding a detector after the last physical dump of the experiment to reconstruct the two-photon decay product 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 40 TW laser, which corresponds to the initial run, and definitely with a 350 TW laser, of the main run with one year of data taking, LUXE-NPOD will be able to probe uncharted territory of both models of pseudo-scalar and scalar fields, and in particular probe natural of scalar theories for masses above 100 MeV.





What happens in strong fields?

The Schwinger critical field (1951)

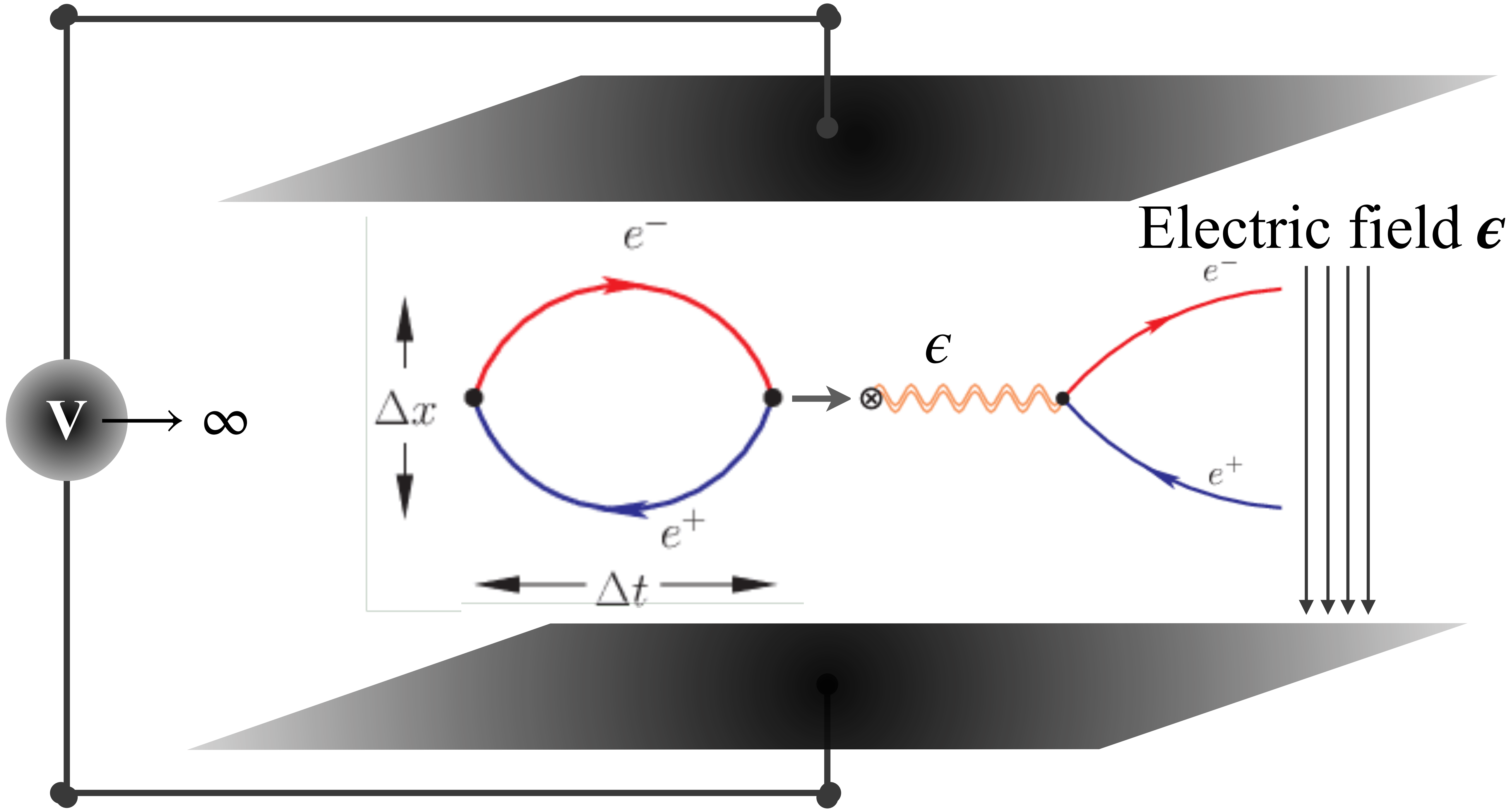
$$\epsilon_S = \frac{m_e^2 c^3}{e\hbar} \simeq 1.32 \cdot 10^{18}\ \frac{\mathrm{V}}{\mathrm{m}}$$

The probability to materialise one virtual e^+e^- pair from the vacuum

$$P \sim \exp\left(-a\frac{\epsilon_S}{\epsilon}\right)$$

non-perturbative with $\epsilon \longrightarrow \epsilon_S$

a = numeric const.



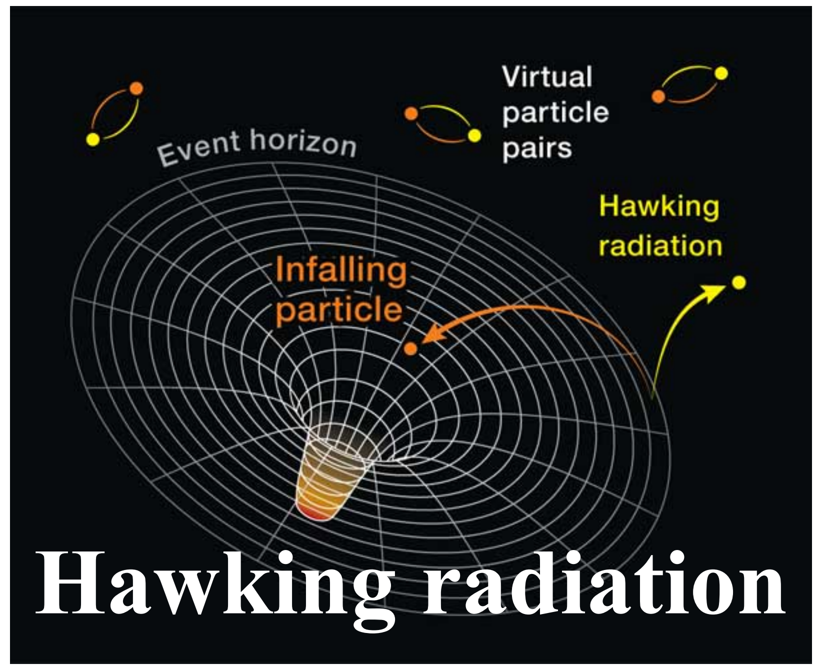
History & Impact

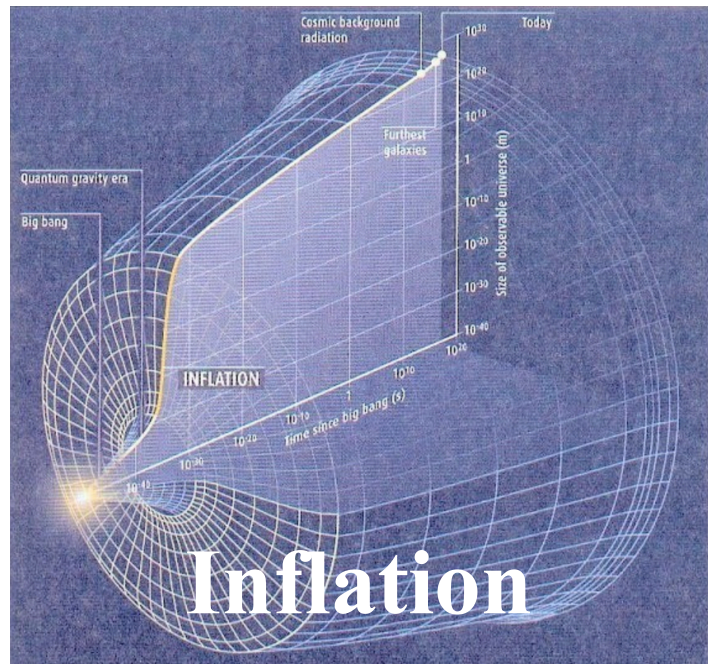
- 1930s — First discussions by Sauter, Heisenberg & Euler
- 1951 — First calculations by Schwinger: ϵ_S
- 1990s — E144 at SLAC first to approach ϵ_S
- 2020s — LUXE: reach ϵ_S and go beyond!

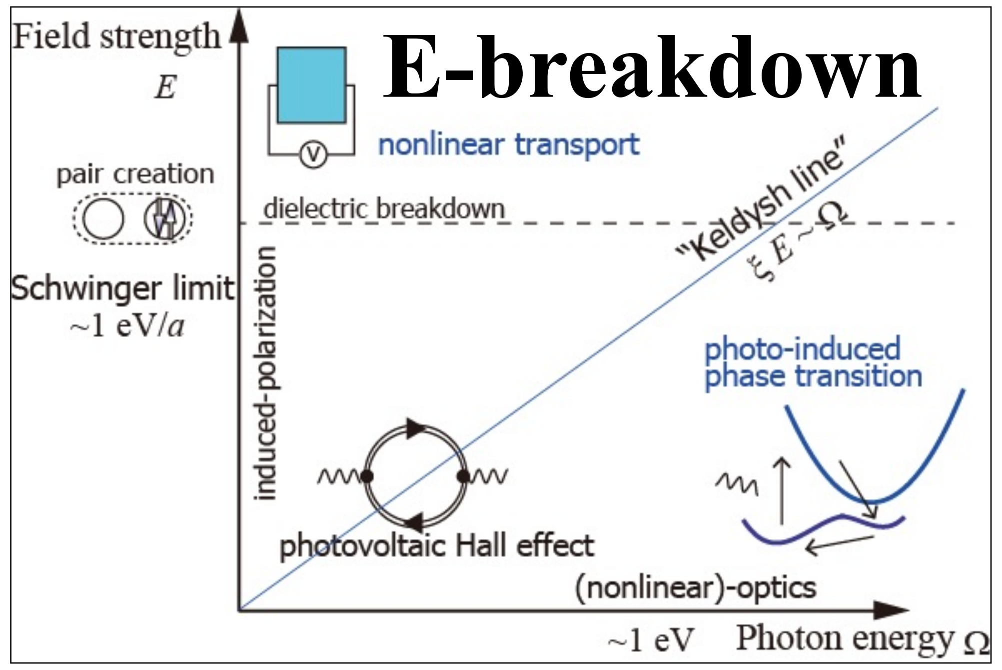
The Schwinger field may be approached/reached only in a highly-boosted system, e.g. the one produced at LUXE

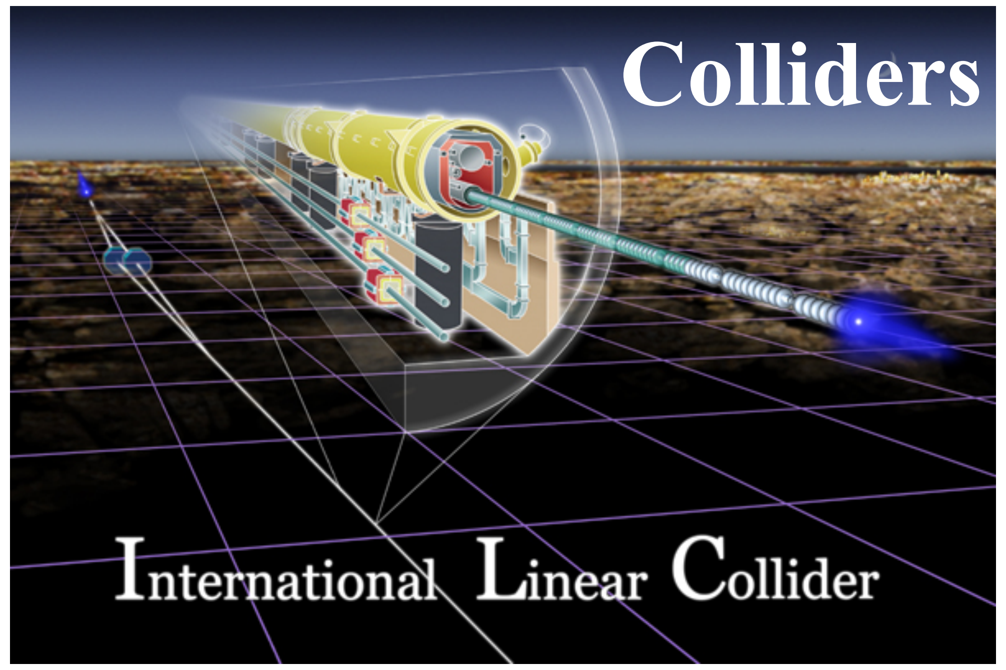
- never been reached in a clean environment*
- test basic predictions in a novel QM regime
- relevant to many areas in physics
- **potential for seeing effects of new physics!**

Today



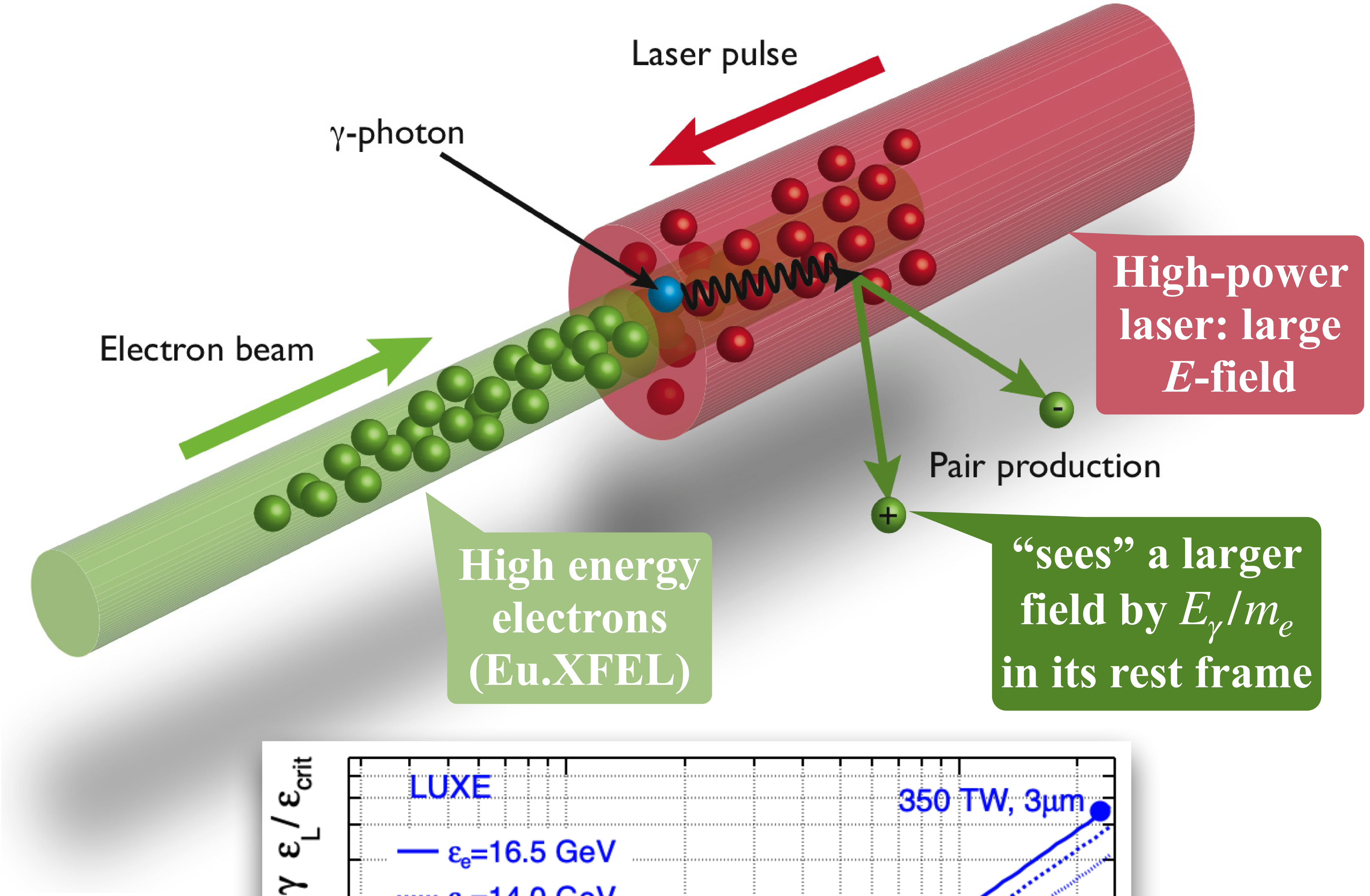


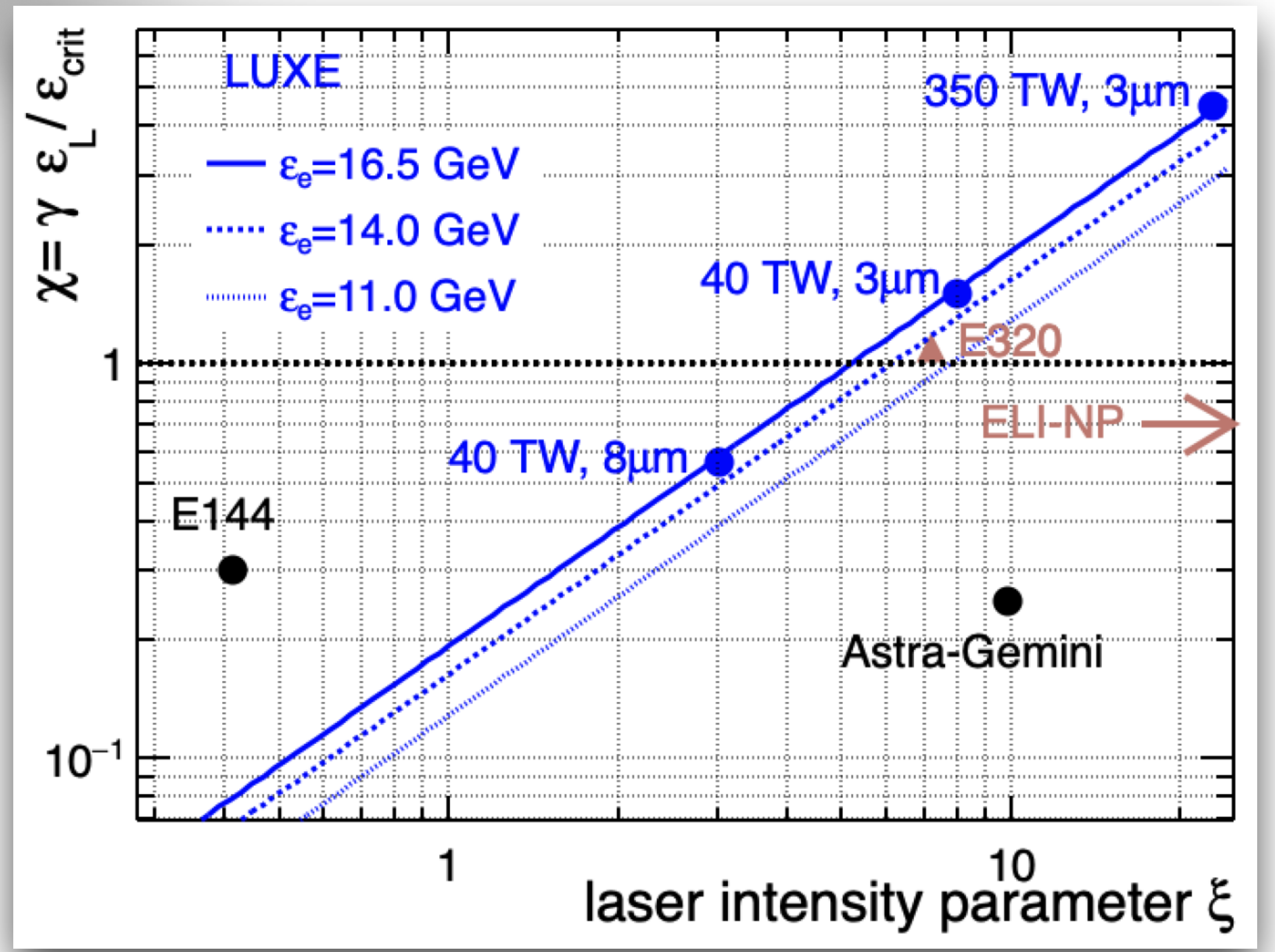


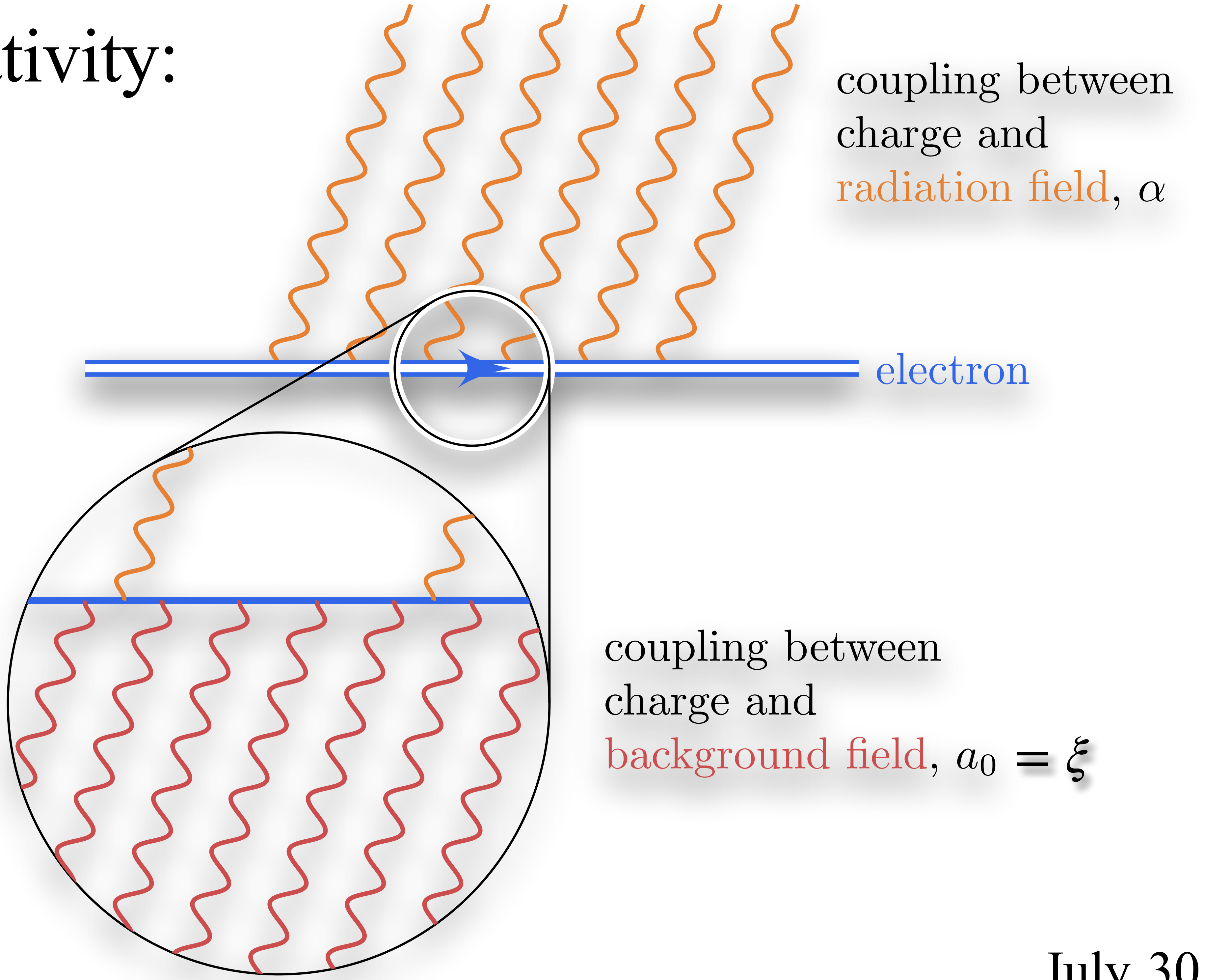


LUXE physics in a nutshell

- Nonlinear Compton scattering followed by Nonlinear Breit-Wheeler pair production
- Fermions inside the pulse are Volkov states
- Characterised by two dimensionless parameters:
  Laser intensity $\boldsymbol{\xi \propto \frac{\epsilon}{\epsilon_S}}$ and Quantum par. $\boldsymbol{\chi \propto \frac{E_e}{m_e}\xi}$
- Non-perturbativity:
  $\boldsymbol{\xi \gg 1}$







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Phys. Rev. D 99, 036008 (2019)
arXiv:2107.02161

LUXE @ the Eu.XFEL

Conceptual Design Report for the LUXE Experiment

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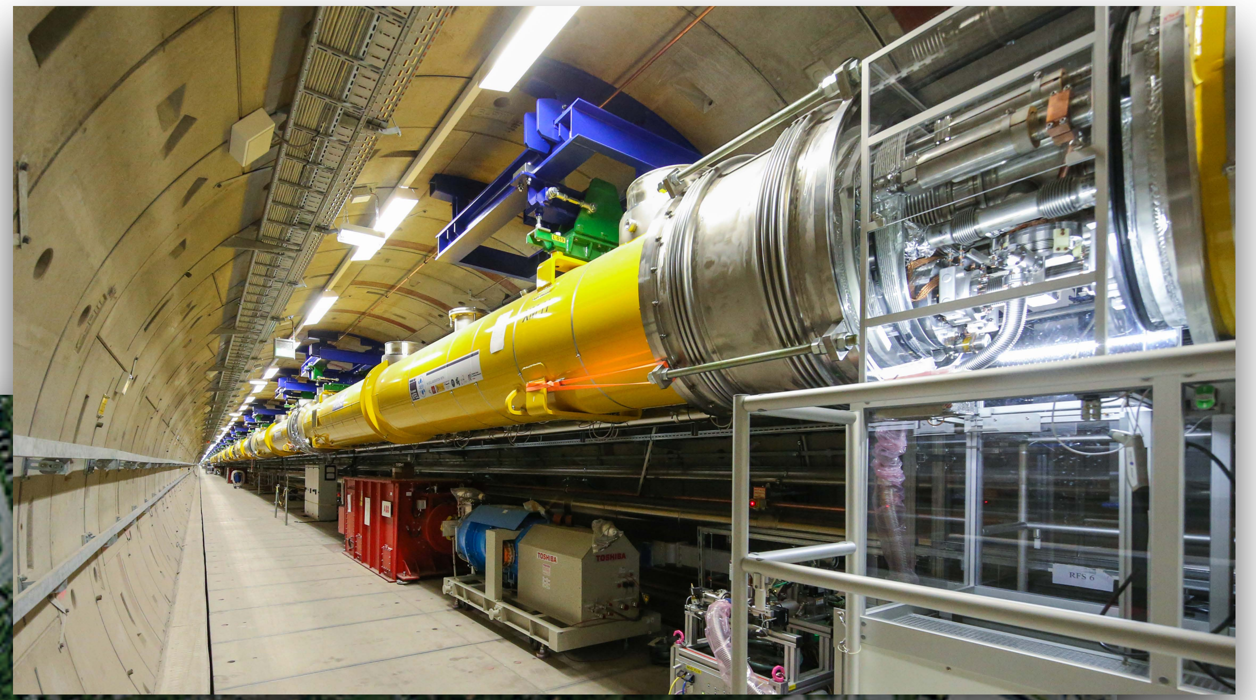
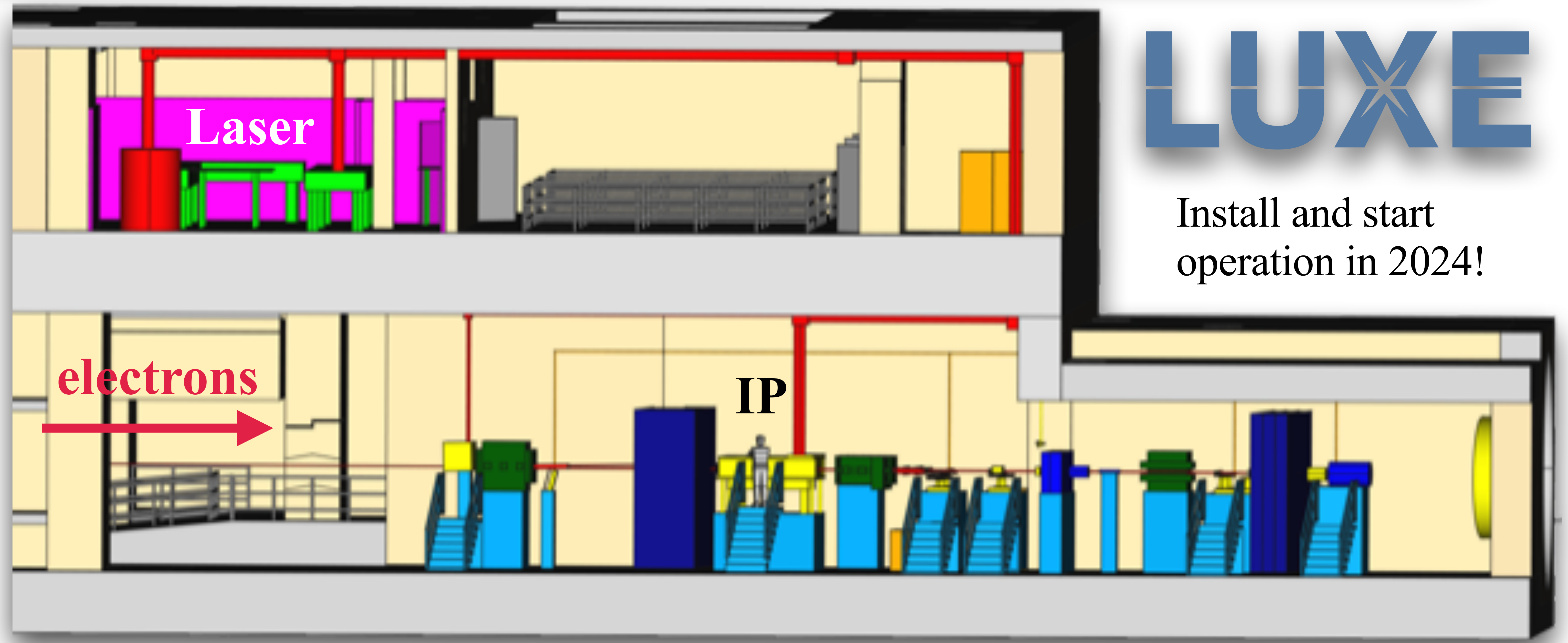


$$\epsilon_{\text{Laser}} \to \epsilon_{\text{Laser}} \times \frac{E_e \sim 10\ \text{GeV}}{m_e \sim 0.5\ \text{MeV}} \sim \epsilon_{\text{Laser}} \times 10^4$$

Electrons	E_e up to **16.5 GeV**, with N_e = **1.5×10⁹ e^-/bunch** and a bunch charge up to 1.0 nC,
	1/2700 bunches/train, ~1+9 Hz (collisions+background), spot r_{xy}=5 μm, l_z=24 μm
Laser	Ti-Sapphire, 800 nm, **40/350 TW**, up to ~10 J, ~10 Hz repetition, 60% losses
	~30-200 fs pulse length, down to 3×3 μm² FWHM spot with up to I~10²¹ W/cm²



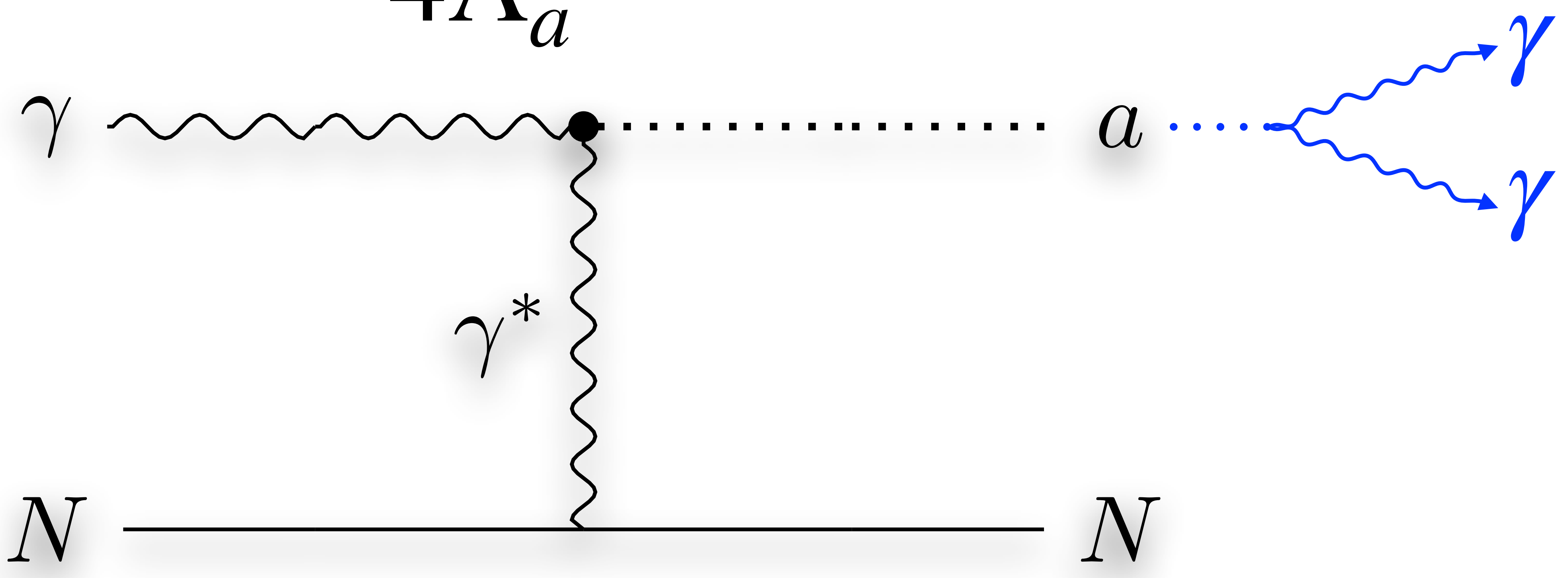
LUXE

Install and start operation in 2024!

New Physics at LUXE

ignore today

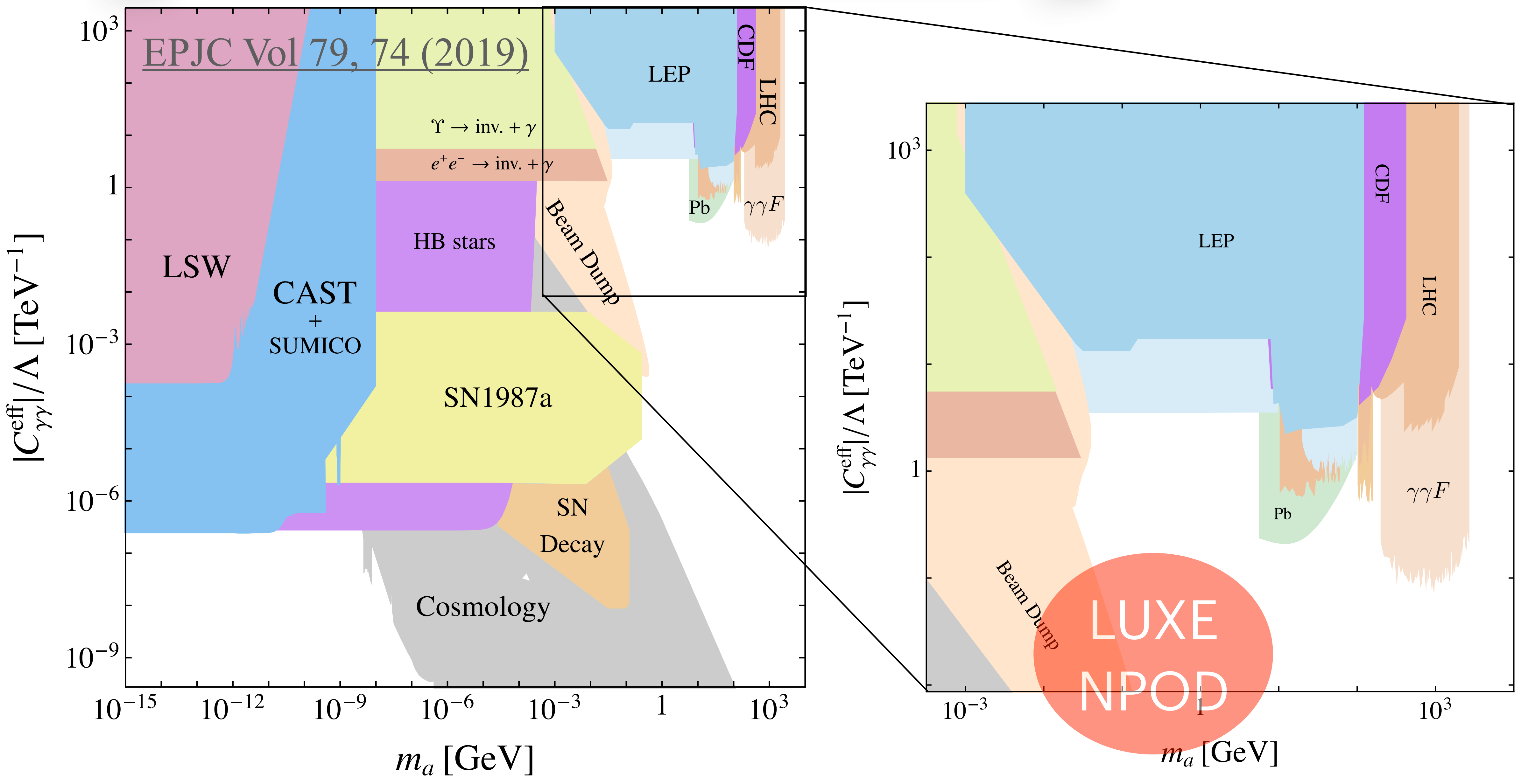
$$\mathscr{L}_a = \frac{a}{4\Lambda_a} F_{\mu\nu}\tilde{F}^{\mu\nu} + \cancel{i g_{ae}}\, a\bar{e}\gamma^5 e$$



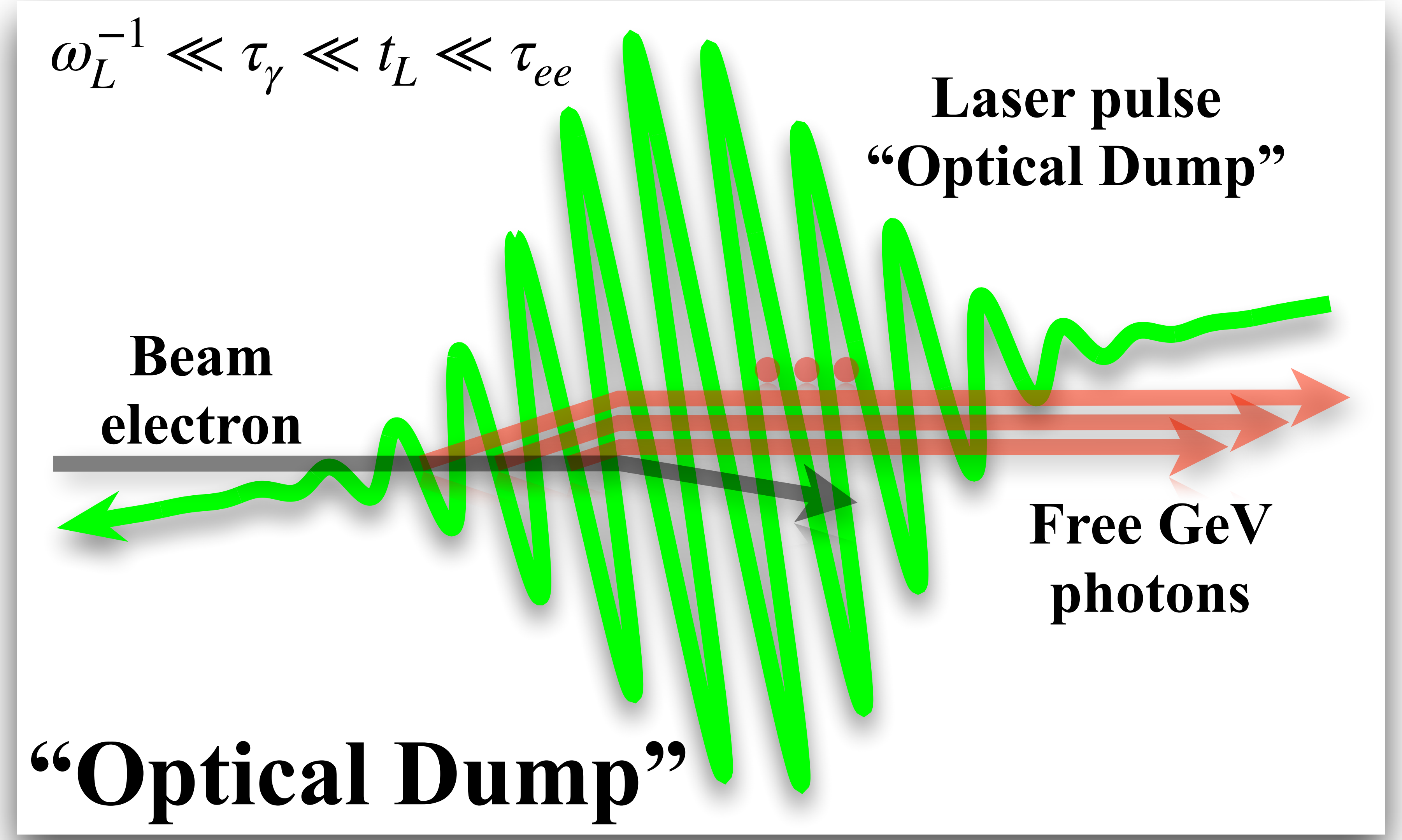
- Focus on axion-like particles (ALP) search
  - in many motivated extensions of the SM
  - addresses the strong CP & the hierarchy problems, valid dark matter candidate,…
  - everything will apply also to scalars with $a \to \phi,\ \tilde{F}_{\mu\nu} \to F_{\mu\nu},\ i\gamma^5 \to 1$

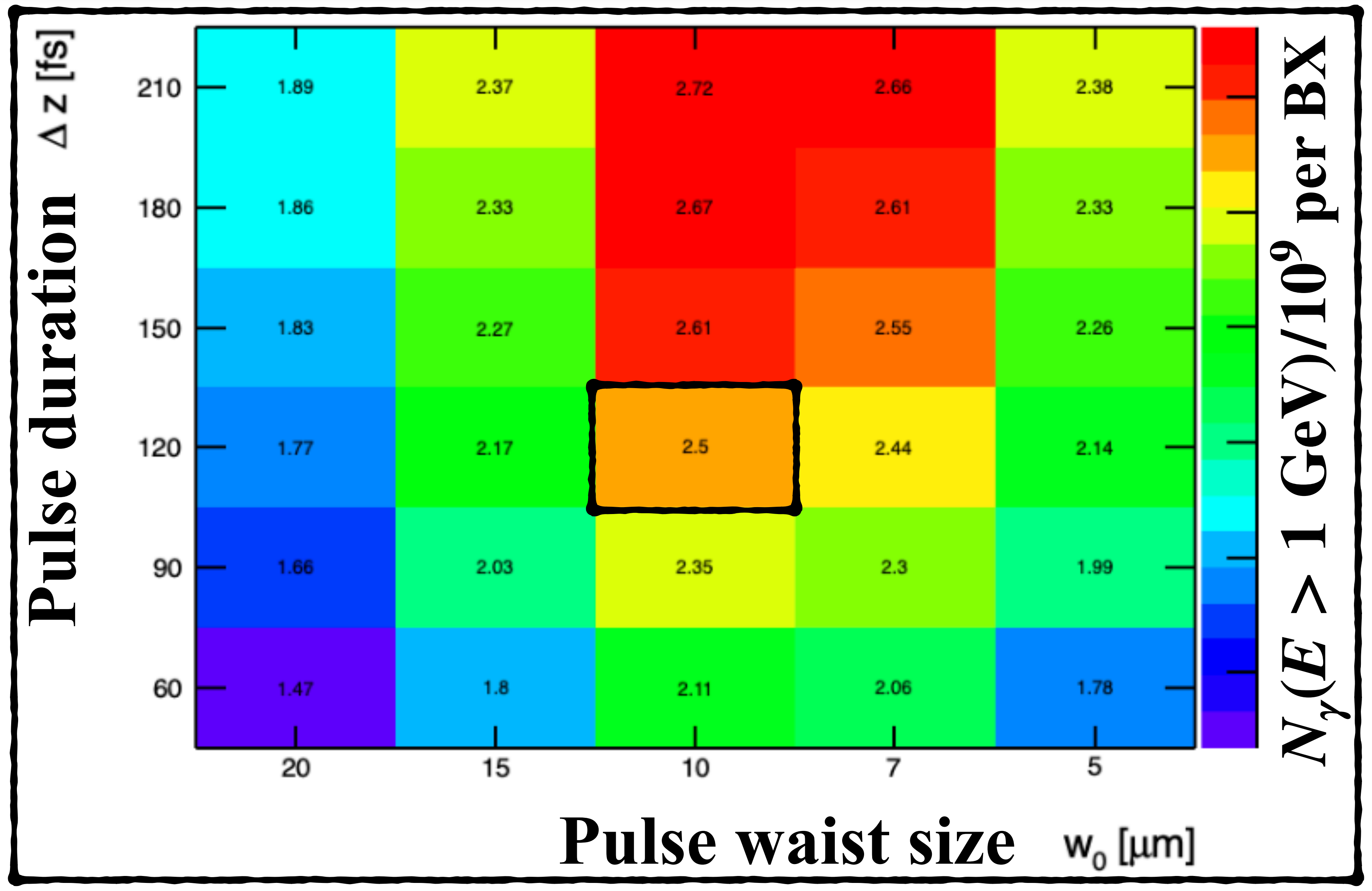
- Focusing on the Primakoff production with a displaced decay to 2 hard photons

- See backup for ALP production discussion

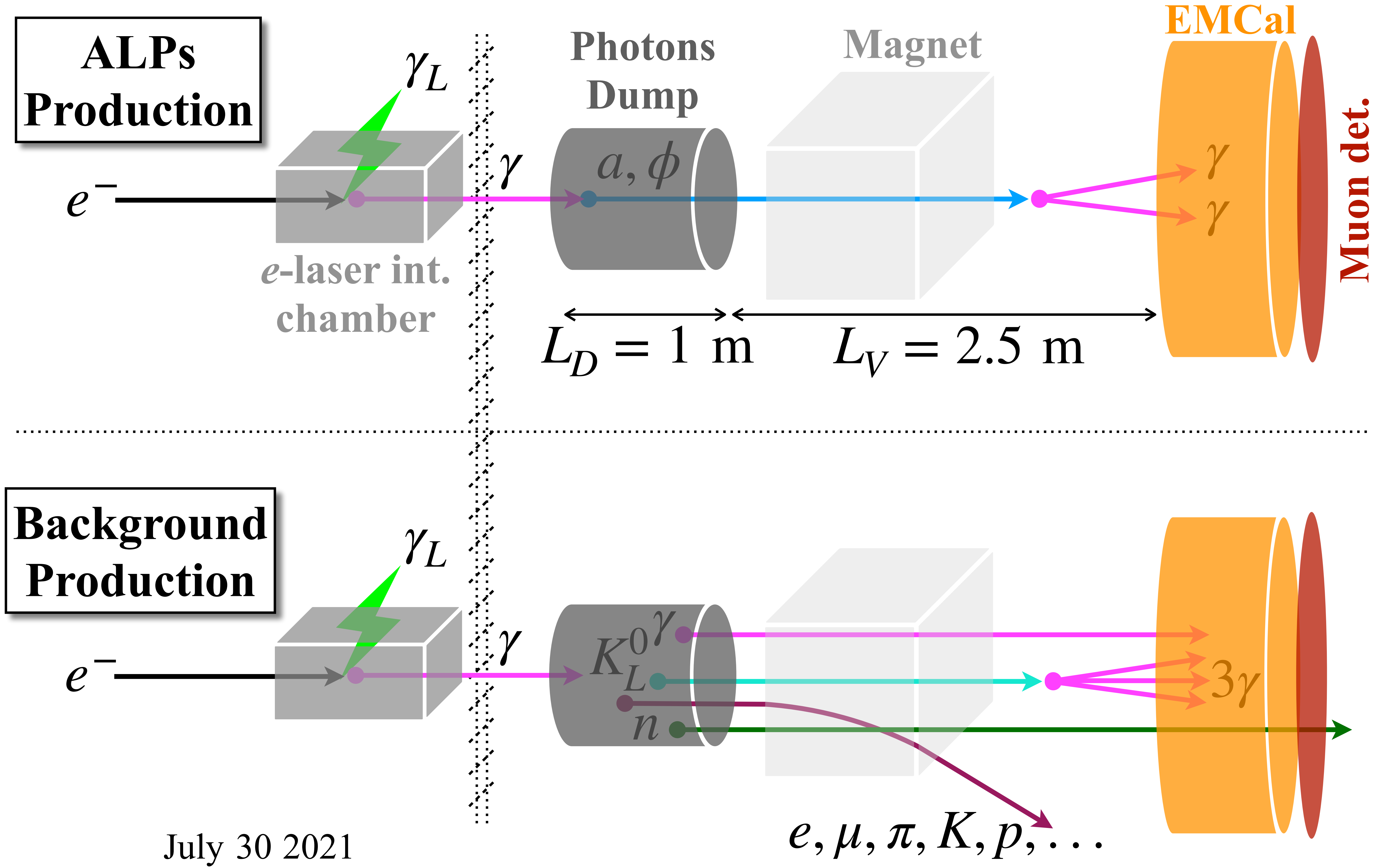


New Physics @ Optical Dump





$$N_a \approx \mathscr{L}_{\text{eff}} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \sigma_a(E_\gamma, Z) \left(e^{-\frac{L_D}{L_a}} - e^{-\frac{L_V + L_D}{L_a}} \right) \mathscr{A}$$

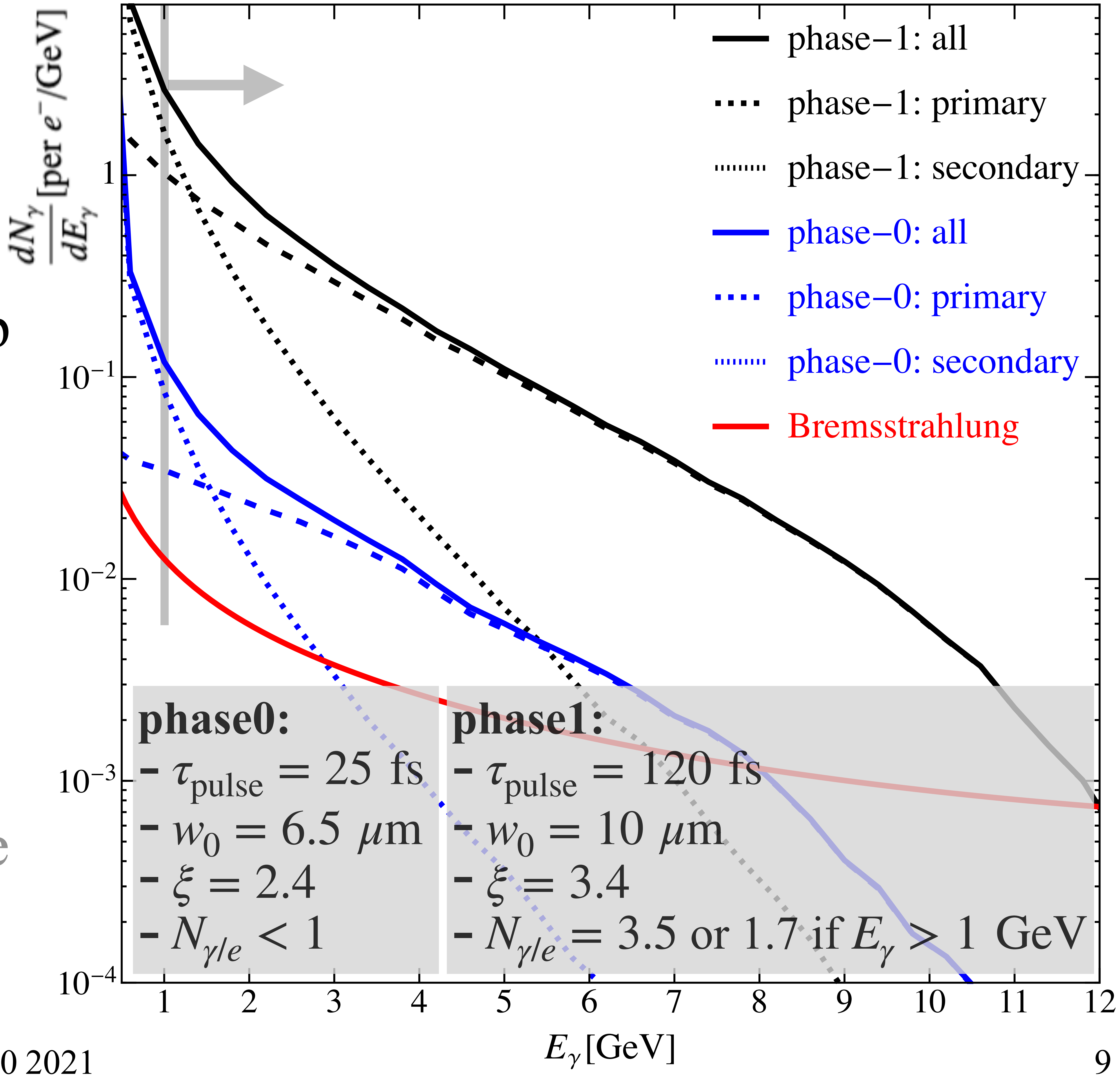


Photon spectra for ALPs production

- Showing spectra per primary electron
  - "primary" from the IP and
  - "secondary" from the shower in the dump

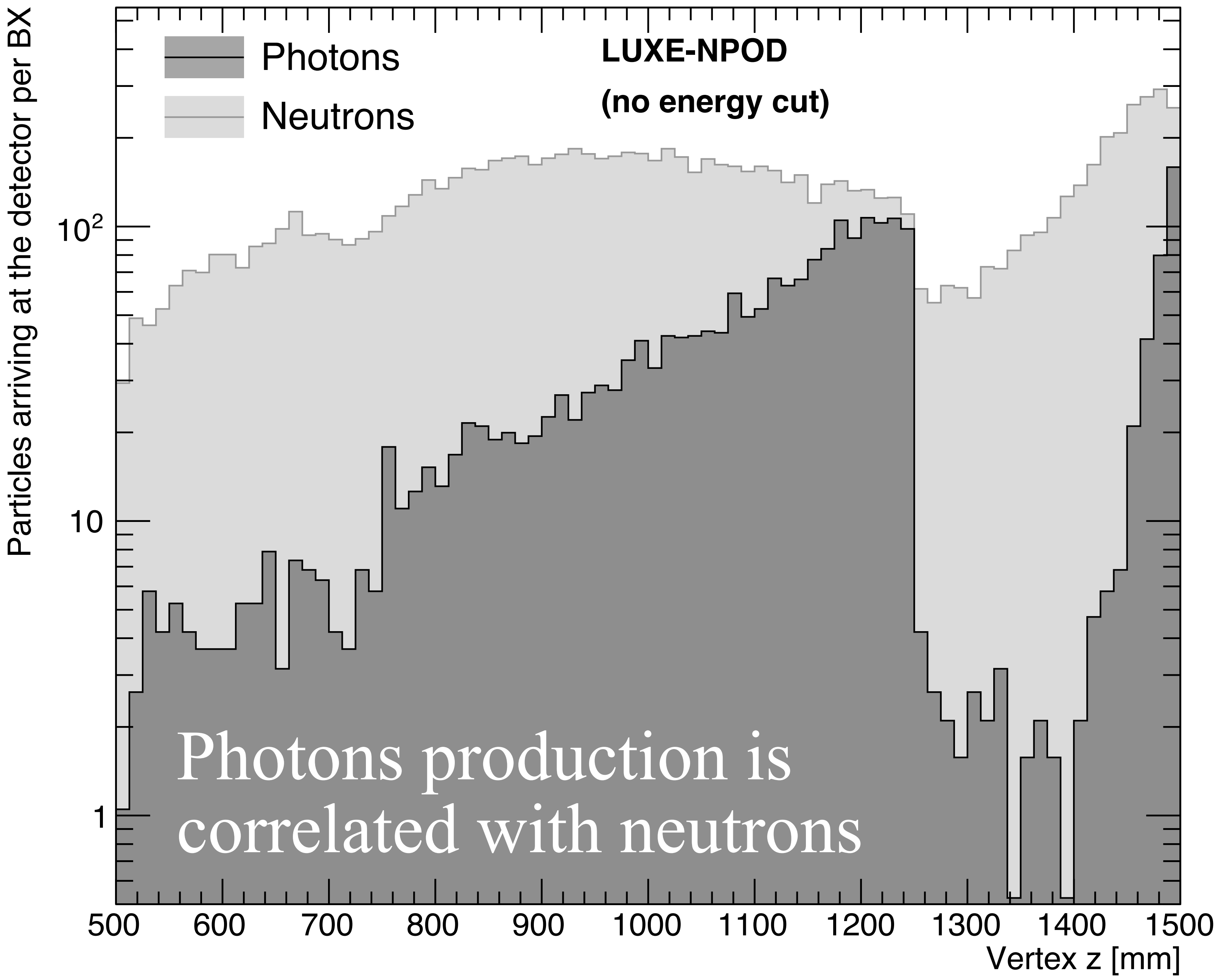
- "Many" photons per electron (phase-1):
  ~3.5 for ($E_\gamma > 0$ GeV)
  ~1.7 for ($E_\gamma > 1$ GeV)

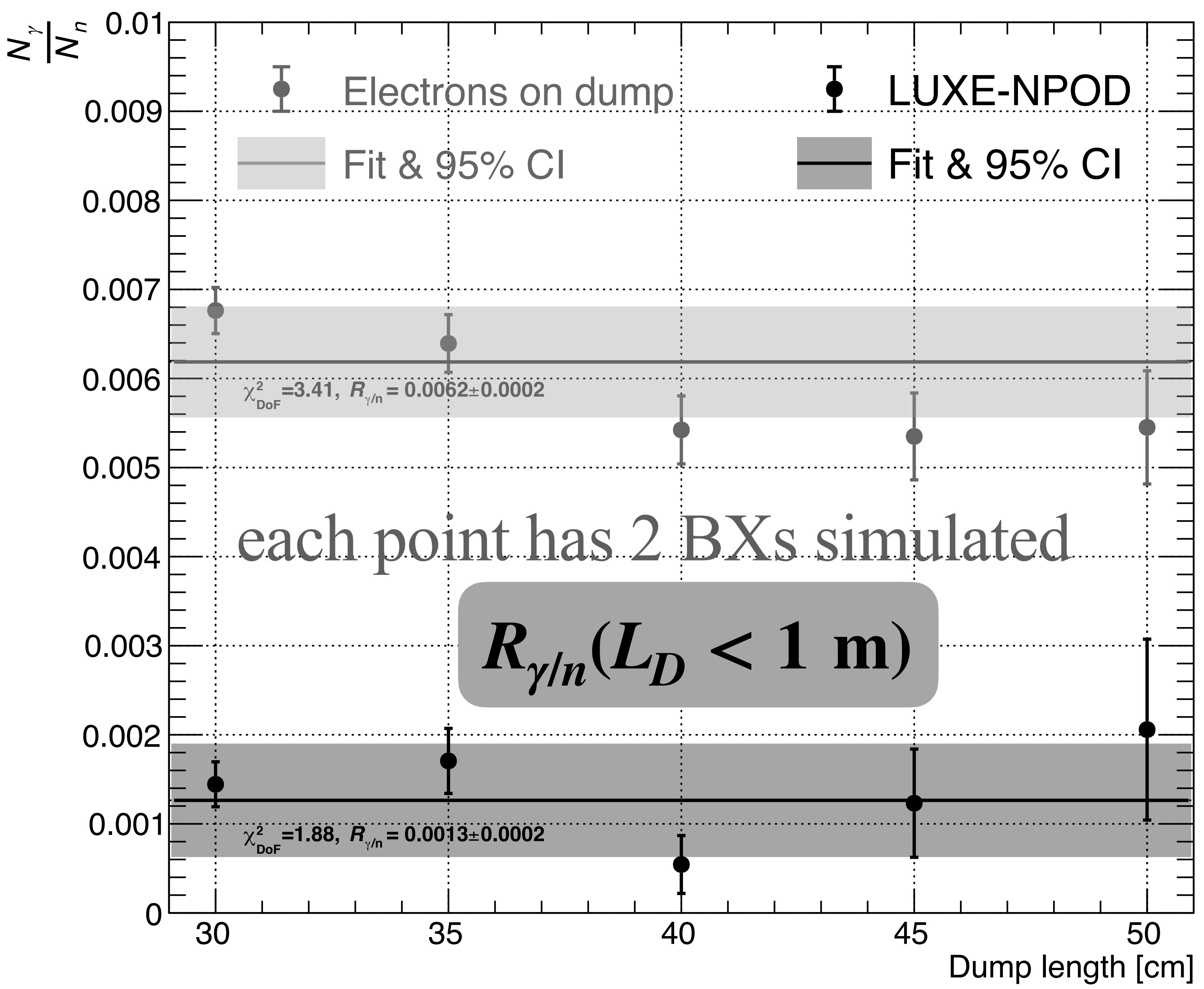
- Not shown: spectra for the electrons-on-dump case. One expects a factor of ~2 more photons - more signal!, **what about bkg?**



Background estimation

- Remaining background is mostly neutrons and photons
  - we get <u>0 photons</u> and 10 neutrons per BX for 2 BXs simulated
- This is inaccurate: need many more BXs for a proper estimate
  - however, the simulation is very intensive computationally
- Instead, we see that the photon production is correlated with the neutrons production (in hadronic processes)
- So, N_γ can be extrapolated from the photons-to-neutrons ratio of shorter L_D dumps where we have enough photons, using: $\boldsymbol{N_\gamma(L_D = 1\ \mathrm{m}) \sim N_n(L_D = 1\ \mathrm{m}) \times R_{\gamma/n}(L_D < 1\ \mathrm{m})}$
- For 1 year of (~10^7 s) with a reasonably good detector we can have $\lesssim 1$ background events hence we may assume bkg-free search

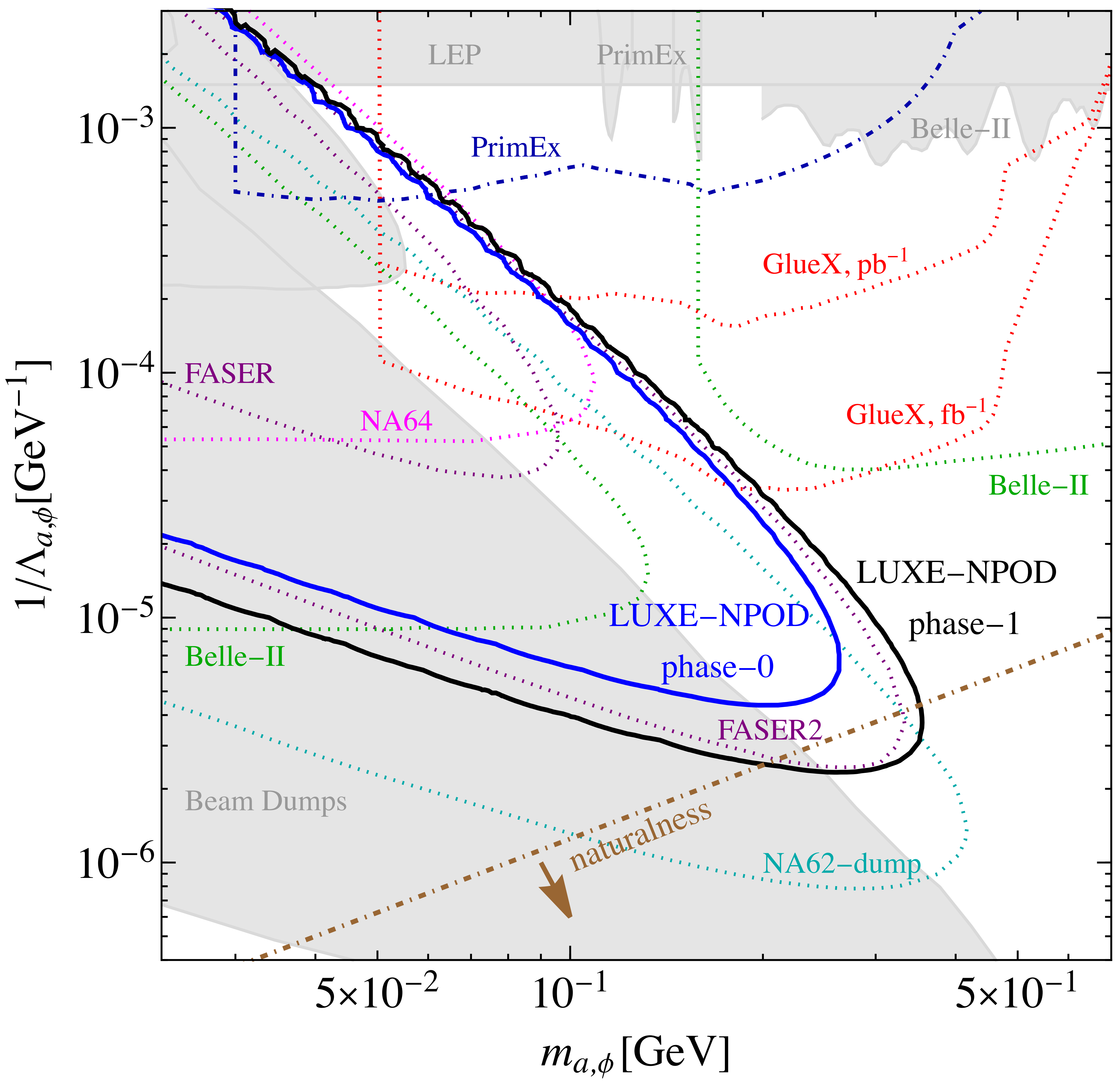




Outlook

- LUXE is a new exciting experiment with a novel baseline plan to test strong-field QED predictions in a region never explored before in clean environments
- Plan is very streamlined: take data in early ~2025
- LUXE can also search for new physics
  - exploiting the optical dump concept
  - see backup for new physics production at the IP
- The proposal is an "easy" addition to the experiment and it can be made effectively background free
  - see paper for discussion about possible technologies
- Our reach is comparable to projections from NA62 (need a dedicated run) and FASER2 (end of HL-LHC)
  - $40 \lesssim m_{a,\phi} \lesssim 350$ MeV and $\Lambda_{a,\phi}^{-1} > 2\times10^{-6}$ GeV^{-1}

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



LUXE

ROYAL HOLLOWAY UNIVERSITY OF LONDON

QUEEN'S UNIVERSITY BELFAST

UCL

UNIVERSITY OF PLYMOUTH

DESY.

mpsd
Max-Planck-Institut für Struktur und Dynamik der Materie

TECHNISCHE UNIVERSITÄT DARMSTADT

HELMHOLTZ
Helmholtz-Institut Jena

université PARIS-SACLAY

UNI FREIBURG

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

INFN
Istituto Nazionale di Fisica Nucleare

Università degli Studi di Padova

UNIVERSITAS GOTHOBURGENSIS 1891

National Research Tomsk State University

Tomsk, Russia

Skoltech
Skolkovo Institute of Science and Technology

SUSTech
Southern University of Science and Technology

Shenzhen, China

MEPhI
NATIONAL RESEARCH NUCLEAR UNIVERSITY • MOSCOW ENGINEERING PHYSICS INSTITUTE

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

TECHNISCHE UNIVERSITÄT DRESDEN

AGH
AGH University of Science and Technology

НАЦІОНАЛЬНА АКАДЕМІЯ НАУК УКРАЇНИ 1918

TECHNION
Israel Institute of Technology

TEL AVIV UNIVERSITY

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

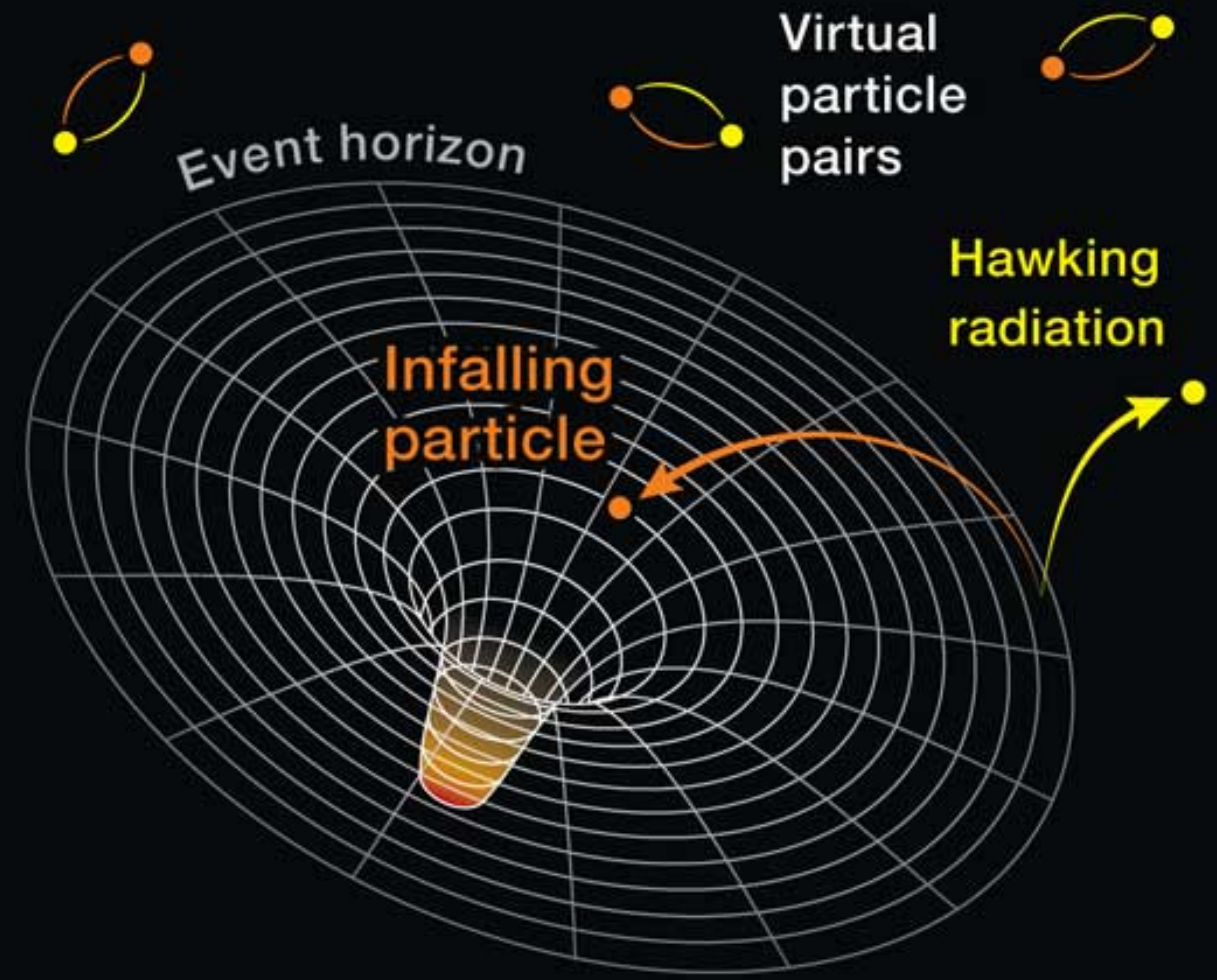

THANK YOU

Backup

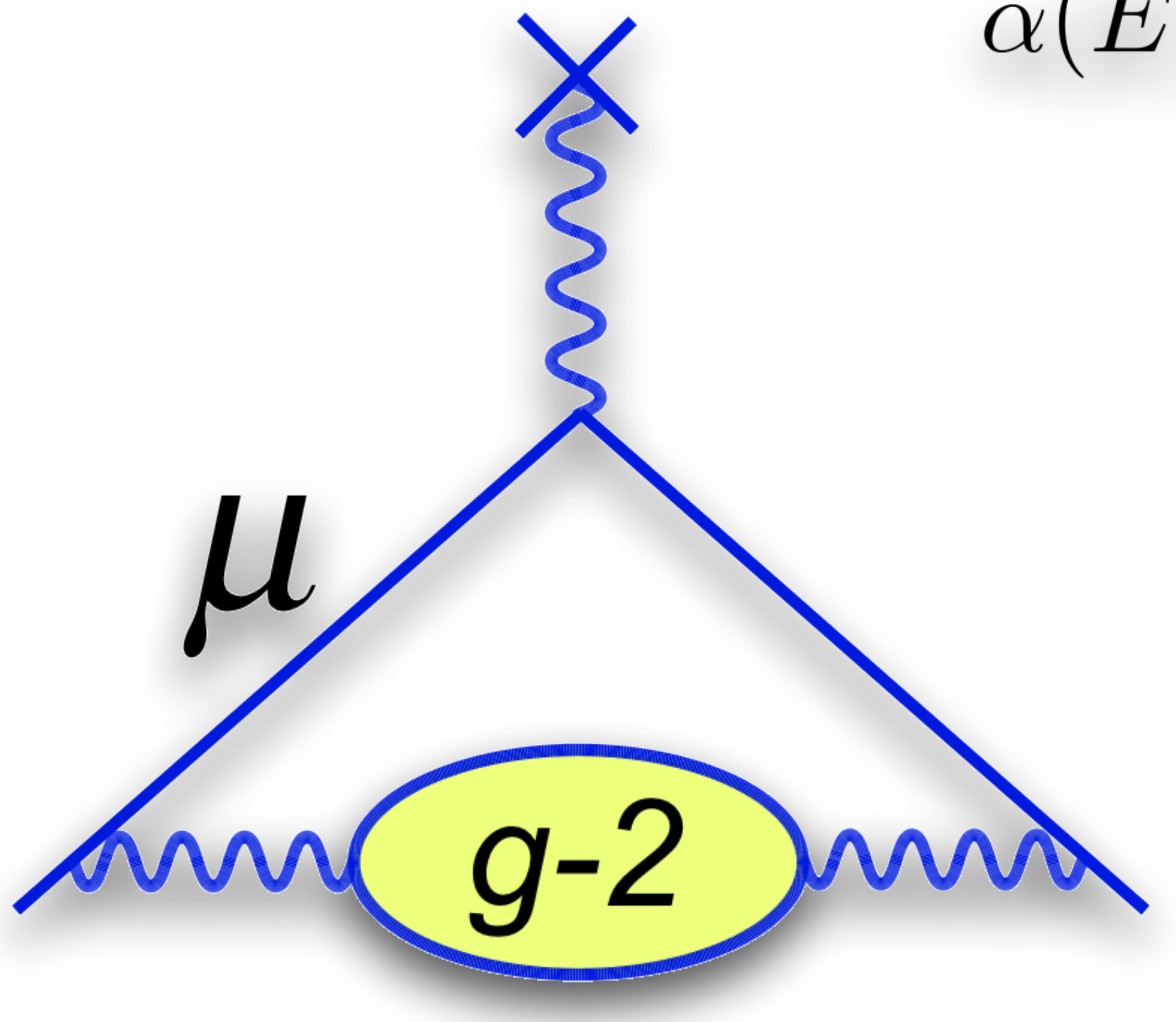
The Hawking equivalent

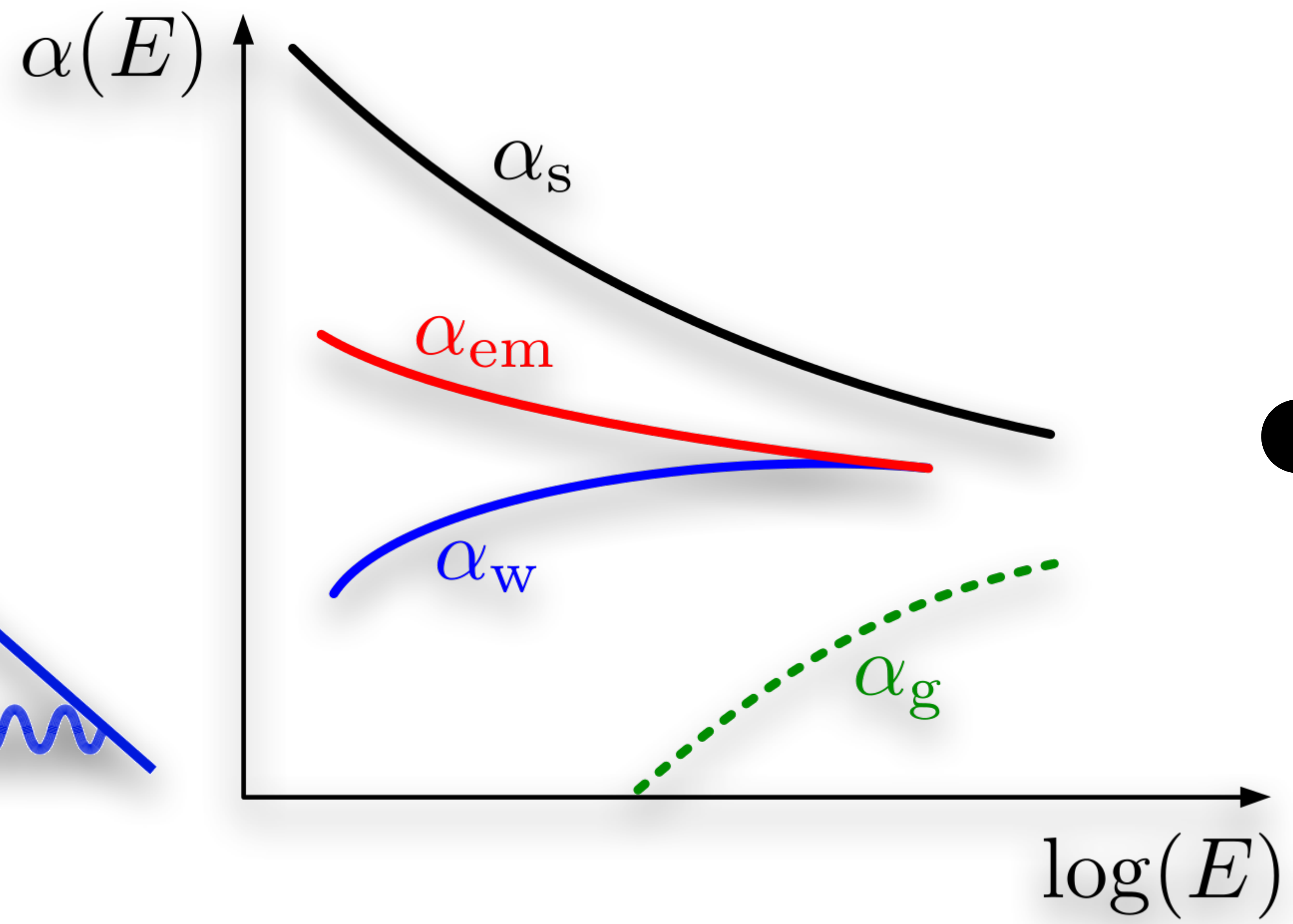
- **Outside observer:** the BH has radiated a particle so the energy must come from it

- **Looking at the system:** the BH energy has decreased so its mass must decrease



Why strong field physics?





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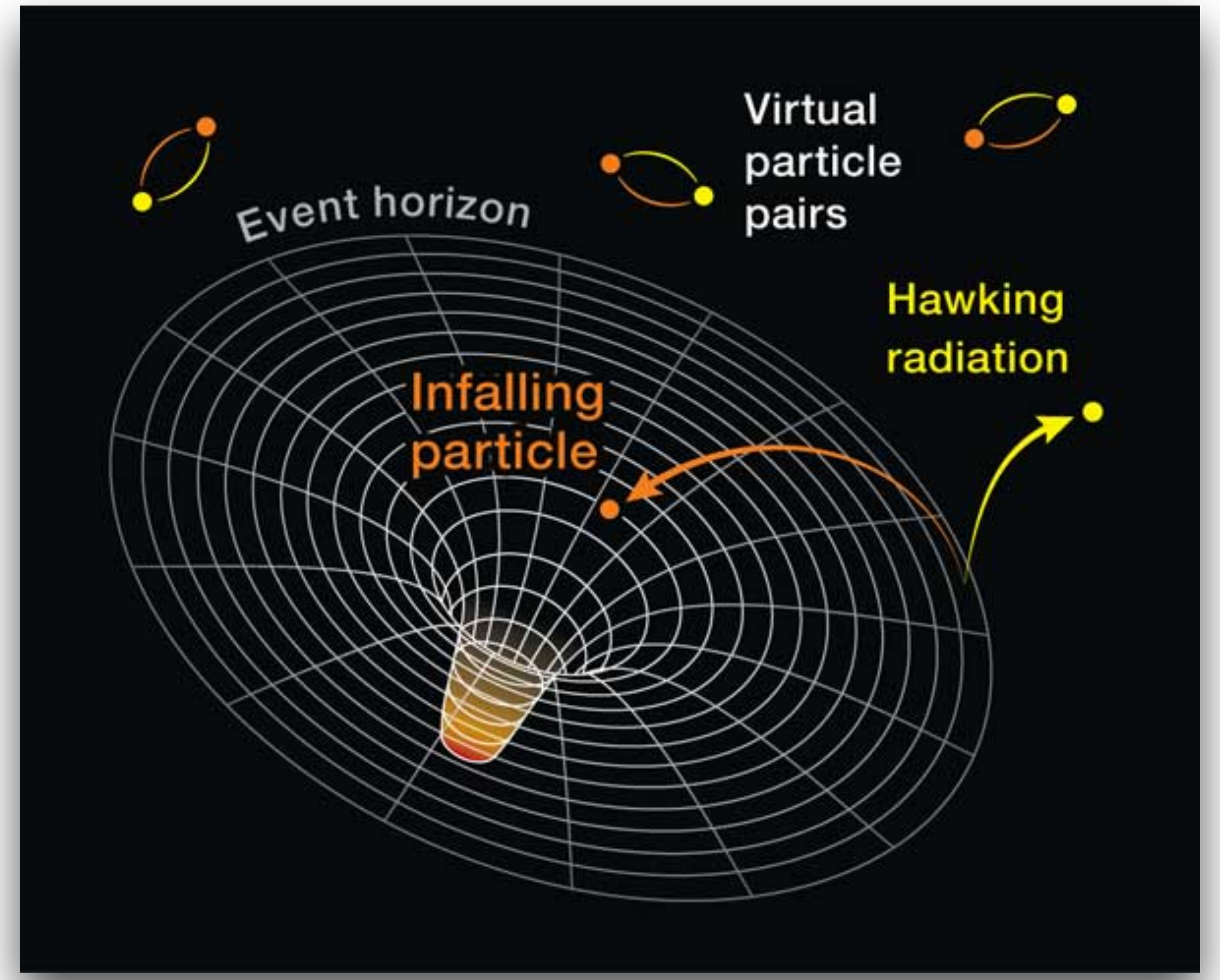


- Reaching ϵ_S is equivalent e.g. to the measurement of the anomalous magnetic moment or the coupling constant and deviations could be a hint for new physics
- Non-perturbative QFT is still being actively developed
- Can provide insight into the vacuum state / Higgs mechanism
- Schwinger effect proposed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

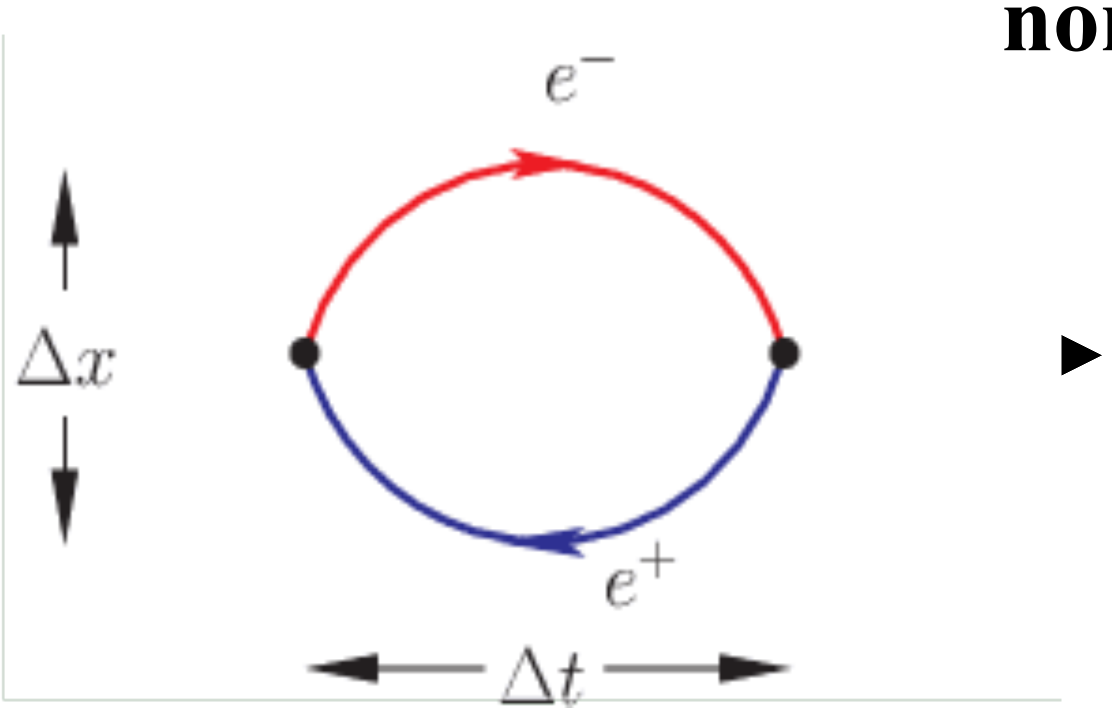
The Schwinger mechanism simplified

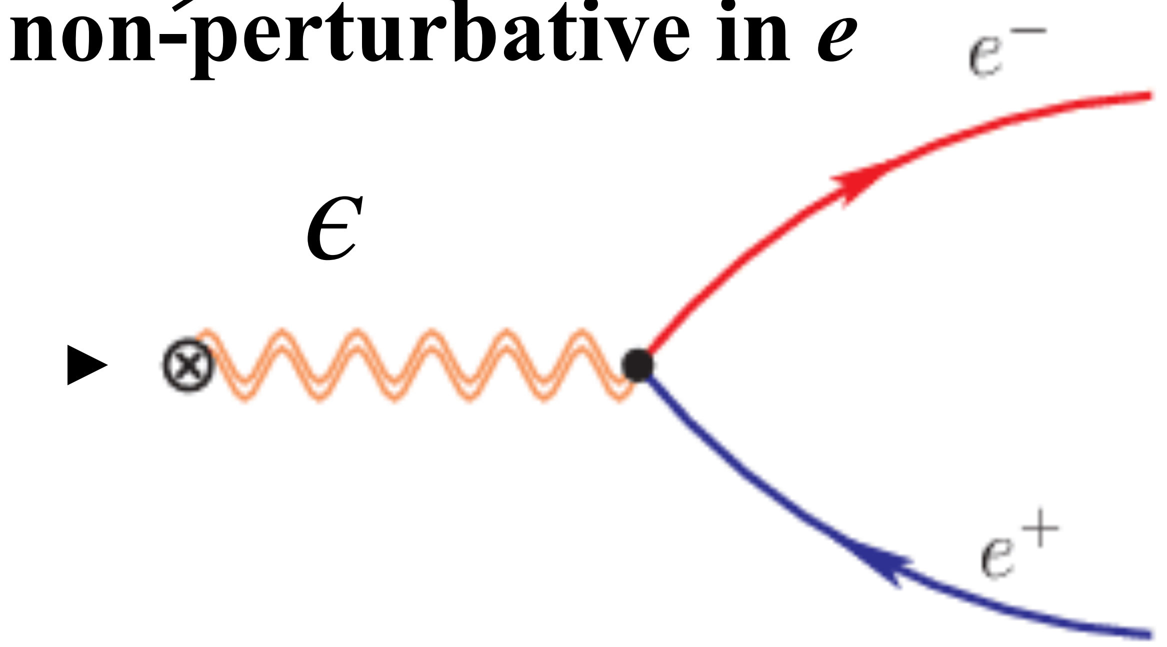
- Force of external static electric field is: $F = e\epsilon$
- Energy to separate the virtual pair in a distance d: $E = F \cdot d = e\epsilon \cdot d$
- Energy required to materialise as a real pair: $E = 2m_e c^2$
- Condition to materialise as a real pair in distance d: $e\epsilon d = 2m_e c^2$
-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

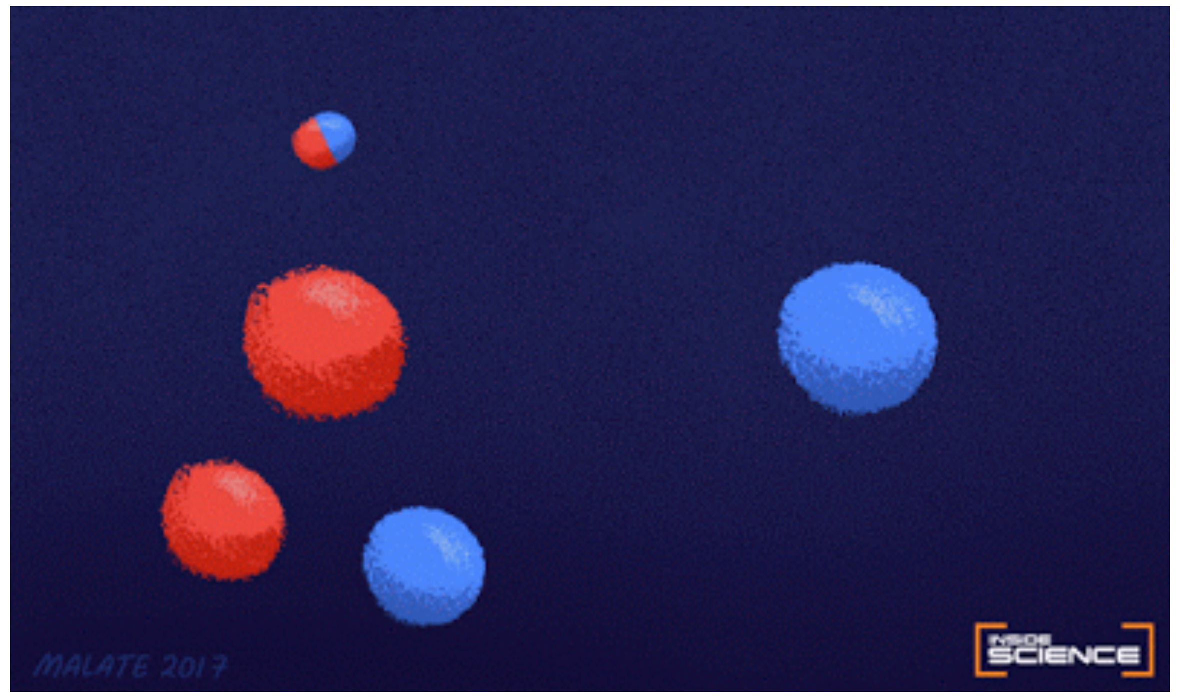
$$P \propto \exp\left(-\frac{d}{\lambda_C}\right) = \exp\left(-2\frac{m_e^2 c^3}{\hbar e \epsilon}\right) = \exp\left(-2\frac{\epsilon_\mathrm{S}}{\epsilon}\right)$$

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

non-perturbative in *e*

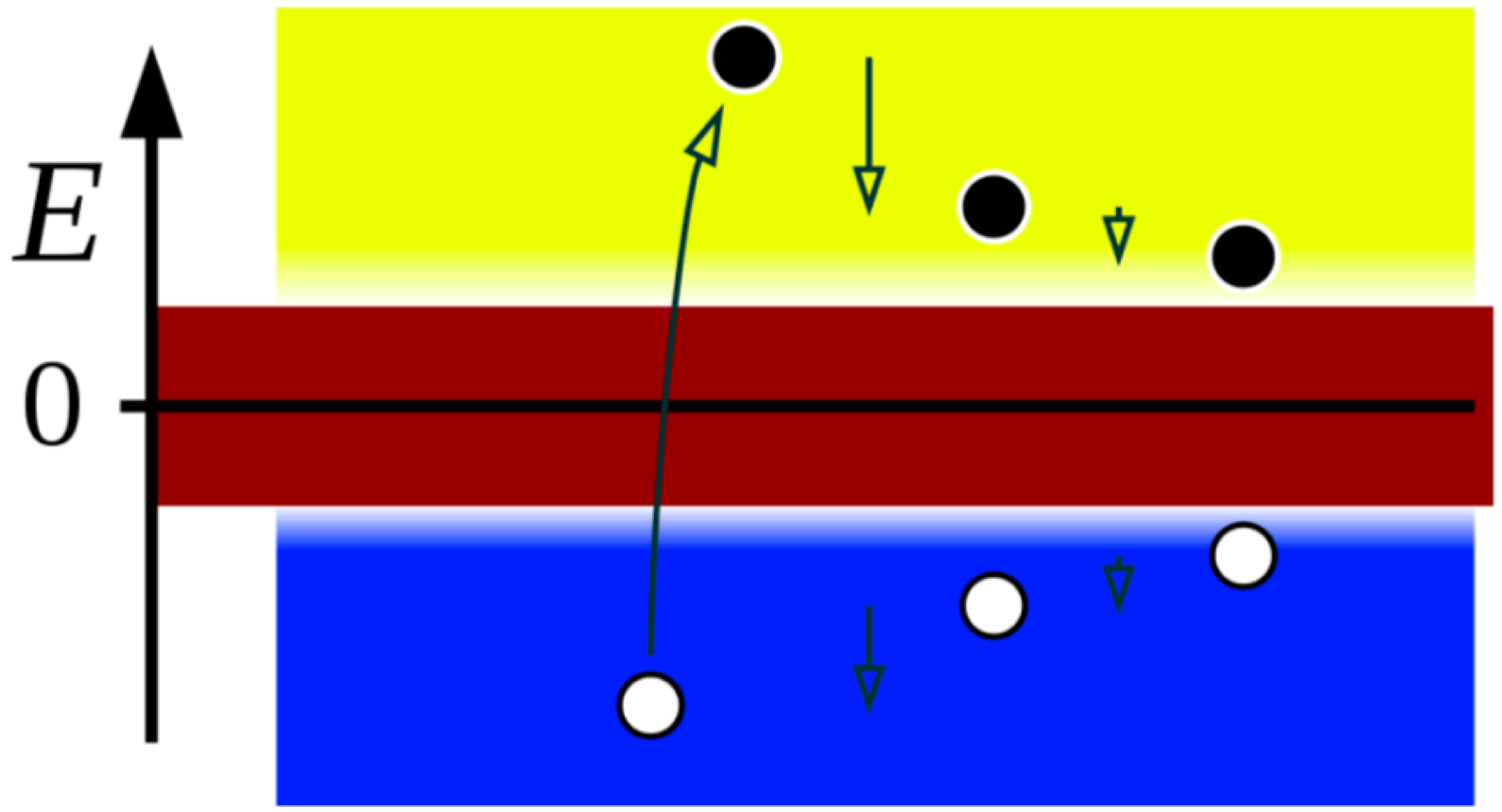






The Furry Picture vacuum

The 2nd 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

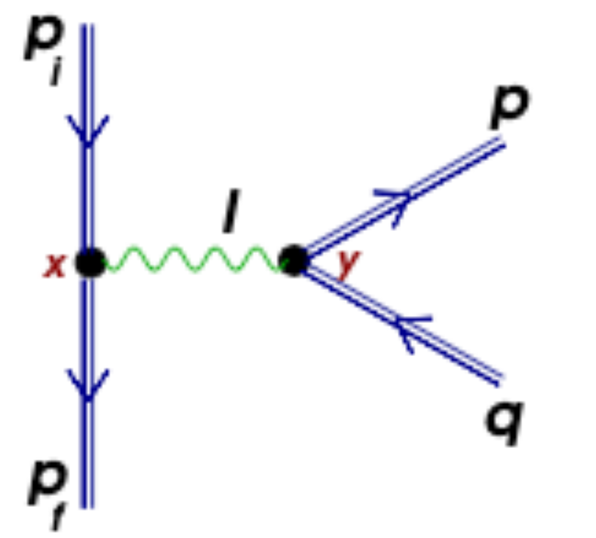
The Furry Picture

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

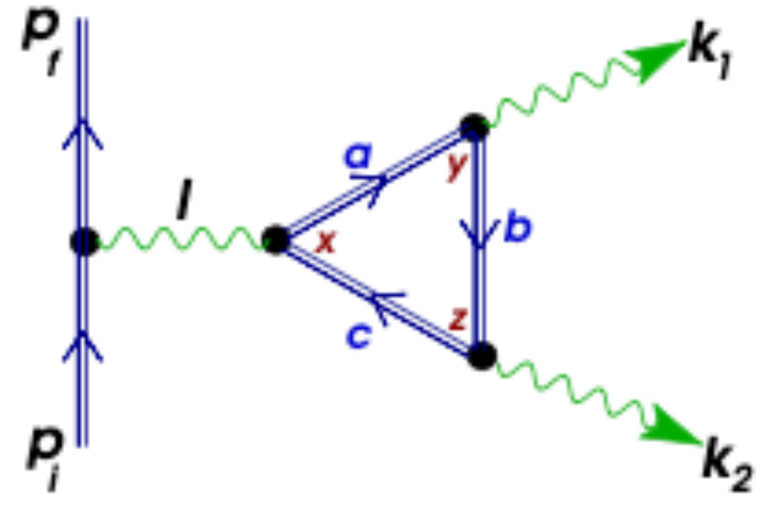
- If the external field is sufficiently strong: quantum interactions with it leave it essentially unchanged and it can be considered to be a classical background field
- Separate the gauge field to external and quantum parts:
  $\mathscr{L}_{\text{Int}} = \bar{\psi}(i\not{\partial} - m)\psi - \frac{1}{4}F_{\mu\nu}^2 - e\bar{\psi}(\not{A}_{\text{ext}} + \not{A})\psi$ 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}: $(i\not{\partial} - e\not{A}_{\text{ext}} - m)\psi^{\text{FP}} = 0$

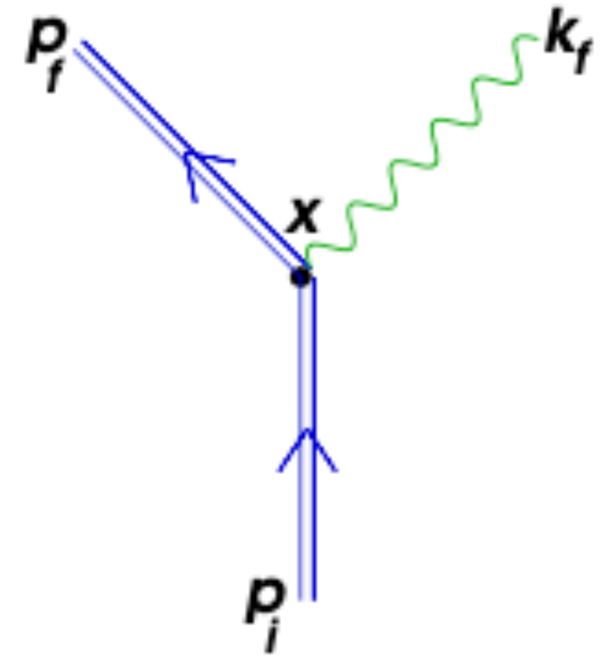
- Exact solutions exist for a certain classes of external fields (plane waves, Coloumb fields and combinations) [Volkov Z Physik 94 250 (1935), Bagrov & Gitman 1990]:
  $\psi^{\text{FP}} = \mathbf{E}_p e^{-ipx} u_p$ with $\mathbf{E}_p = \text{Exp}\left[-\frac{1}{2k\cdot p}\left(e\not{A}_{\text{ext}}\not{k}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



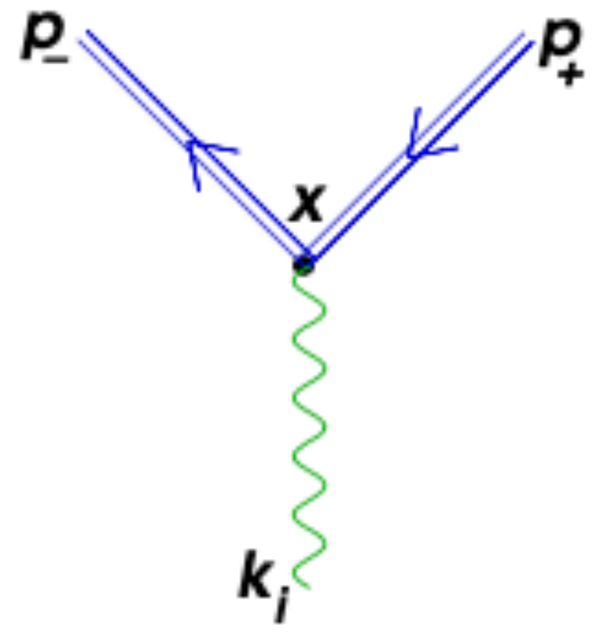
Trident process (vacuum resonance)



Photon splitting (vacuum birefringence)



High intensity Compton scatter (HICS)



One photon pair production (OPPP)

Boiling point of QED

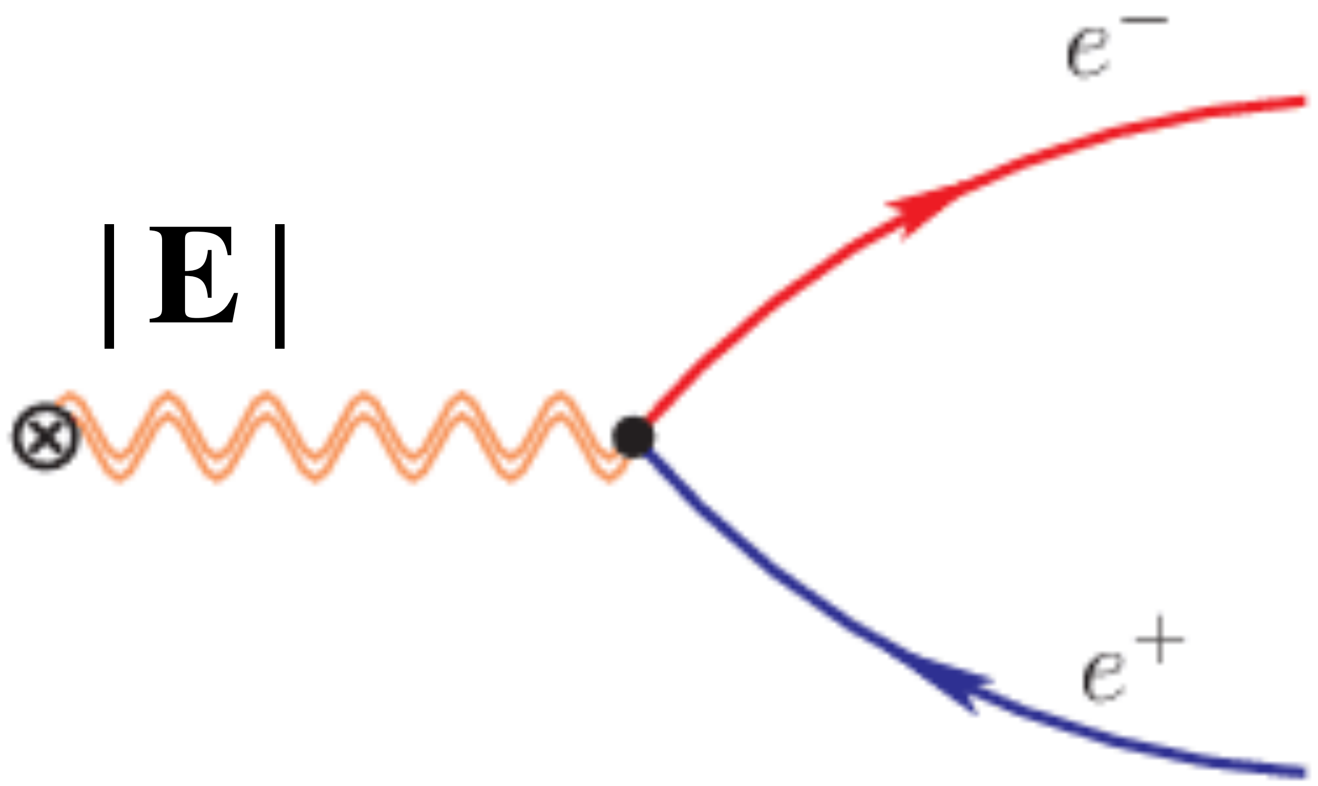
- **Weak fields:** many accurate predictions of observables through ordinary perturbative expansion in the EM coupling (α_{EM})

- **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:

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

non-perturbative in α



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

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Lasers strong field "how-to"

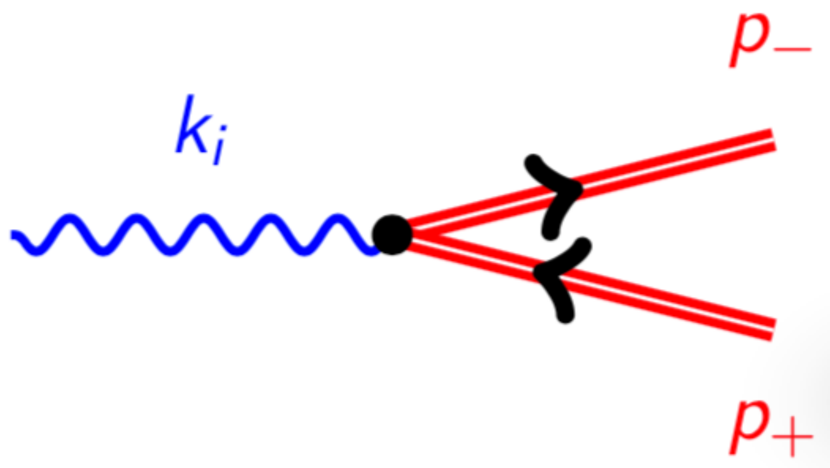
- Laser-assisted one photon pair production, OPPP (SPP $\longrightarrow$OPPP)
  - the laser's E-field frequency is ω, with momentum $k = (\omega, \mathbf{k})$
  - the laser's E-field strength is $|\epsilon|$, with $I \sim |\epsilon|^2$
  - The e^+e^- pair picks up momentum from the laser photons

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

Dimensionless and Lorentz-invariant

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

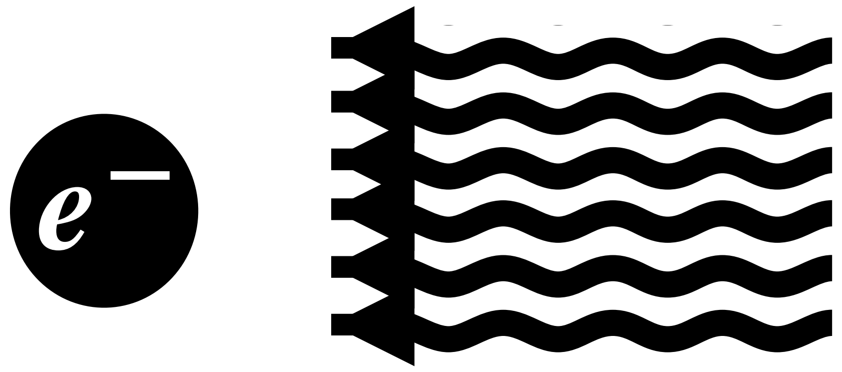
Initial photon : $k_i = (\omega_i, \mathbf{k}_i)$



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

Understanding ξ

Electron "at rest"



Infinite E-field plane wave with frequency ω

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

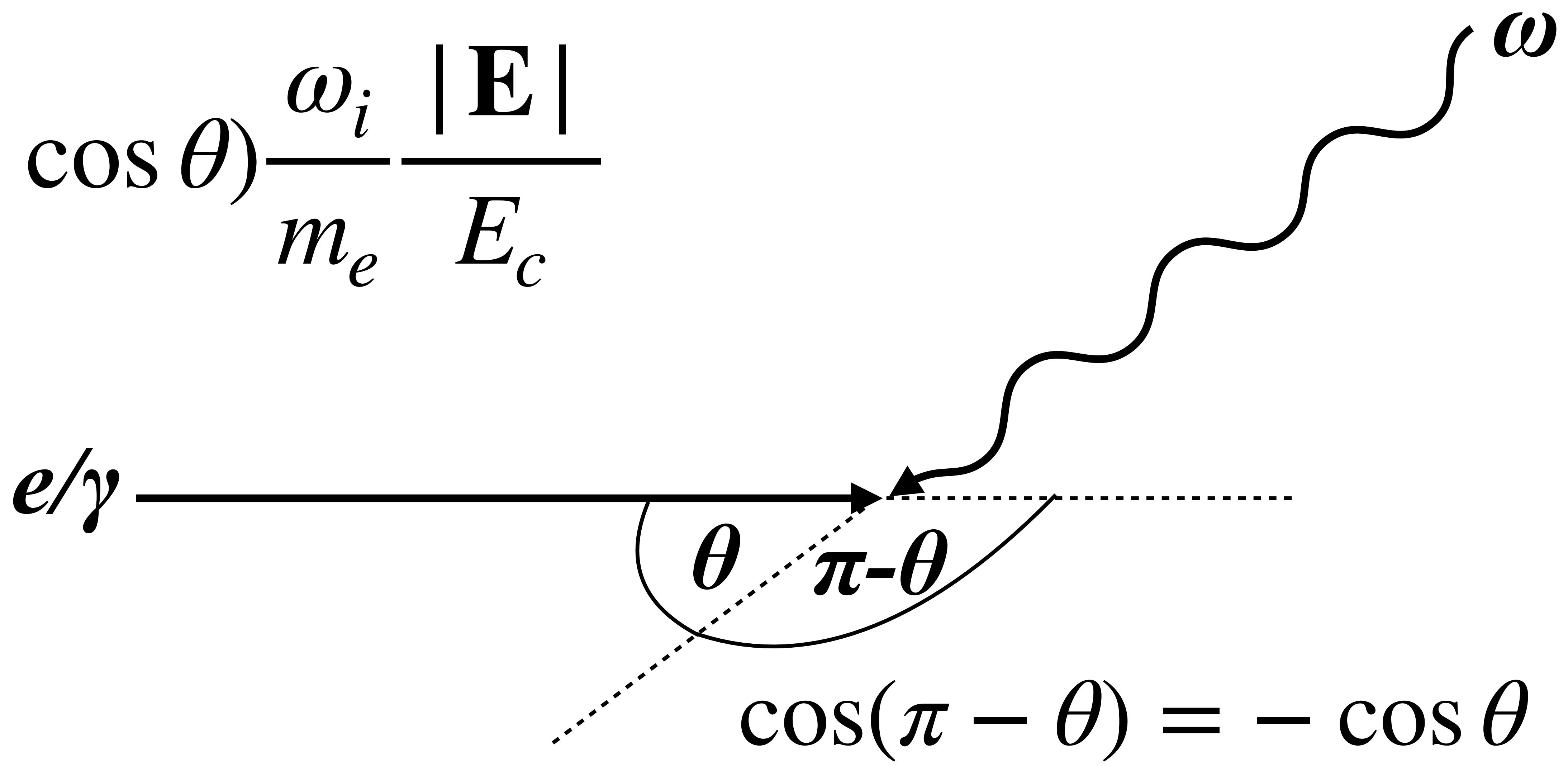
The electron's maximum velocity is: $v_{\max} = a \cdot \Delta t = \frac{eE}{m_e} \cdot \frac{1}{\omega}$

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



$\cos(\pi - \theta) = -\cos\theta$

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

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

As the laser intensity ξ increases

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

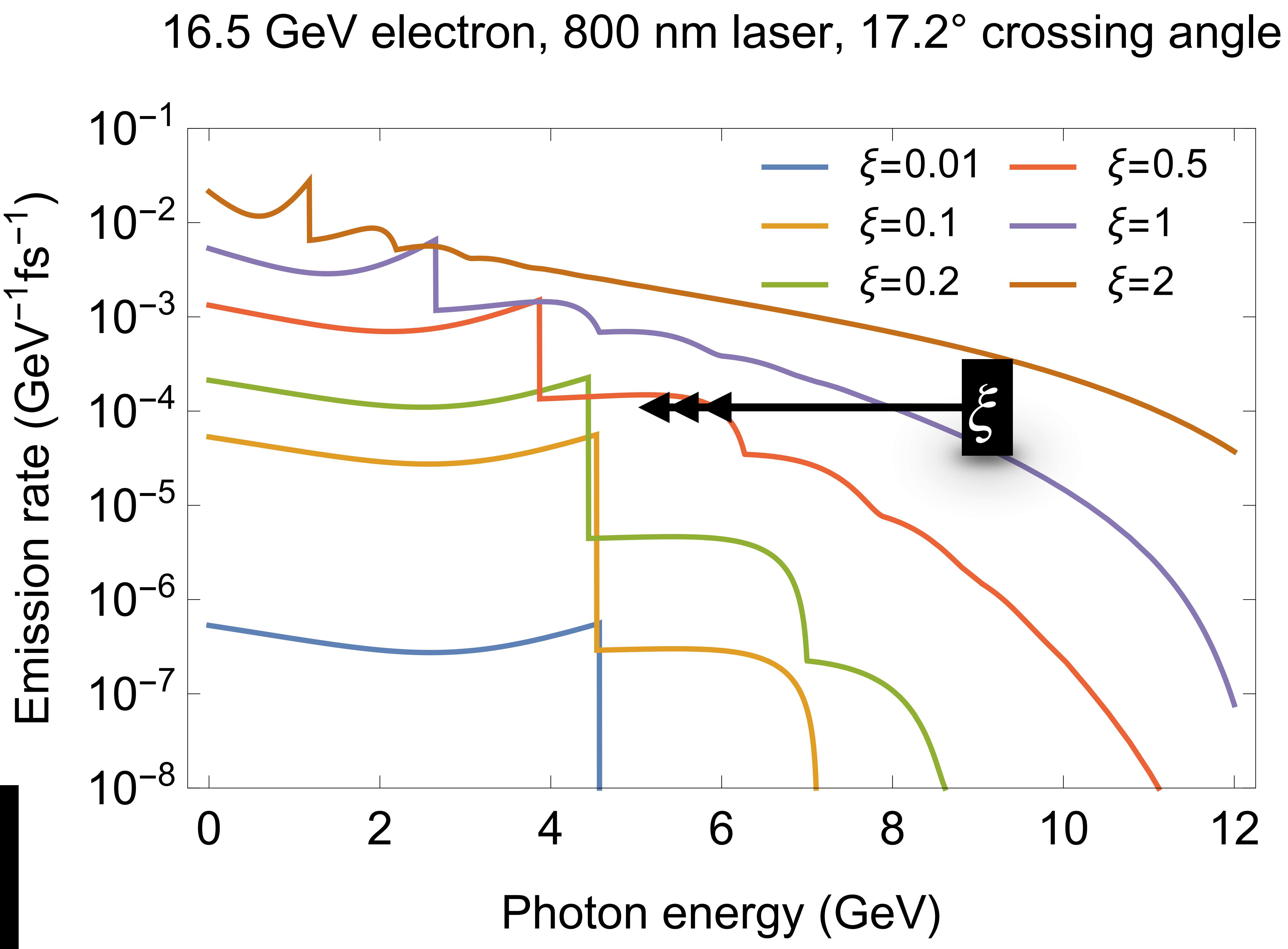
Assumption1: the laser E-field is a circularly polarised infinite plane wave

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

Compton edges

- With increasing laser intensity ξ:
- higher order (n) contributions become more prominent
- edge shifts to lower energies due to electron's higher effective mass

- Cannot go much beyond $\xi \sim 1$ to produce high energy photons

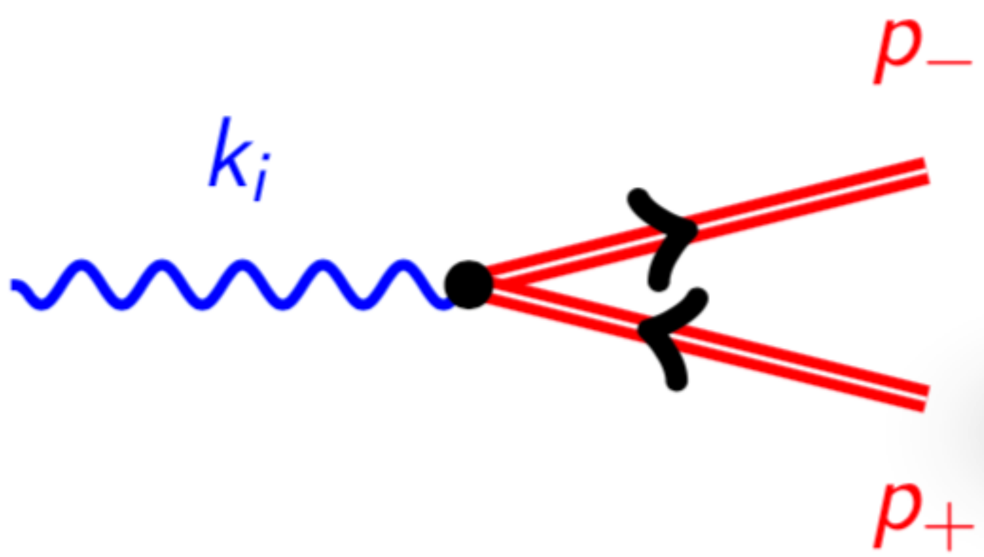


The rate is a series of Compton edges for n=1,2,3,… absorbed photons and the edges shift down with increasing ξ

Γ_{OPPP} asymptotically

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

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



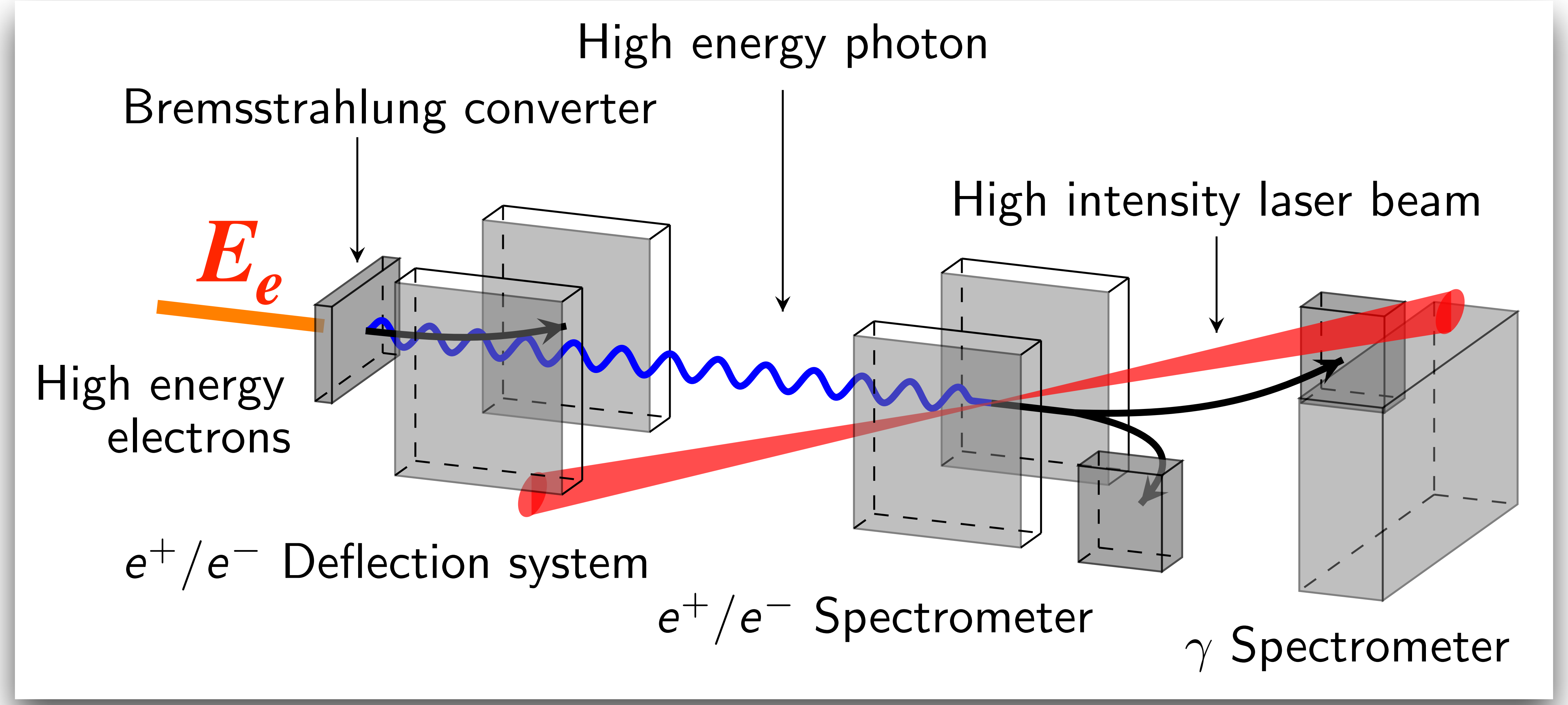
e^+e^- pair is boosted and the E-field is enhanced

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

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

High-energy photons?

- An $\sim \mathcal{O}(10~\mathrm{GeV})$ electron beam can be sent onto a high-Z target
- Converted into a collimated high-energy γ-beam (Bremsstrahlung)
- These photons are crossed with the high-intensity laser beam
- Laser-assisted bremsstrahlung photon pair production (BPPP)



E_e is the energy of the incident electrons

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

$$\Gamma_{\mathrm{BPPP}} = \frac{\alpha m_e^2}{4} \int_0^{E_e} \frac{d\omega_i}{\omega_i} \underbrace{\frac{dN_\gamma}{d\omega_i}}_{\text{Bremsstrahlung “PDF”}} F_\gamma(\xi, \chi_\gamma(\omega_i))$$

Asymptotically

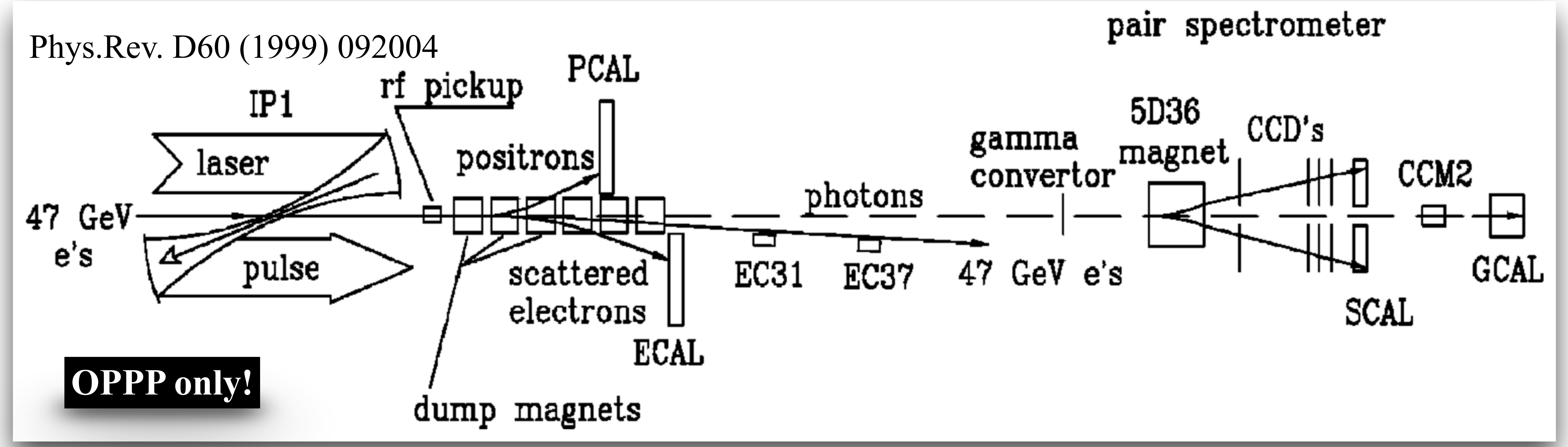
- For a target of thickness $X \ll X_0$, where X_0 is the radiation length:

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

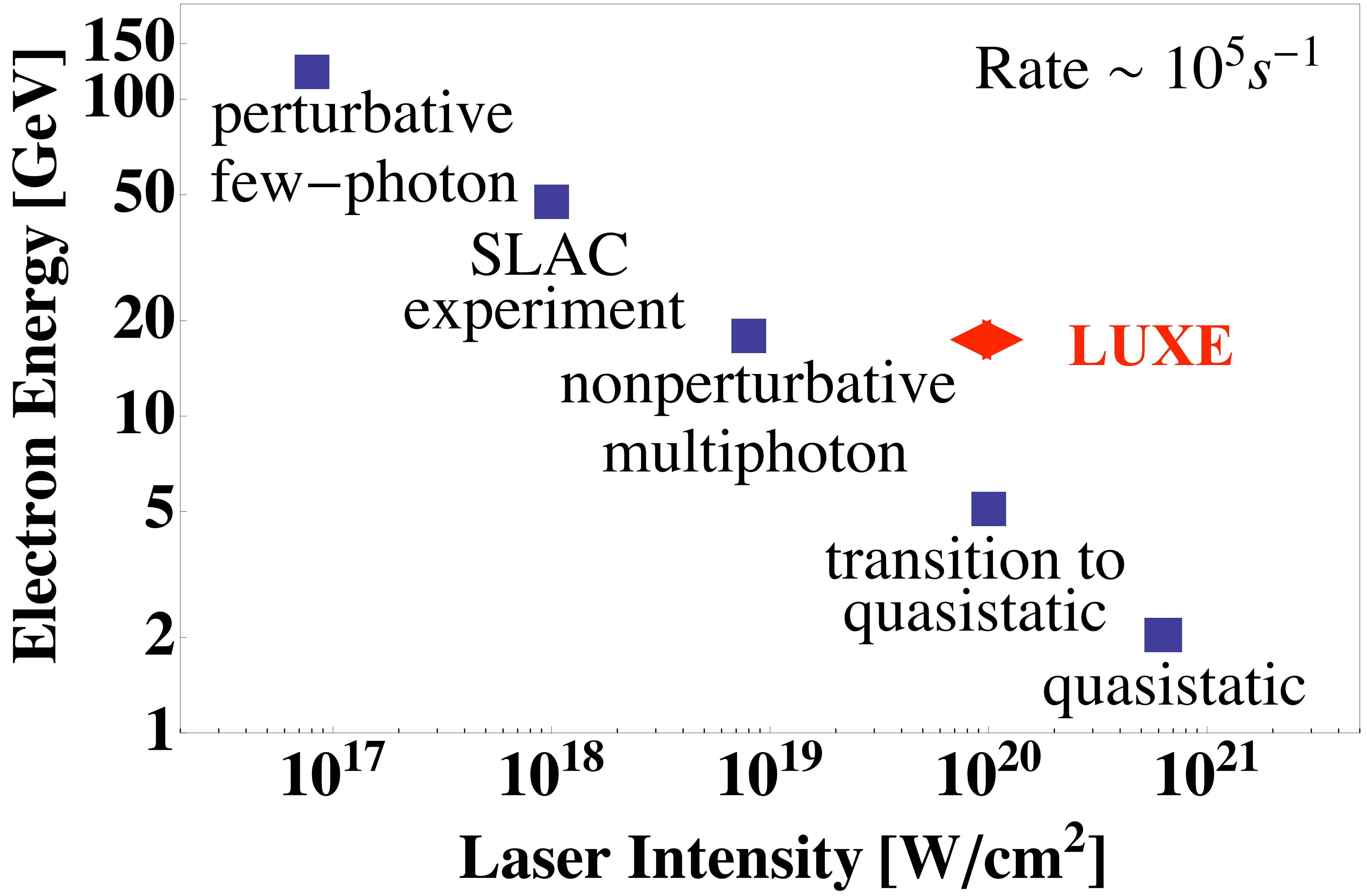
- Similarly to OPPP, replacing χ_γ with χ_e, the BPPP rate is:

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

History: E144 @ SLAC



- 46.6 GeV electron beam
- 5×10^9 electrons per bunch
- Bunch rates up to 30 Hz
- Terawatt laser pulses
- Intensity of $\sim0.5\times10^{18}$ W/cm^2
- Frequency of 0.5 Hz for wavelengths 1053 nm, 527 nm
- electrons-laser crossing angle: 17^o



History: E144 @ SLAC

OPPP only!

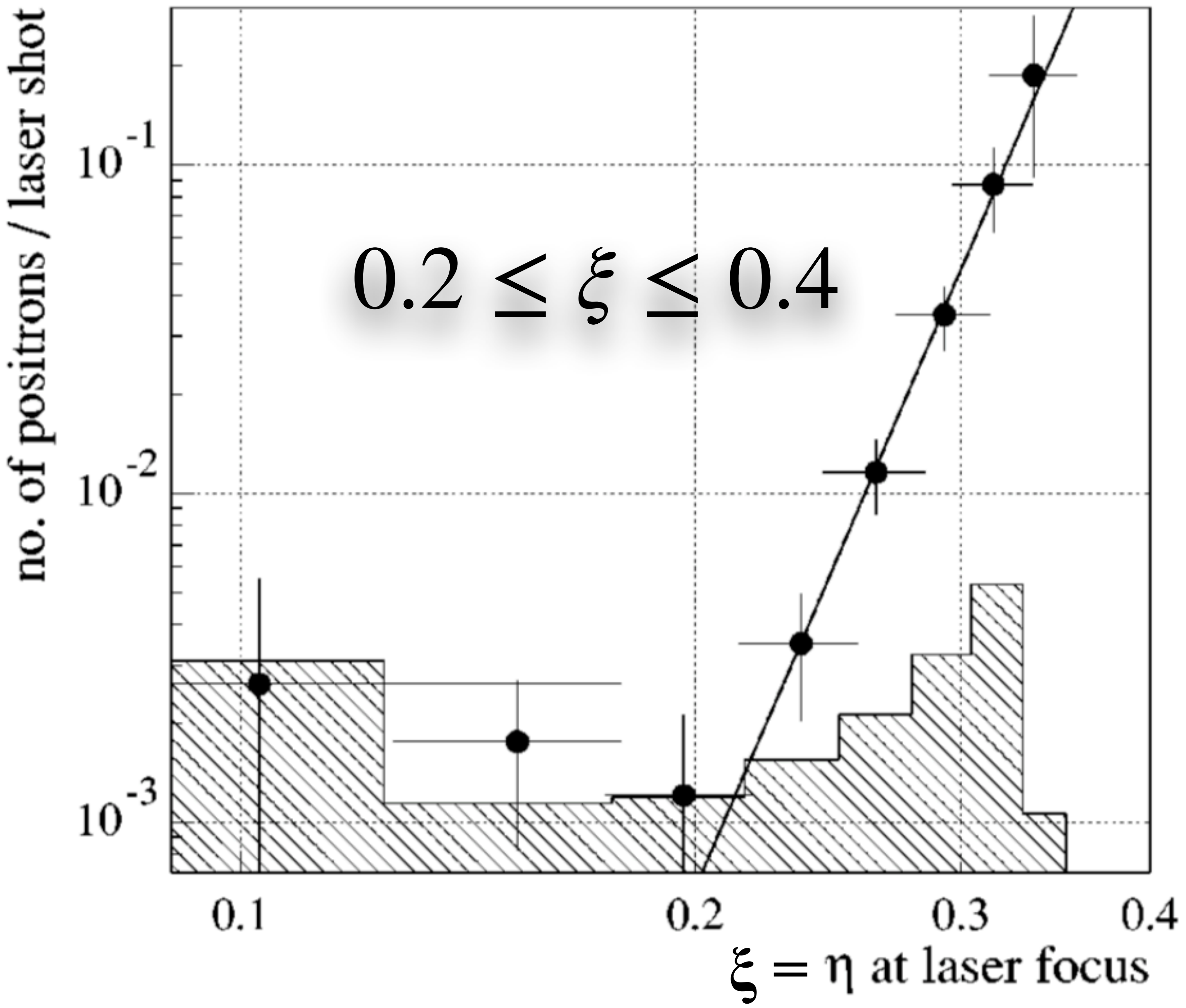


FIG. 44. The dependence of the positron rate per laser shot on the laser field-strength parameter η. The line shows a power law fit to the data. The shaded distribution is the 95% confidence limit on the residual background from showers of lost beam particles after subtracting the laser-off positron rate.

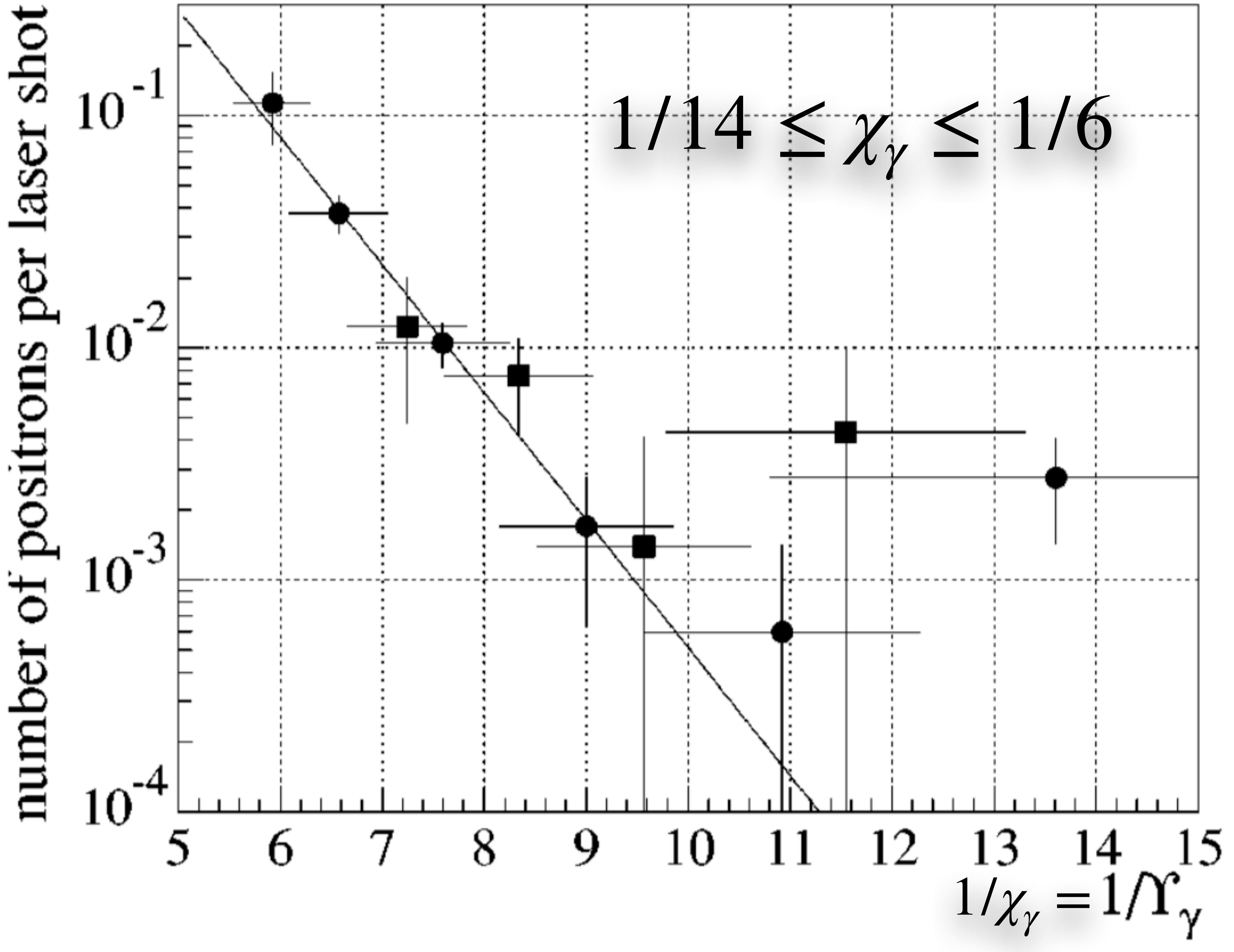


FIG. 49. Number of positrons per laser shot as a function of $1/\Upsilon_\gamma$. The circles are the 46.6 GeV data whereas the squares are the 49.1 GeV data. The solid line is a fit to the data.

Phys.Rev. D60 (1999) 092004

History: E144 @ SLAC

- Measured non-linear Compton scattering with $n = 4$ photons absorbed and pair production (with $n = 5$)
- Observed the strong rise $\sim \xi^{2n}$ but not asymptotic limit (still perturbative)
- Measurement well described by theory
- Large uncertainty on the laser intensity
- Did not achieve the critical field - the <u>peak</u> E-field of the laser: 0.5×10^{18} V/m

Phys.Rev. D60 (1999) 092004

Mass shift

- Electron motion in a circularly polarised field, ϵ_L, with frequency ω_L:
  - Force: $F_\perp = e\epsilon_L = m_e a = m_e v^2/R \implies R = m_e v^2/e\epsilon_L$
  - Velocity: $v = \omega_L R = \omega_L m_e v^2/e\epsilon_L \implies v = e\epsilon_L/\omega_L m_e = \xi$
  - Momentum: $p_\perp = m_e v = m_e \xi$
  - Energy: $E = m_e^2 + \overrightarrow{p}^2 = m_e^2 + p_\perp^2 + p_\parallel^2 = m_e^2\left(1+\xi^2\right) + p_\parallel^2 = \bar{m}_e^2 + p_\parallel^2$
  - Mass shift:

  $$m_e \longrightarrow \bar{m}_e = m_e\sqrt{1+\xi^2}$$
- The 4-momentum of the electron inside an EM wave is altered due to continuous absorption and emission of photons
  - the laser photon 4-momentum is: k_μ
  - outside the field, the (free) charged particle 4-momentum is: p_μ
  - inside the field, the effective 4-momentum (q_μ) and mass are:

  $$q_\mu = p_\mu + \frac{\xi^2 m_e^2}{2(k\cdot p)}k_\mu \quad \Rightarrow \quad \bar{m}_e = \sqrt{q_\mu q^\mu} = m_e\sqrt{1+\xi^2}$$

Mass shift ⟶ kinematic edge

- if n is the number of absorbed laser photons in the nonlinear Compton process, the energy-momentum conservation: $q_\mu + nk_\mu = q'_\mu + k'_\mu$
- The maximum value for the scattered photon energy, ω', corresponds to the minimum energy, or, "kinematic edge" of the scattered electron. It depends on the number of absorbed laser photons:
  $\omega'_{\min} = \dfrac{\omega}{1 + 2n(k \cdot p)/\bar{m}_e^2}$, where $\bar{m}_e = m_e\sqrt{1 + \xi^2}$
- This energy decreases with increasing number of photons absorbed
- The electron is effectively getting more massive with ξ and recoils less
  - the min energy of the scattered electron (kinematic edge) is higher

Electric field vs Intensity

$$I = (1 - f_{\text{Losses}}) \times \frac{E_{\text{pulse}}}{T_{\text{pulse}} \times S_{\text{pulse}}} \rightarrow \frac{(1 - 60\%) \times 9\ [\text{J}]}{30\ [\text{fs}] \times (3 \times 3\ [\mu\text{m}^2])}$$

$$I = 0.4/30\ [\text{J/fs}/\mu\text{m}^2] \sim 1.33 \times 10^{-2} \times 10^{15} \times 10^{8}\ [\text{J/s/cm}^2]$$

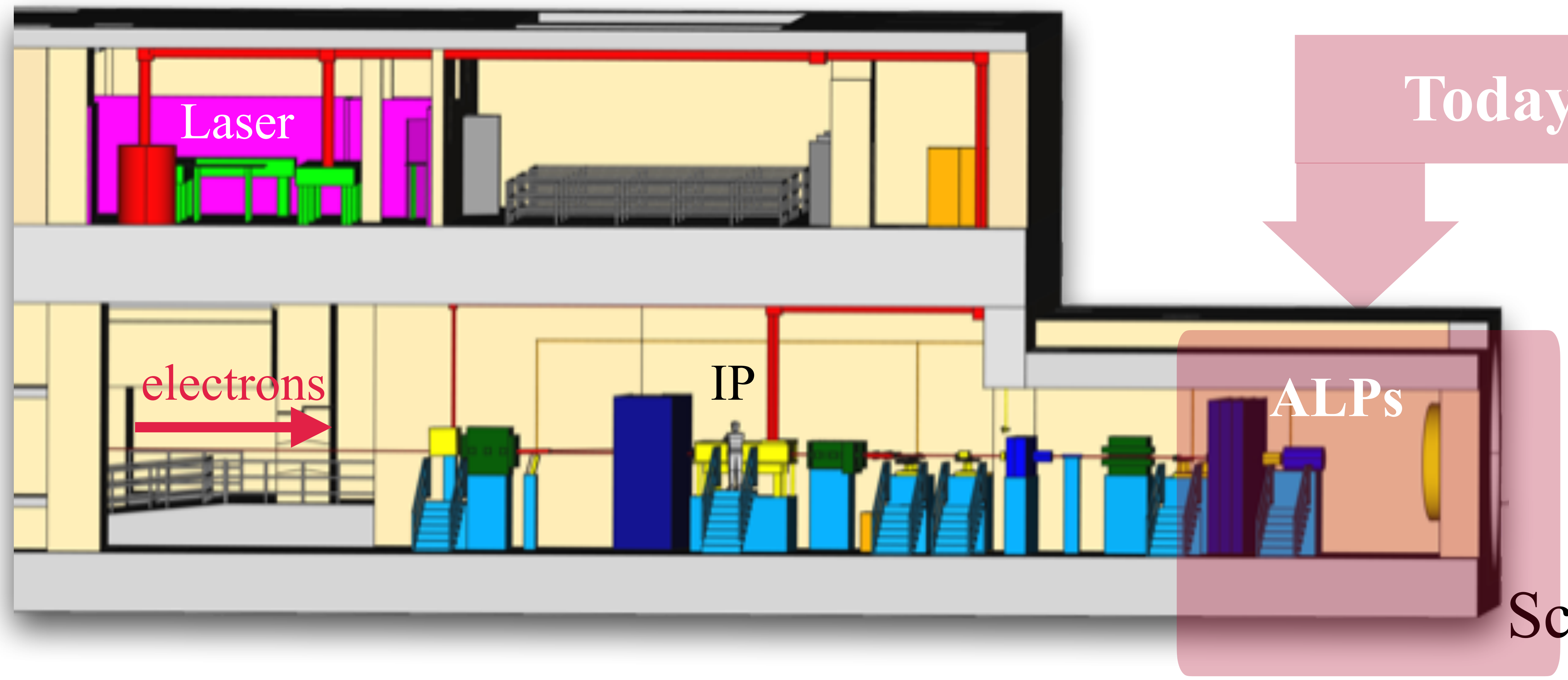
$$I = 1.33 \times 10^{21}\ [\text{J/s/cm}^2] = 1.33 \times 10^{21}\ [\text{W/cm}^2]$$

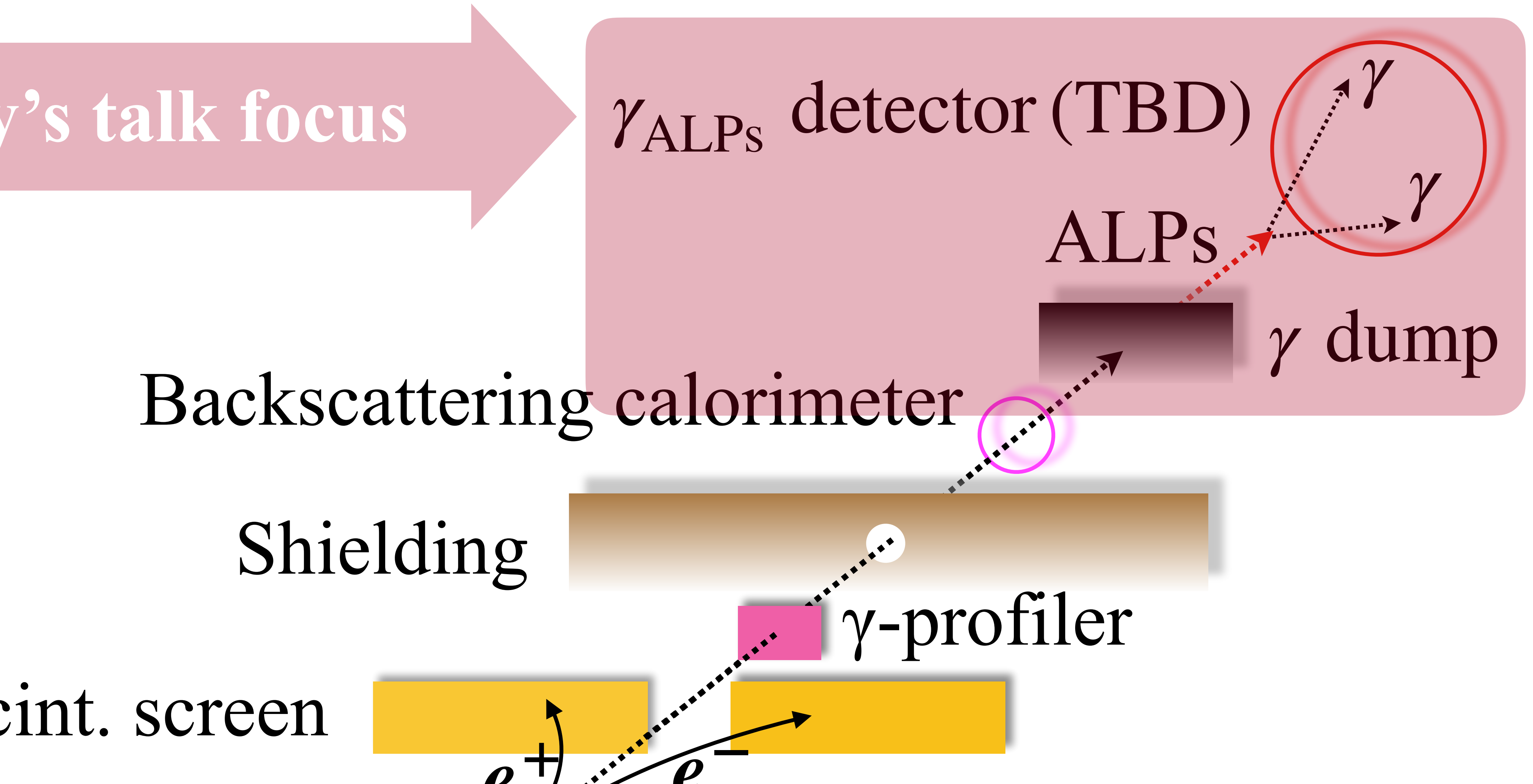
$$\epsilon_L = \sqrt{\frac{I}{cn\epsilon_0}} \underbrace{\longrightarrow}_{n=1} \sim \sqrt{\frac{1.33 \times 10^{21}}{(2.99 \times 10^{8}) \times (8.85 \times 10^{-12})}} \left[\sqrt{\frac{(\text{N} \cdot \text{m/s})/\text{cm}^2}{(\text{m/s}) \times (\text{N/V}^2)}}\right] \sim 0.71 \times 10^{12}\ [\text{V/cm}]$$

$$\text{Boost}: \ \epsilon_L \longrightarrow \epsilon'_L = \epsilon_L \times (3.23 \times 10^{4}) \sim 2.3 \times 10^{16}\ [\text{V/cm}] = 1.77 \times \epsilon_{\text{Schwinger}}$$

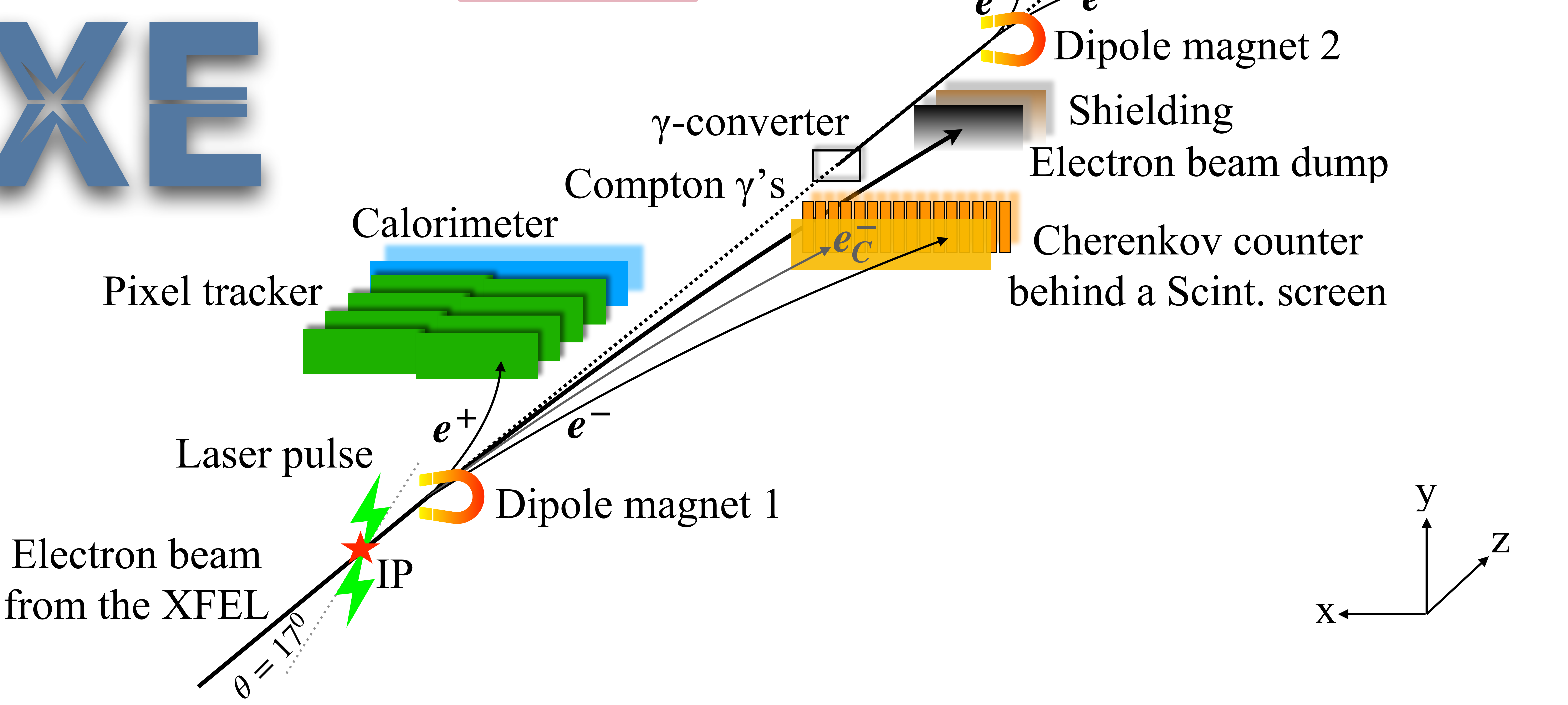
$$\boxed{\begin{aligned} c &= 2.99 \times 10^{8} [\text{m/s}] \\ \epsilon_0 &= 8.85 \times 10^{-12} [\text{N/V}^2] \\ [I] &= [\text{W}] = [\text{N} \cdot \text{m/s}] \end{aligned}}$$

$$\epsilon_{\text{Schwinger}} \sim 1.3 \times 10^{16}\ [\text{V/cm}]$$

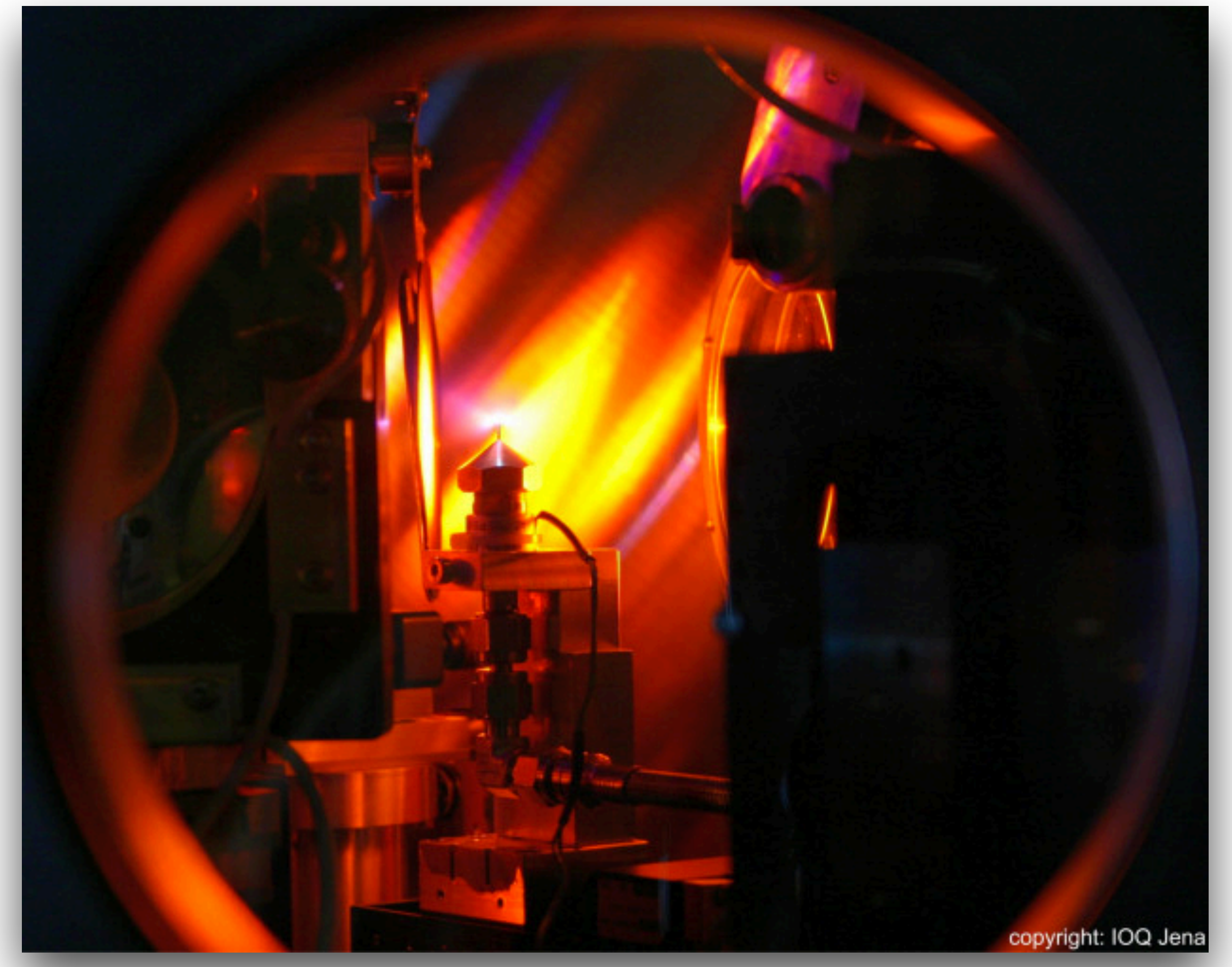

Laser
electrons
IP
ALPs


Today's talk focus
$\gamma_{\rm ALPs}$ detector (TBD)
γ
γ
ALPs
γ dump
Backscattering calorimeter
Shielding
γ-profiler
Scint. screen

LUXE


e^+
e^-
Dipole magnet 2
Shielding
Electron beam dump
γ-converter
Compton γ's
e_C^-
Cherenkov counter
behind a Scint. screen
Calorimeter
Pixel tracker
e^+
e^-
Laser pulse
Dipole magnet 1
Electron beam
from the XFEL
IP
$\theta = 17^0$
y
z
x

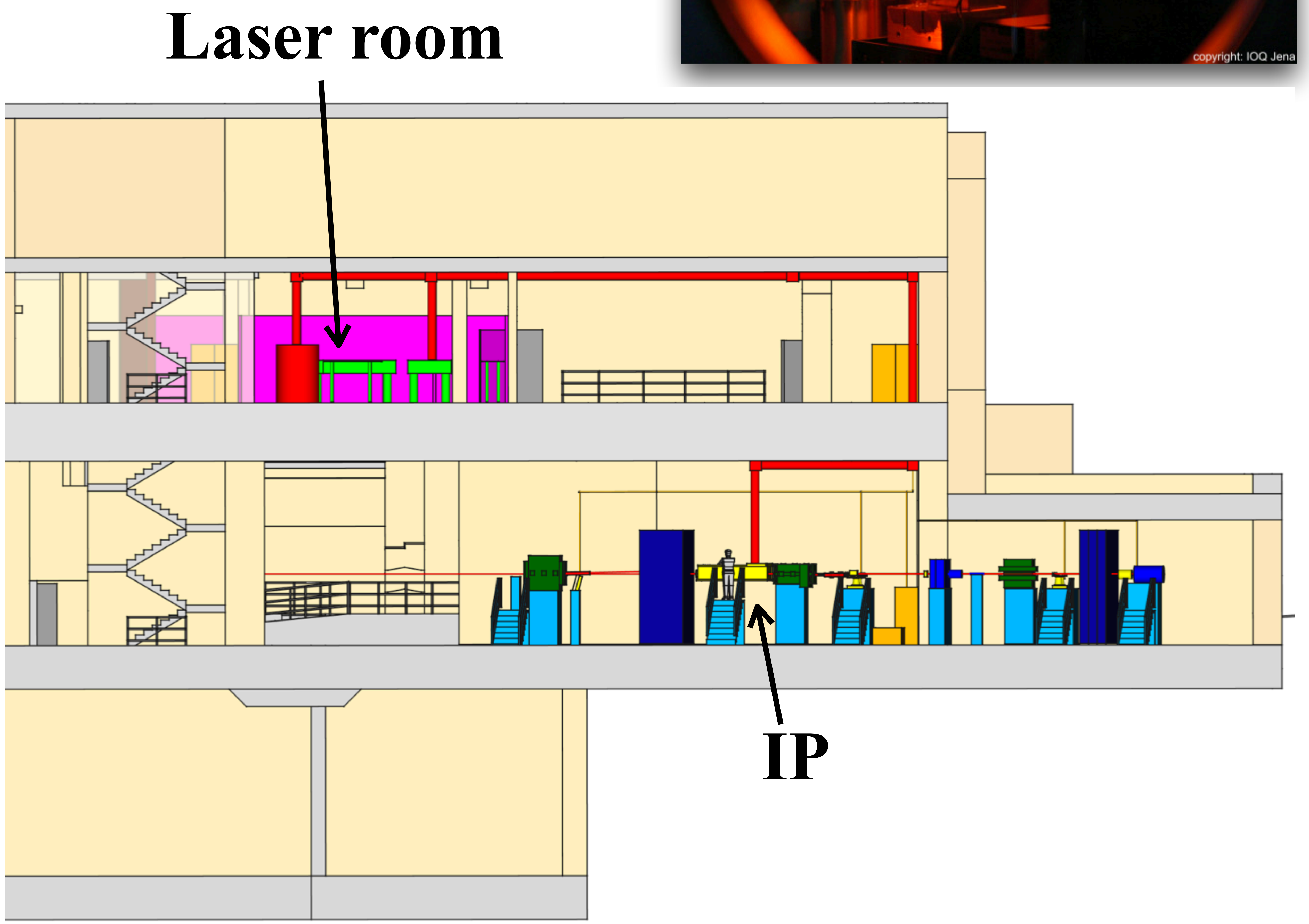
Laser



- 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 3×3 μm² 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



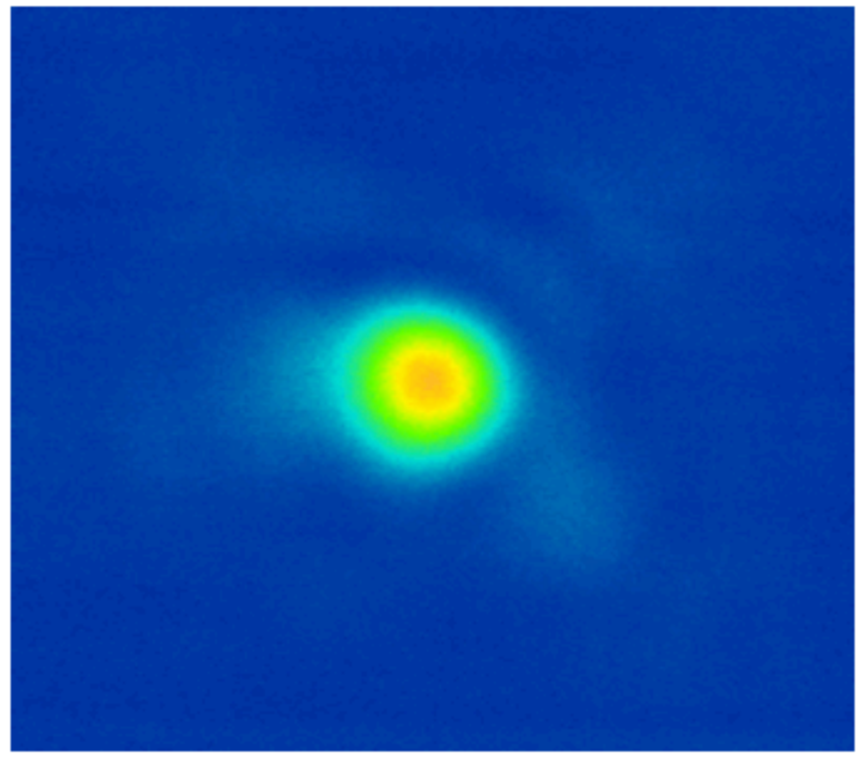
Laser diagnostics

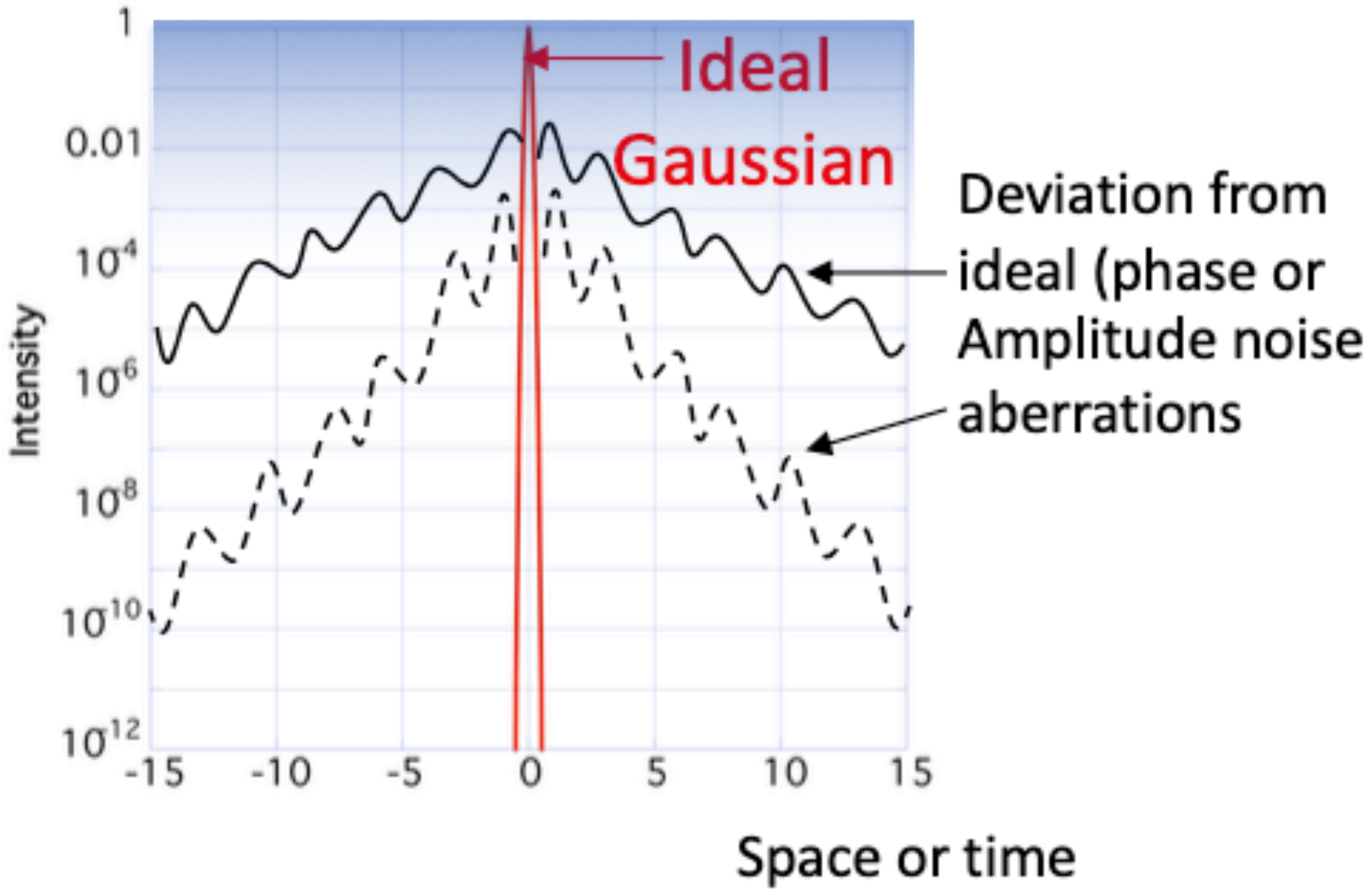
- Measure laser parameters to infer the intensity, I
  - can be indirect and direct, relative and absolute
- Small fluctuations in I lead to large rate fluctuations
  - air movement, vibrations, temp-drift, pump discharge variations, etc.
- The laser beam will be attenuated and imaged on the return path to the diagnostics 10s of meters away from the IP

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

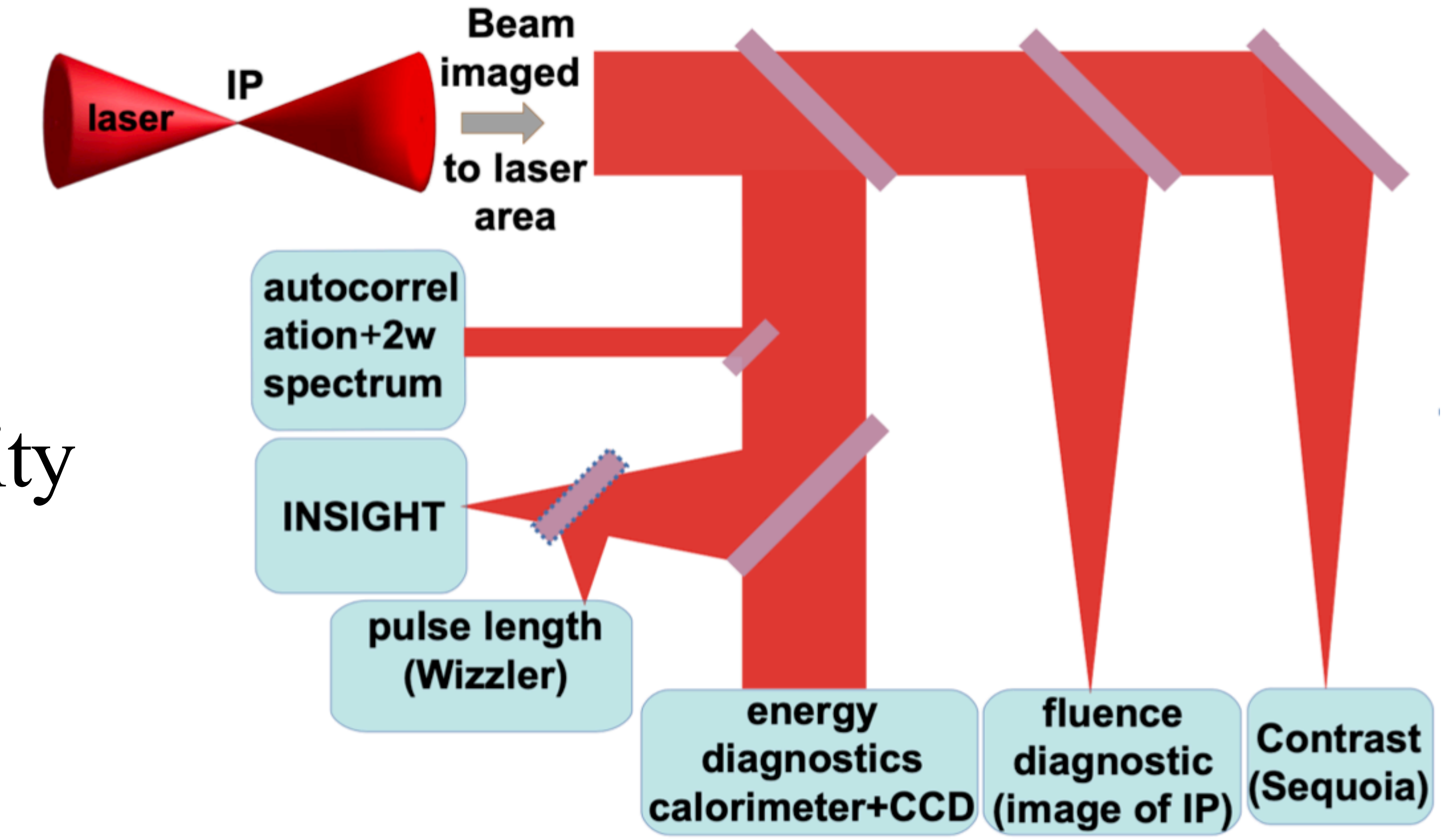
← pulse energy

← pulse spot size × duration

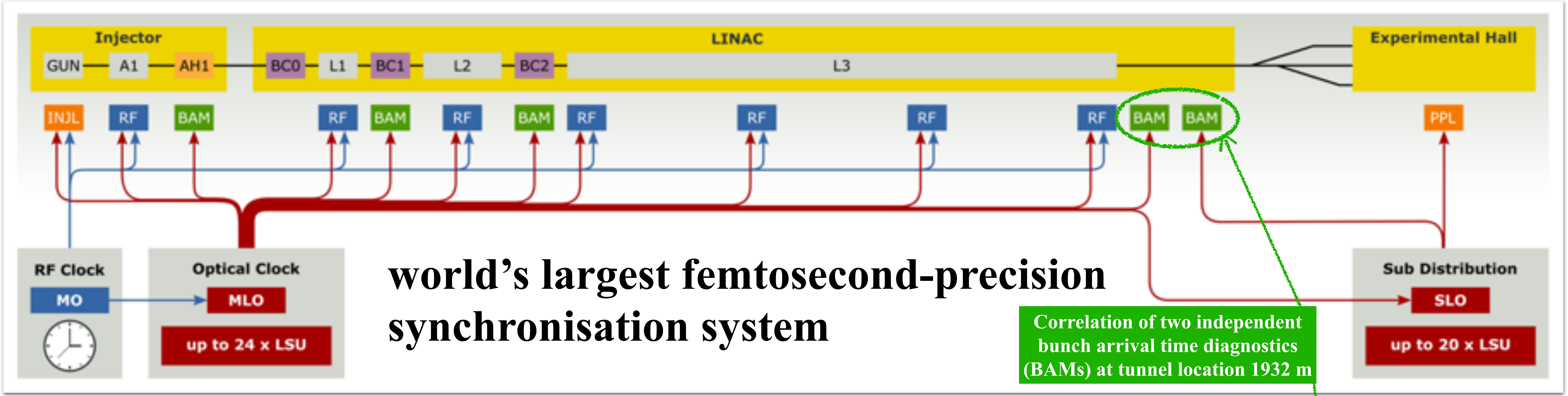


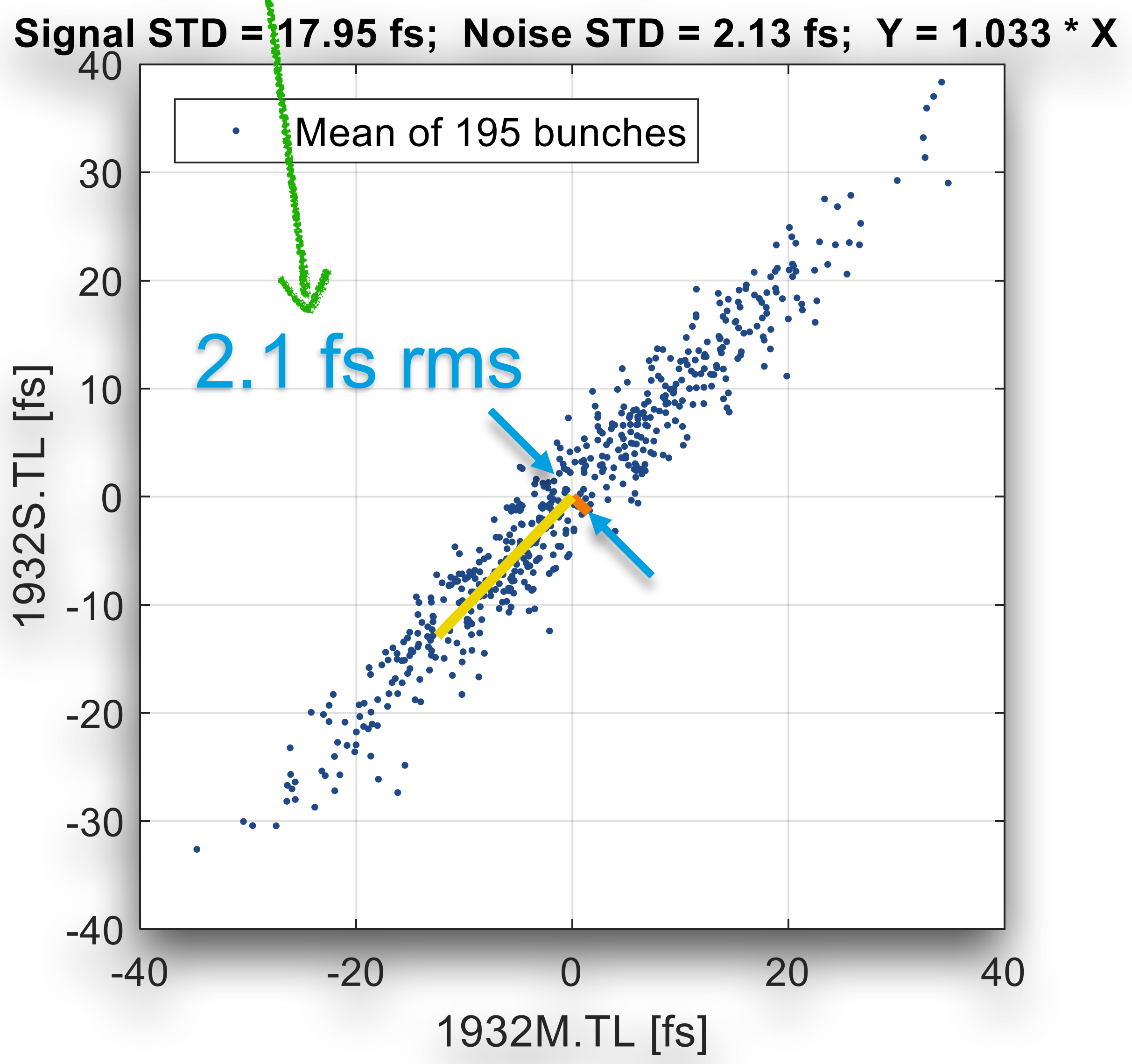


Diagnostics
- relative intensity
- pulse duration
- beam size



Synchronisation & Trigger





Synchronisation of the XFEL:

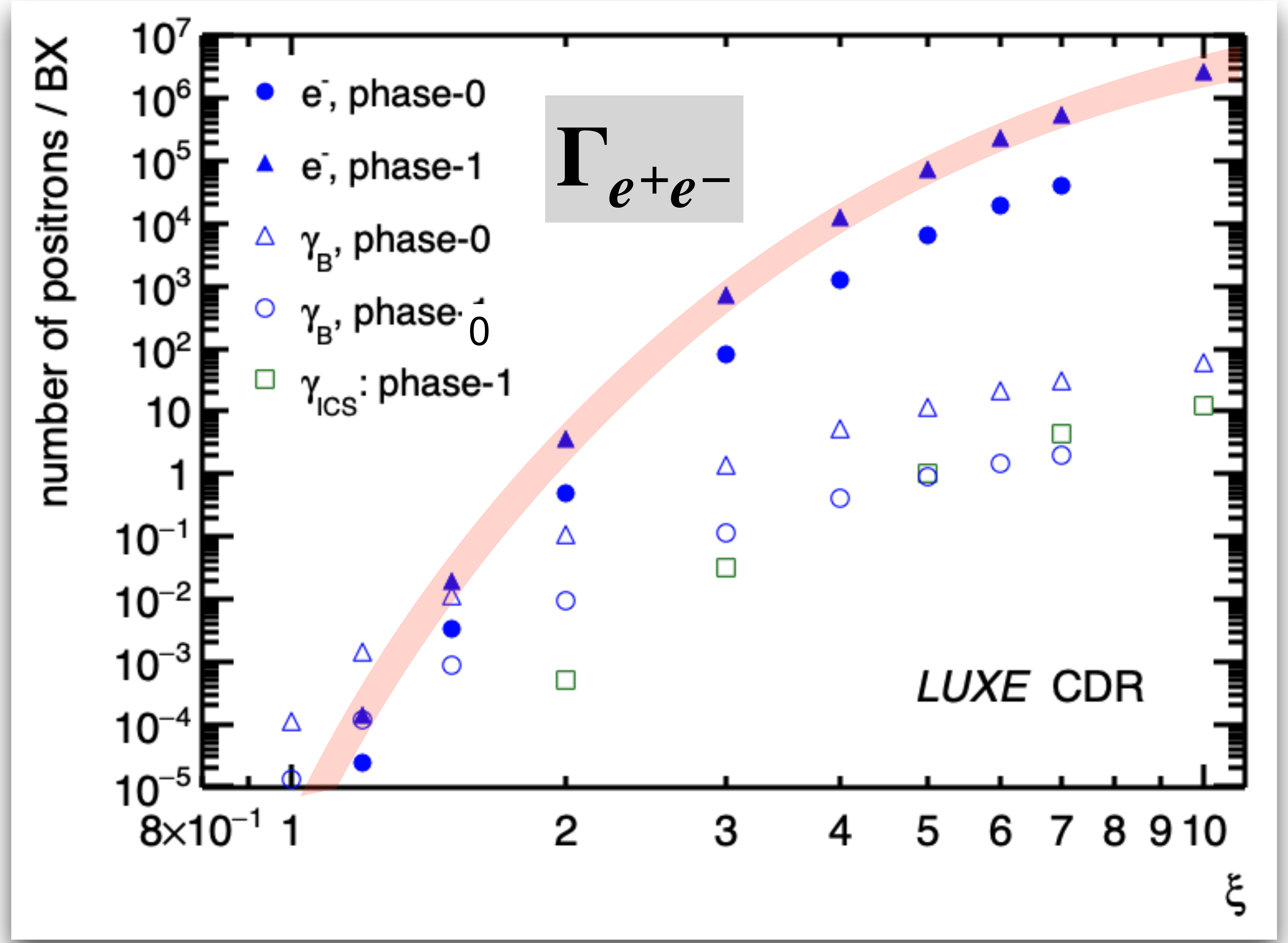
- Optical clock (master laser oscillator, MLO) provides stable pulsed optical reference (Phase-locked to radio frequency (RF) oscillator (MO))
- Optical reference distributed via length-stabilised optical fibre links for laser locking and RF re-sync

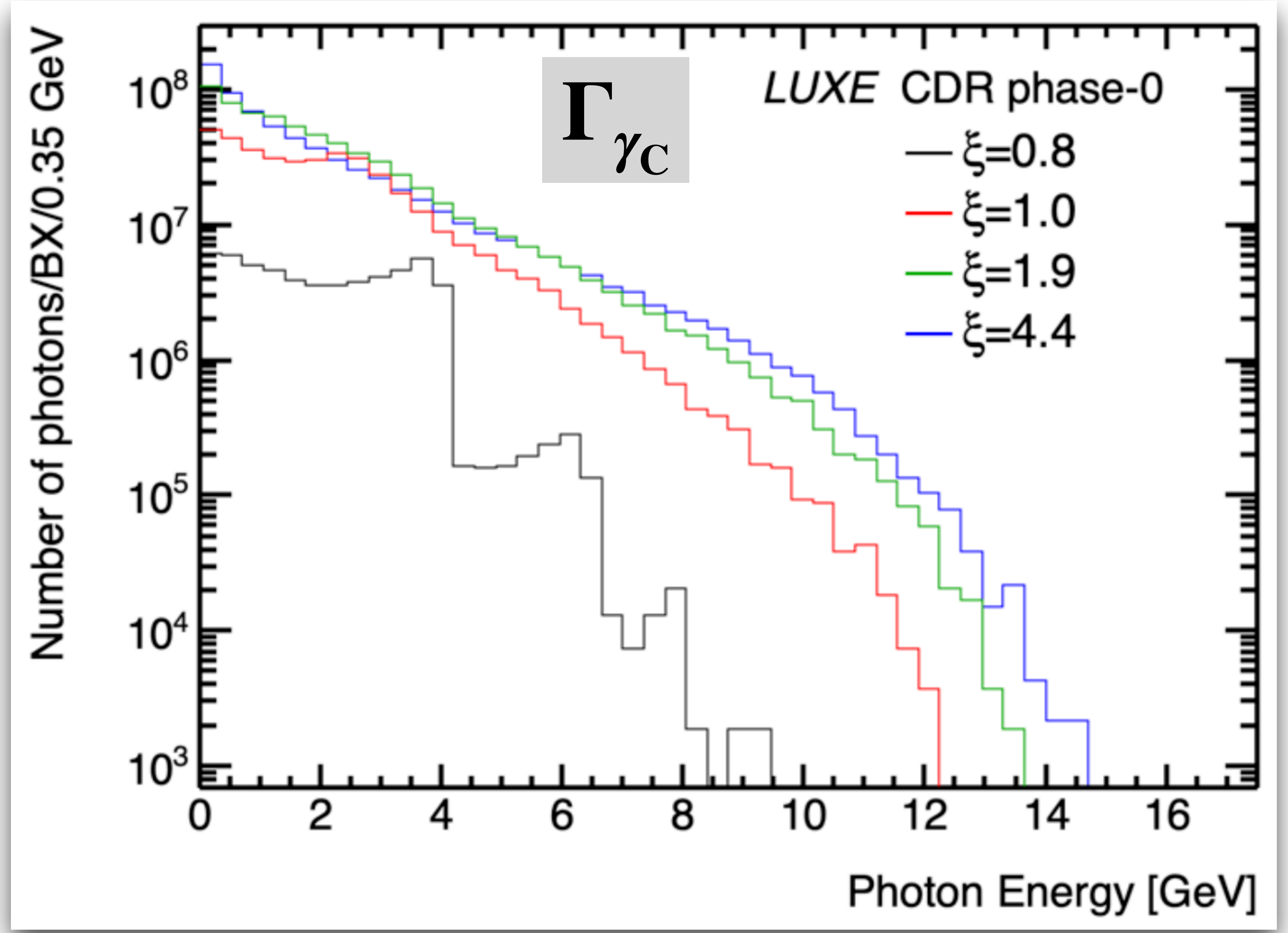
LUXE's laser oscillator:

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

LUXE at Eu.XFEL

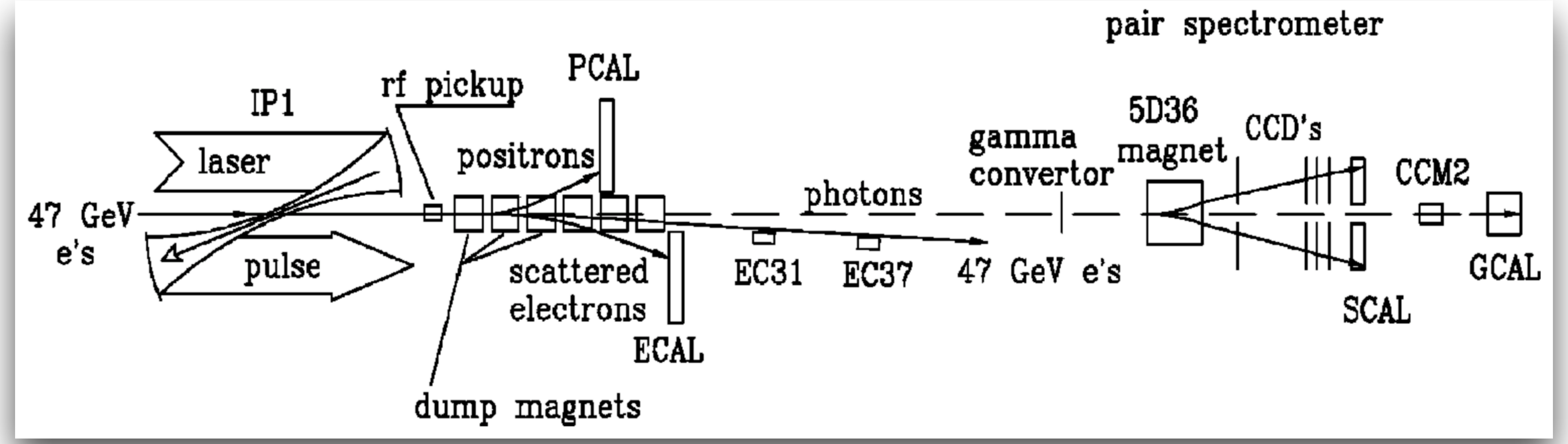
arXiv:2102.02032, will achieve $\epsilon \sim \epsilon_S$

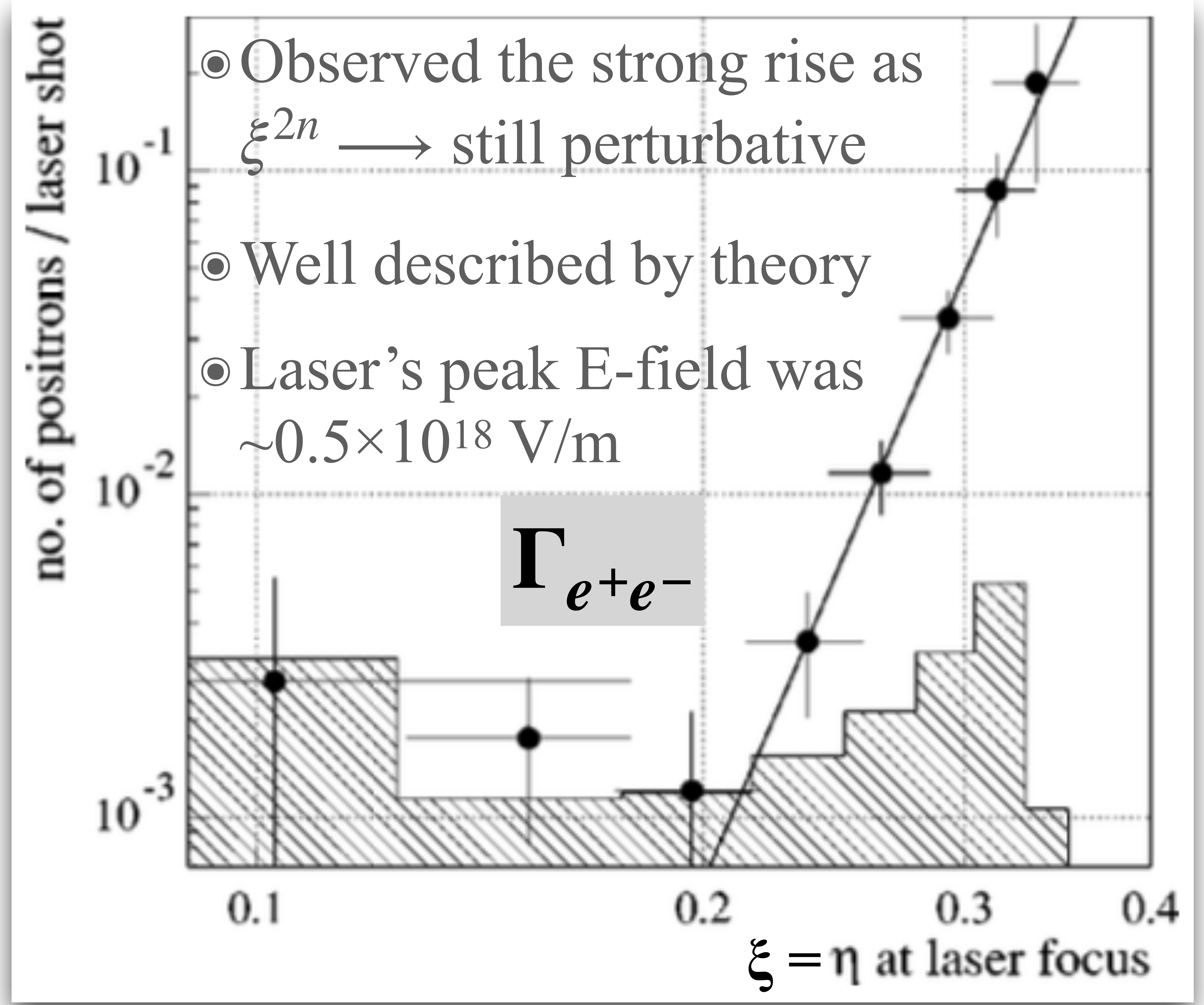


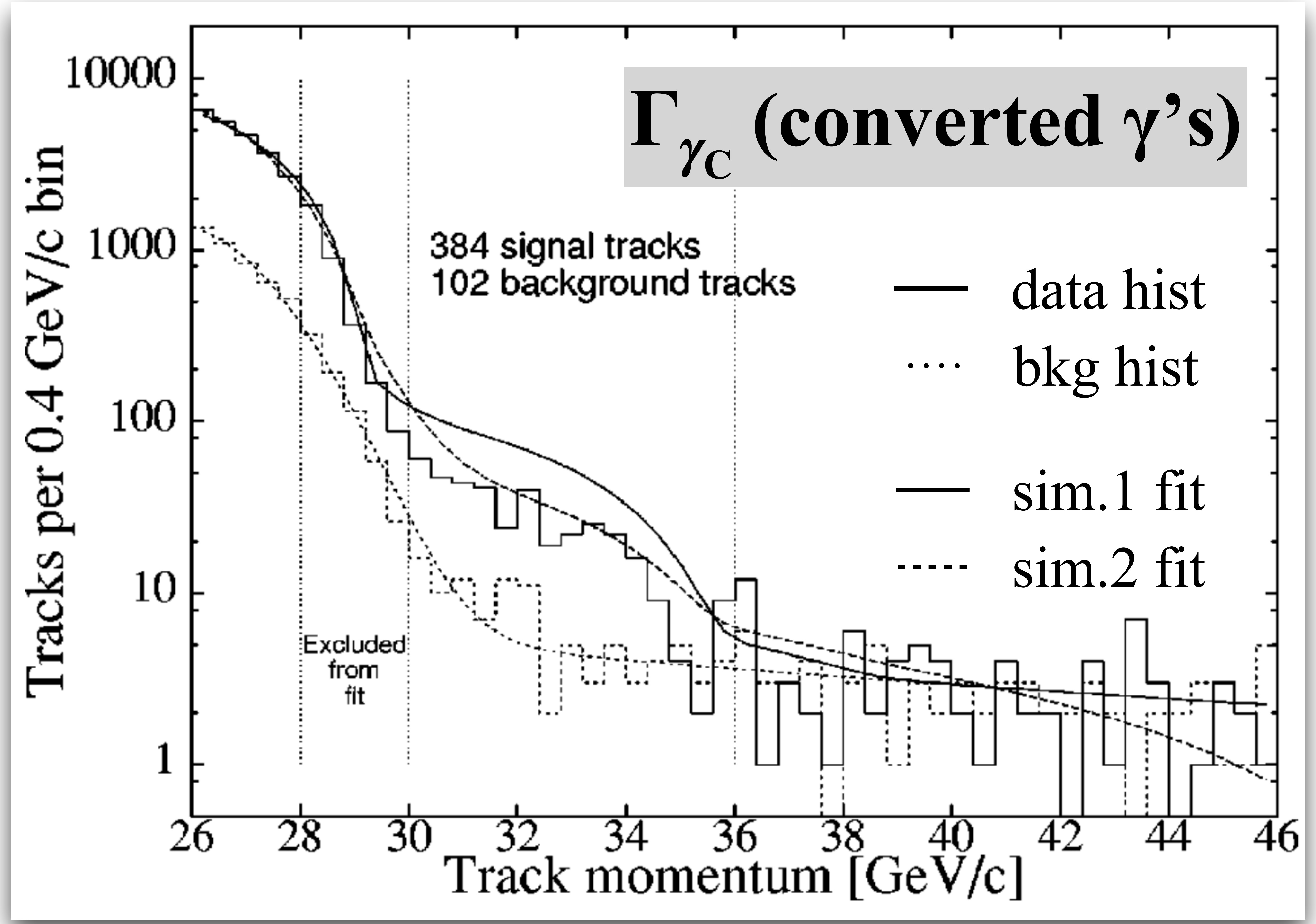


E144 at SLAC (99)

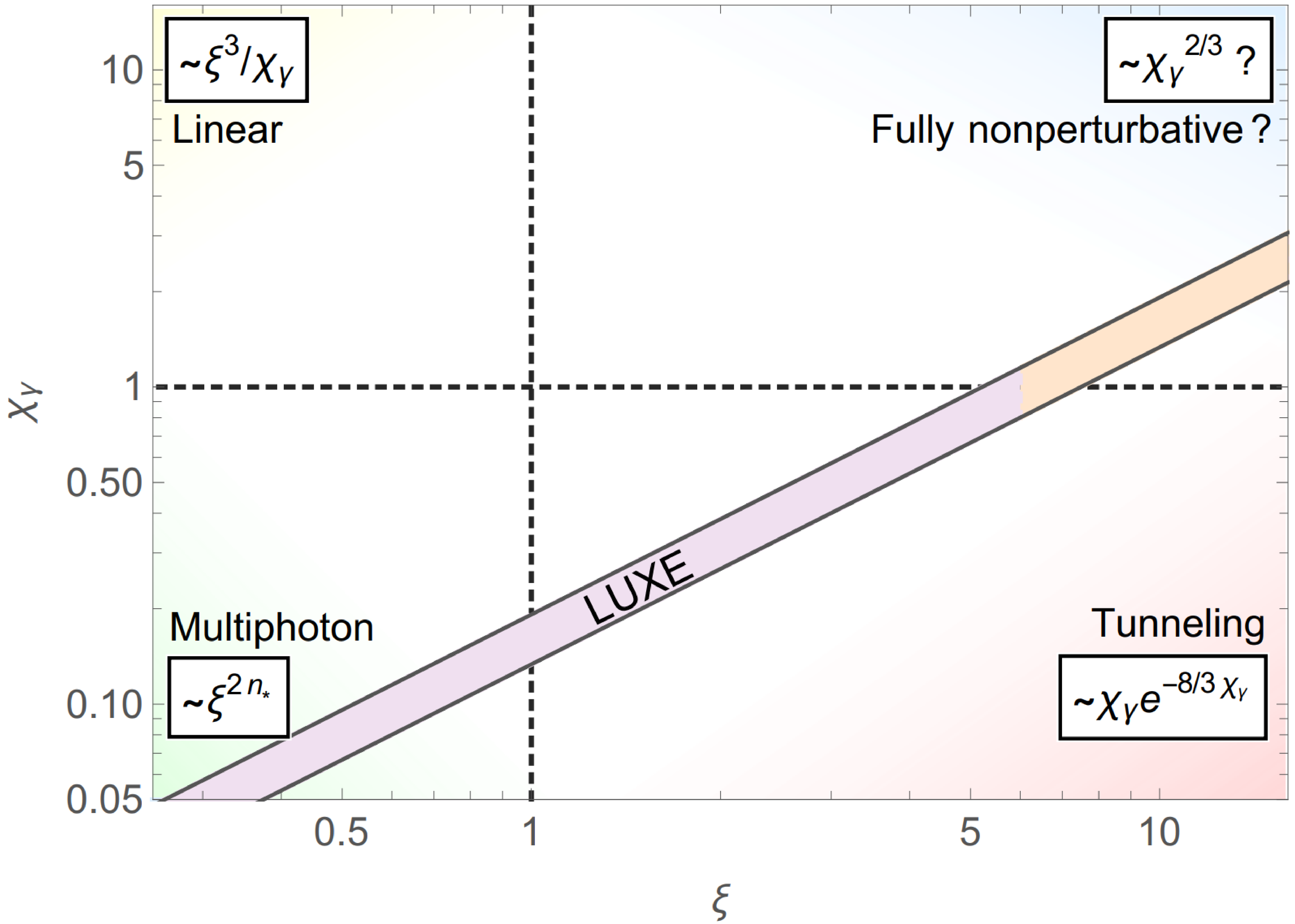
Phys.Rev. D, Vol 60, 092004, achieved $\epsilon \lesssim \epsilon_S/4$



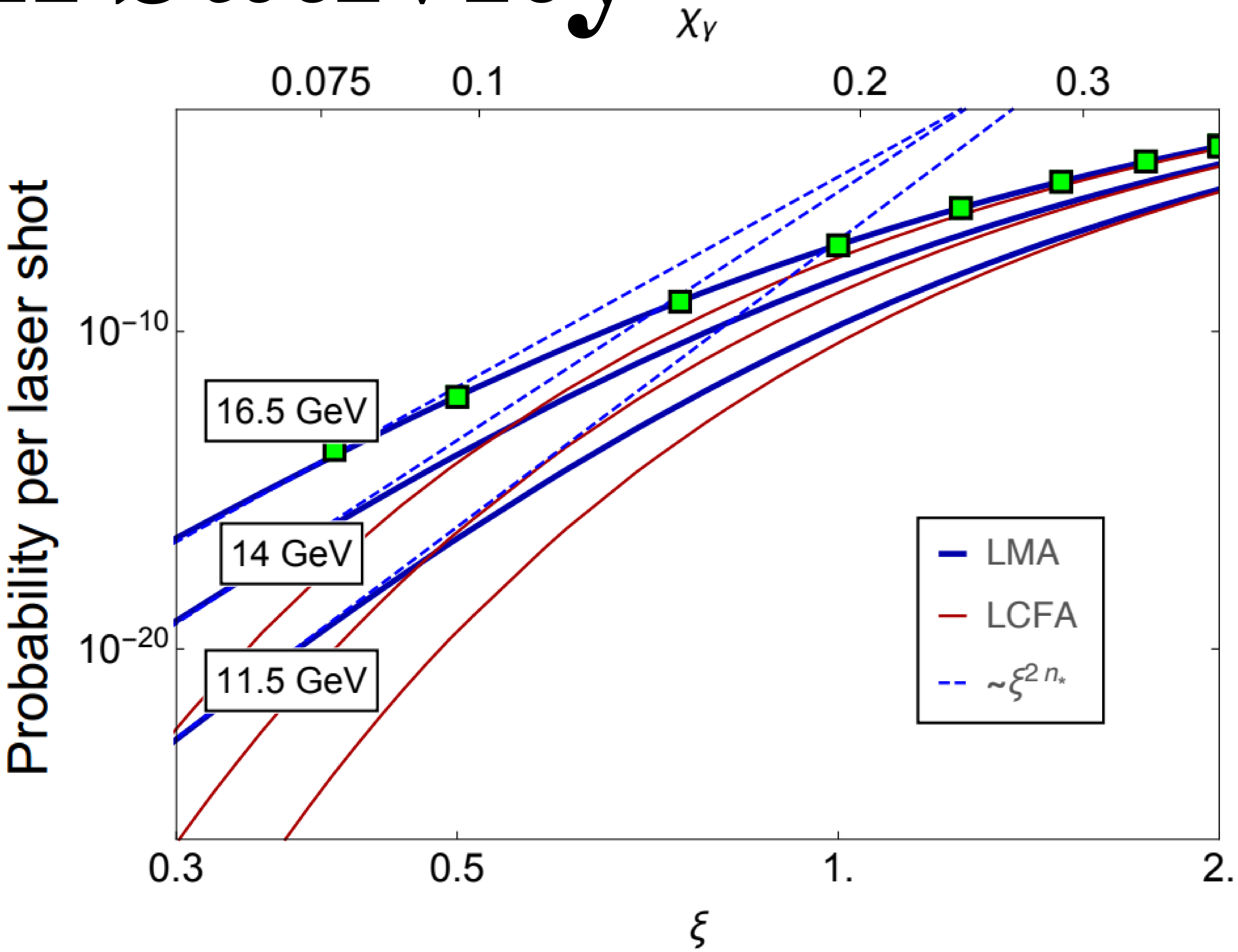




Non-perturbativity

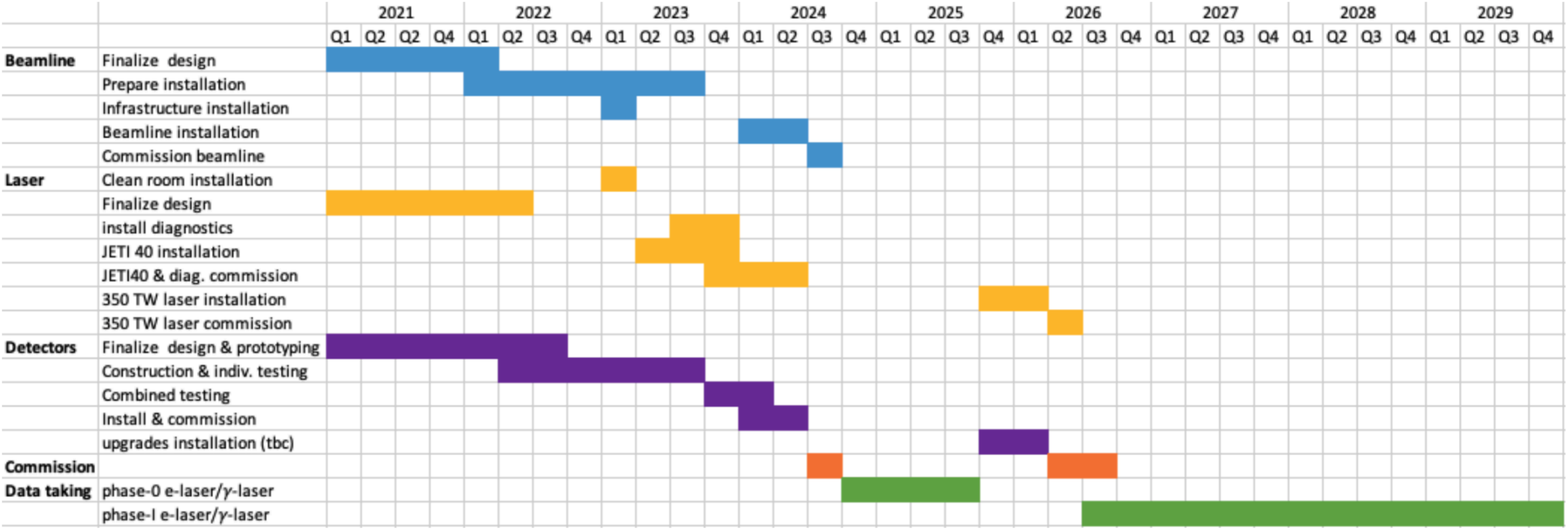


The parameter region LUXE will probe, compared to the asymptotic scaling of the Breit-Wheeler process at large and small ξ and χ parameters



The dependency of probability for the Breit-Wheeler process on the intensity parameter ξ for a probe photon colliding at 17.2 degrees with otherwise standard laser pulse parameters. The blue dashed lines indicate multi-photon scaling and the plot markers are the analytical QED plane-wave results for a photon energy of 16.5GeV

LUXE Planning



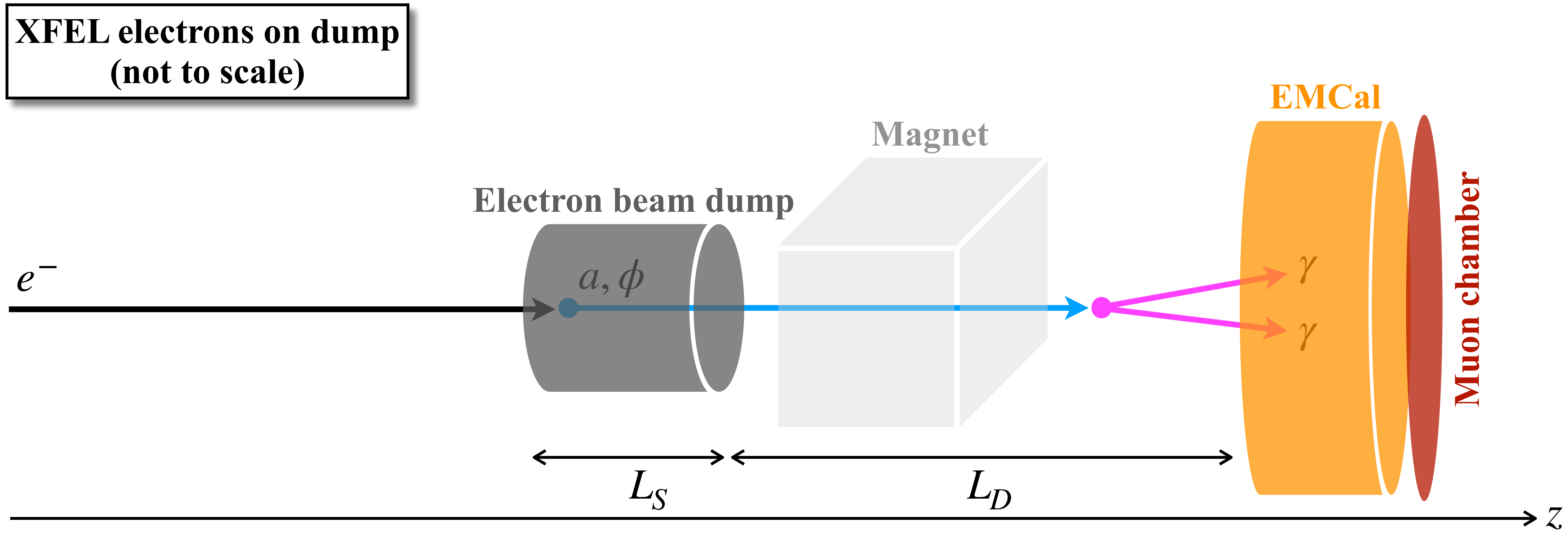
- CDR released in Feb 2021 & passed an international review. Now working toward TDR for 2022
- Experiment must be installed by 2024 during the long shutdown of the Eu.XFEL
- Phase-0: data taking in 2024 with the 40 TW laser in e-laser mode and move to γ-laser in 2025
- Phase-1: upgrade laser to 350 TW in 2026 and run until the Eu.XFEL needs the tunnel (~2029)

Time scales @ LUXE-NPOD

- 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

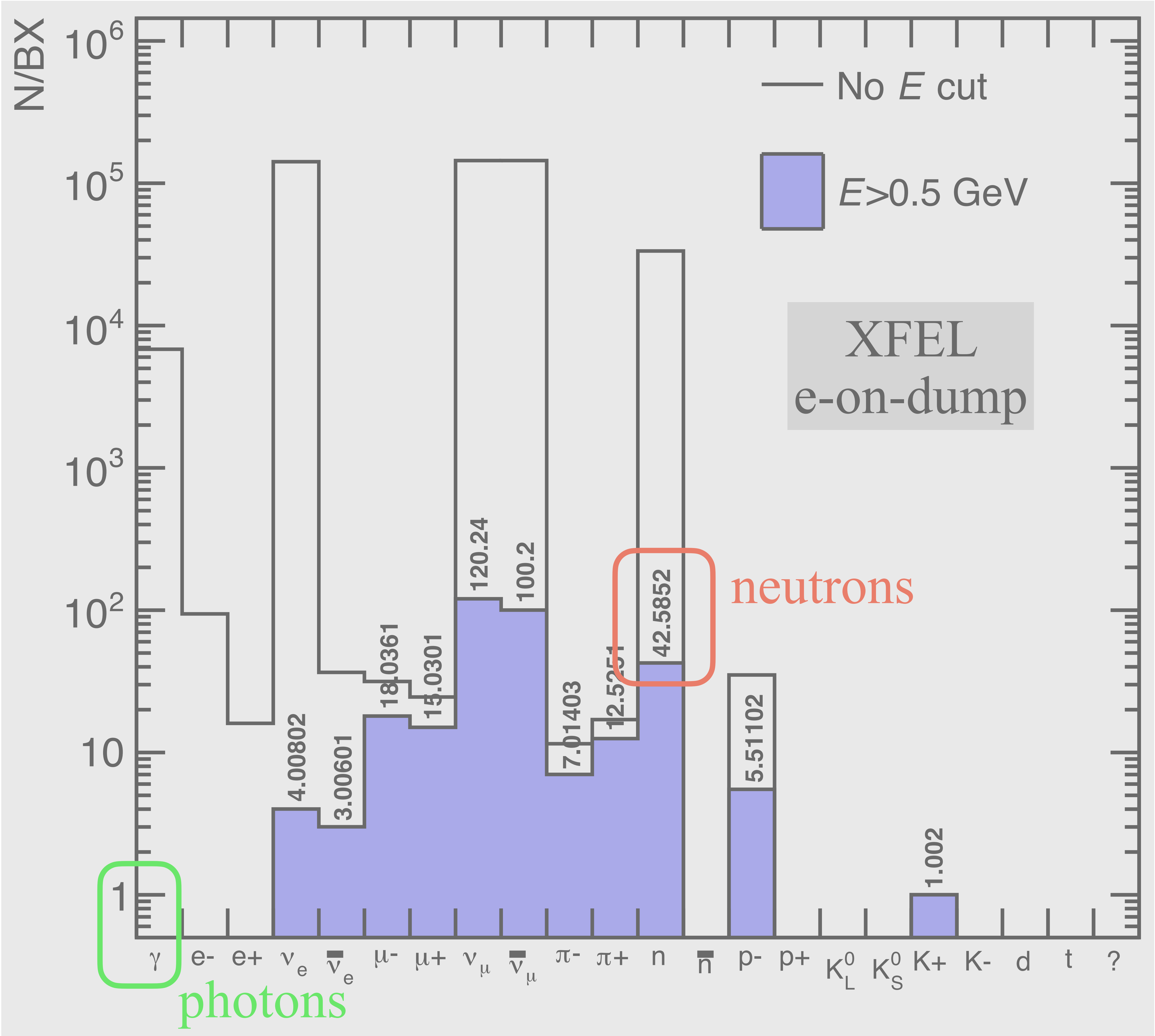
- Therefore: $\omega_L^{-1} \ll \tau_\gamma \ll t_L \ll \tau_{ee}$

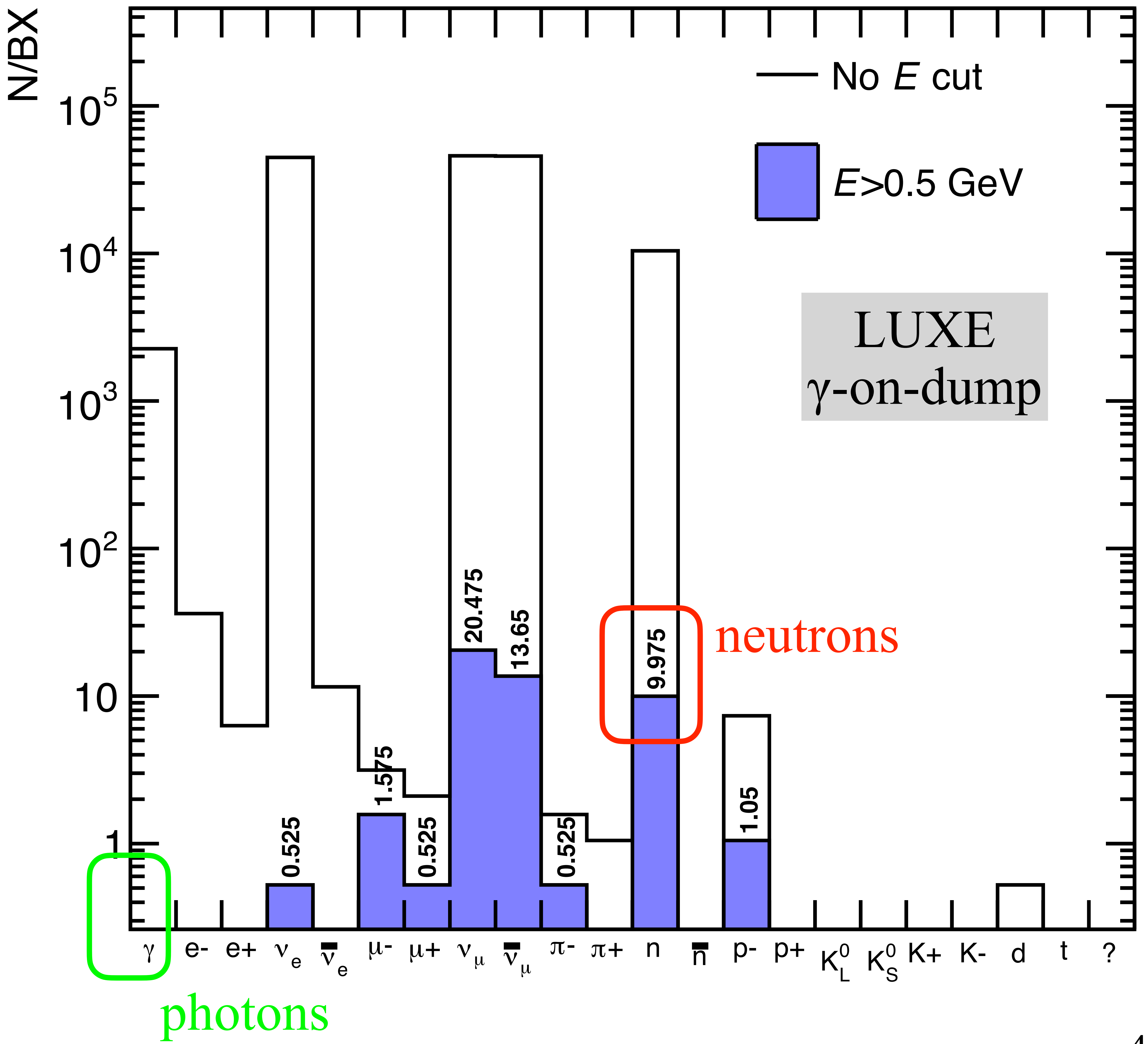
Why not electrons-on dump?



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



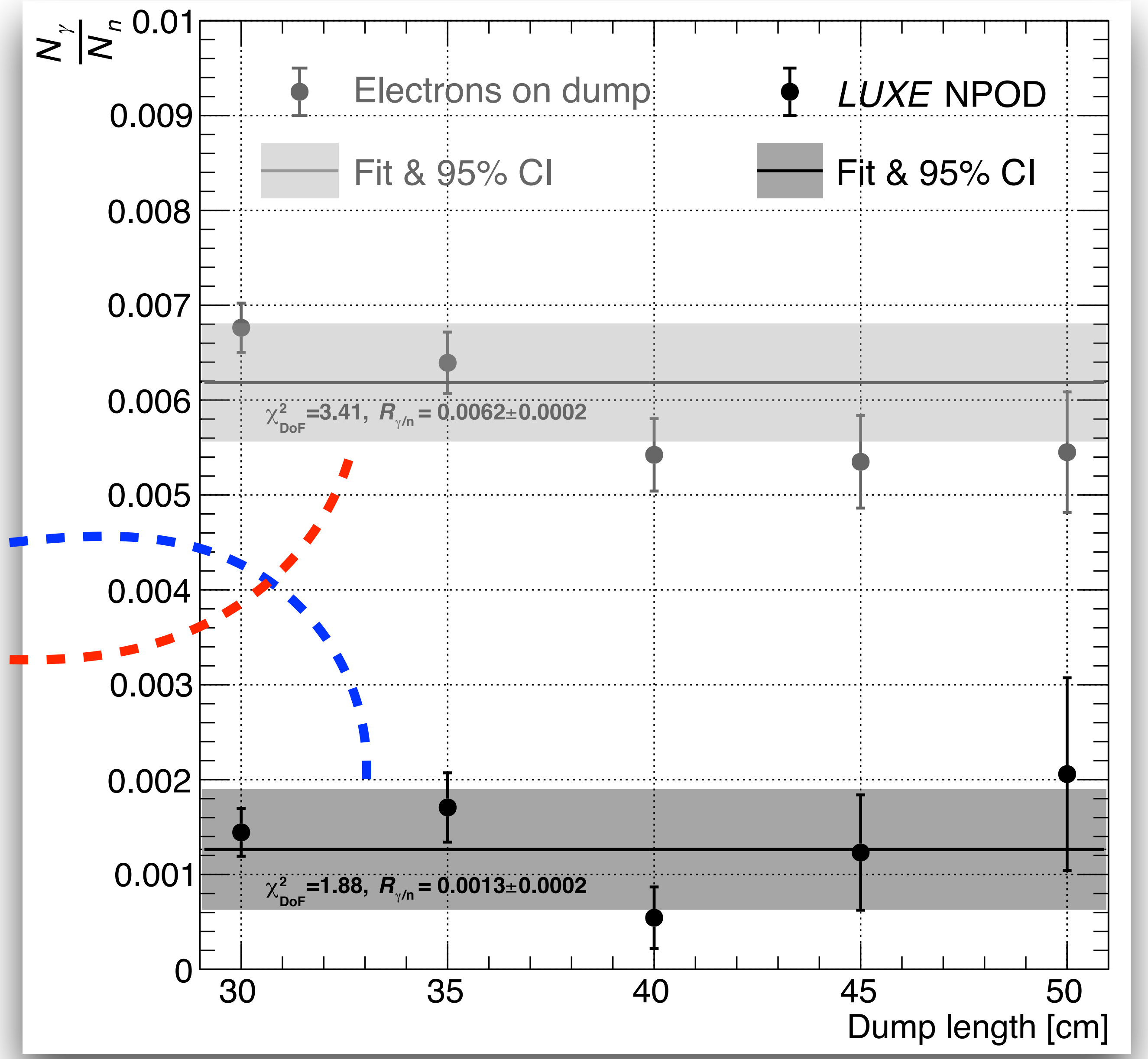


Probability to get 2 real photons

- $P_{m_\gamma} = \dfrac{\lambda_\gamma^{m_\gamma} e^{-\lambda_\gamma}}{m_\gamma!}$

- $\lambda_\gamma = 0.013 \pm 0.004$ since the fit gives $R_{\gamma/n} = 0.0013 \pm 0.0002$ and since $N_n \simeq 10$, with $\lambda_\gamma = N_n R_{\gamma/n}\left(1 \pm \sqrt{\dfrac{1}{N_n} + \dfrac{\Delta^2 R_{\gamma/n}}{R_{\gamma/n}}}\right)$

  (or in the e-on-dump case: $\lambda_\gamma \simeq 0.26 \pm 0.04$ for $R_{\gamma/n} \simeq 0.0062 \pm 0.0002$ and $N_n \simeq 42.6$)



- $P_{2\gamma} = \dfrac{\lambda_\gamma^2 e^{-\lambda_\gamma}}{2!} \simeq 8.34 \times 10^{-5}$ (or in the e-on-dump case: 2.7×10^{-2})

Probability to get 2 fake photons

- $P_{n\to\gamma} = f_{n\to\gamma}$
- $\lambda_n = \lambda_n(1\ \mathrm{m}) = 10$ (or in the e-on-dump case: $\lambda_n \simeq 42.6$)
- $P_{2n\to 2\gamma} = \sum_{m_n=2}^{\infty} \frac{\lambda_n^{m_n} e^{-\lambda_n}}{m_n!} C(2, m_n, P_{n\to\gamma})$
- $P_{2n\to 2\gamma} = \sum_{m_n=2}^{\infty} \left(\frac{\lambda_n^{m_n} e^{-\lambda_n}}{m_n!}\right)\left(\frac{m_n!}{2!(m_n-2)!} P_{n\to\gamma}^2 \times (1-P_{n\to\gamma})^{m_n-2}\right) = \sum_{m_n=2}^{\infty} \frac{\lambda_n^{m_n} e^{-\lambda_n} \times P_{n\to\gamma}^2 \times (1-P_{n\to\gamma})^{m_n-2}}{2!(m_n-2)!}$
- $P_{2n\to 2\gamma} = \frac{P_{n\to\gamma}^2 e^{-\lambda_n} \lambda_n^2}{2}\left(1 + \lambda_n(1-P_{n\to\gamma}) + \frac{\lambda_n^2(1-P_{n\to\gamma})^2}{2!} + \dots\right) = \frac{P_{n\to\gamma}^2 e^{-\lambda_n} \lambda_n^2}{2}\left(\sum_{k=0}^{\infty} \frac{(\lambda_n(1-P_{n\to\gamma}))^k}{k!}\right) = \frac{P_{n\to\gamma}^2 e^{-\lambda_n} \lambda_n^2}{2} \underbrace{\sum_{k=0}^{\infty} \frac{x^k}{k!}}_{e^x}$
- $P_{2n\to 2\gamma} = \frac{P_{n\to\gamma}^2 \lambda_n^2 e^{-\lambda_n} e^{\lambda_n(1-P_{n\to\gamma})}}{2} = P_{n\to\gamma}^2 e^{-\lambda_n P_{n\to\gamma}} \frac{\lambda_n^2}{2} = 50 f_{n\to\gamma}^2 e^{-10 f_{n\to\gamma}}$ (or in the e-on-dump case: $\frac{42.6^2}{2} f_{n\to\gamma}^2 e^{-42.6 f_{n\to\gamma}}$)

Probability to get 1 real + 1 fake photons

- For photons: $\lambda_\gamma = 0.013 \pm 0.004$, $P_{m_\gamma} = \dfrac{\lambda_\gamma^{m_\gamma} e^{-\lambda_\gamma}}{m_\gamma!} \Rightarrow P_{1\gamma} = \lambda_\gamma e^{-\lambda_\gamma}$

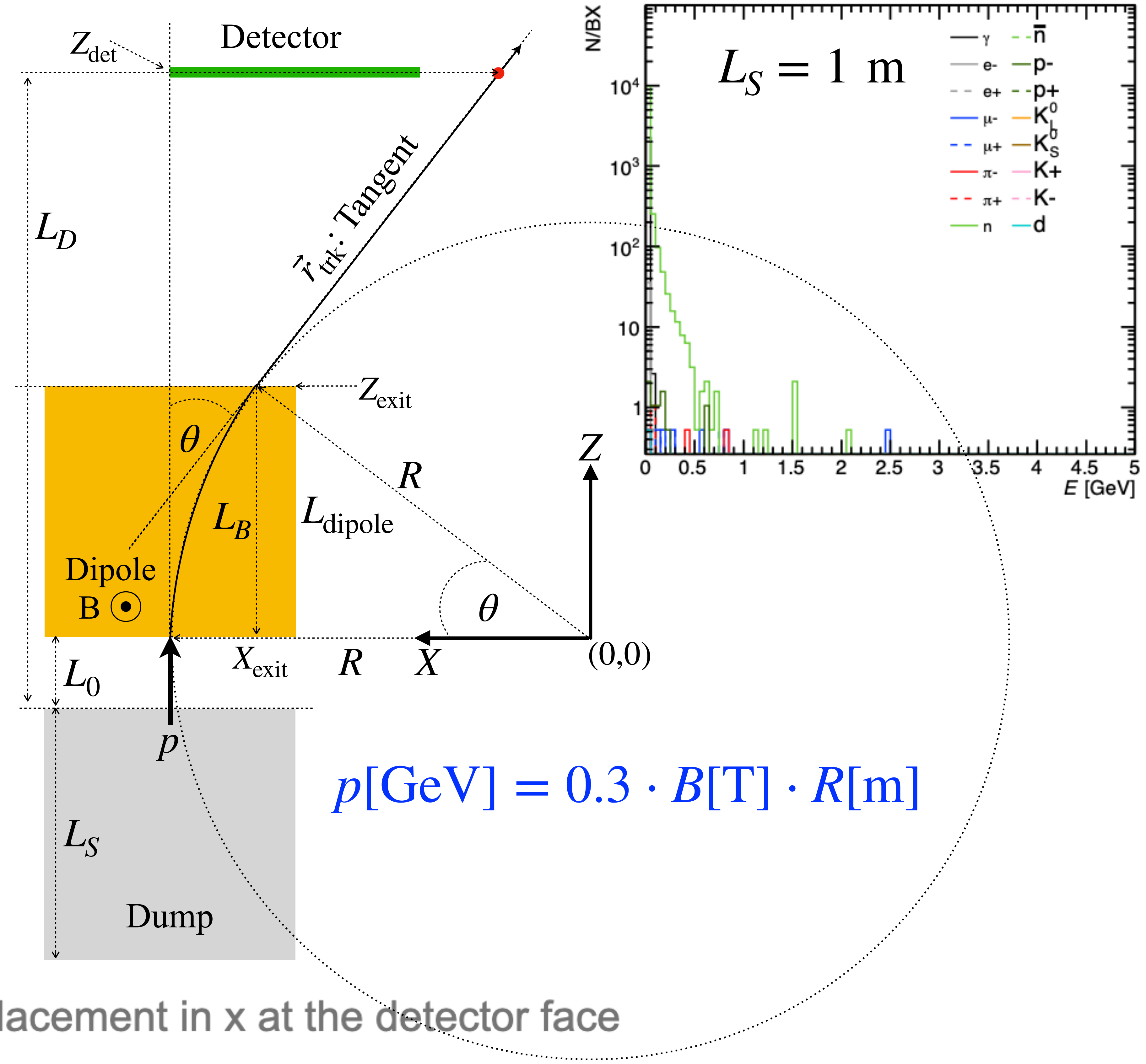
- For neutrons: $P_{n\to\gamma} = f_{n\to\gamma}$, $\lambda_n = 10 \pm 2.3$, $P_{1n\to 1\gamma} = \sum_{m_n=1}^{\infty} \dfrac{\lambda_n^{m_n} e^{-\lambda_n}}{m_n!} C(1, m_n, P_{n\to\gamma})$

$$P_{1n\to 1\gamma} = \sum_{m_n=1}^{\infty} \left(\frac{\lambda_n^{m_n} e^{-\lambda_n}}{m_n!}\right)\left(\frac{m_n!}{1!(m_n-1)!} P_{n\to\gamma} \times (1-P_{n\to\gamma})^{m_n-1}\right) = \sum_{m_n=1}^{\infty} \frac{\lambda_n^{m_n} e^{-\lambda_n} \times P_{n\to\gamma} \times (1-P_{n\to\gamma})^{m_n-1}}{(m_n-1)!}$$

$$P_{1n\to 1\gamma} = P_{n\to\gamma} e^{-\lambda_n} \lambda_n \left(1 + \lambda_n(1-P_{n\to\gamma}) + \frac{\lambda_n^2 (1-P_{n\to\gamma})^2}{2!} + \dots\right) = P_{n\to\gamma} e^{-\lambda_n} \lambda_n \left(\sum_{k=0}^{\infty} \frac{(\lambda_n(1-P_{n\to\gamma}))^k}{k!}\right) = P_{n\to\gamma} e^{-\lambda_n} \lambda_n \underbrace{\sum_{k=0}^{\infty} \frac{x^k}{k!}}_{e^x}$$

$$P_{1n\to 1\gamma} = P_{n\to\gamma} \lambda_n e^{-\lambda_n} e^{\lambda_n(1-P_{n\to\gamma})} = P_{n\to\gamma} e^{-\lambda_n P_{n\to\gamma}} \lambda_n$$

- For one neutron and one photon: $P_{n+\gamma\to 2\gamma} = P_{1n\to 1\gamma} \cdot P_{1\gamma} = \left(\lambda_n f_{n\to\gamma} e^{-\lambda_n f_{n\to\gamma}}\right) \cdot \left(\lambda_\gamma e^{-\lambda_\gamma}\right) \simeq 0.128 f_{n\to\gamma} e^{-10 f_{n\to\gamma}}$
  (or in the e-on-dump case: $1.12 f_{n\to\gamma} e^{-42.6 f_{n\to\gamma}}$)



Magnet requirements

Circle equation wrt the origin at the centre of the circle defined by the track: $X^2 + Z^2 = R^2$

Therefore: $Z_{\rm exit} = L_B$ and hence $X_{\rm exit} = \sqrt{R^2 - L_B^2}$

The tangent equation is: $Z = m_{\rm T} \cdot X + c_{\rm T}$. The tangent gradient, m, is -1 over the gradient of the radius line itself, at the point where the tangent is defined at the point $\left(Z_{\rm exit}, X_{\rm exit}\right)$, i.e.:

$$m_{\rm T} = -1/m_{\rm R} = -1/(\Delta Z/\Delta X)_{\text{radius slope}} = -\frac{\left(X_{\rm exit} - 0\right)}{\left(Z_{\rm exit} - 0\right)} = -\frac{\sqrt{R^2 - L_B^2}}{L_B} = -\sqrt{\frac{R^2}{L_B^2} - 1}$$

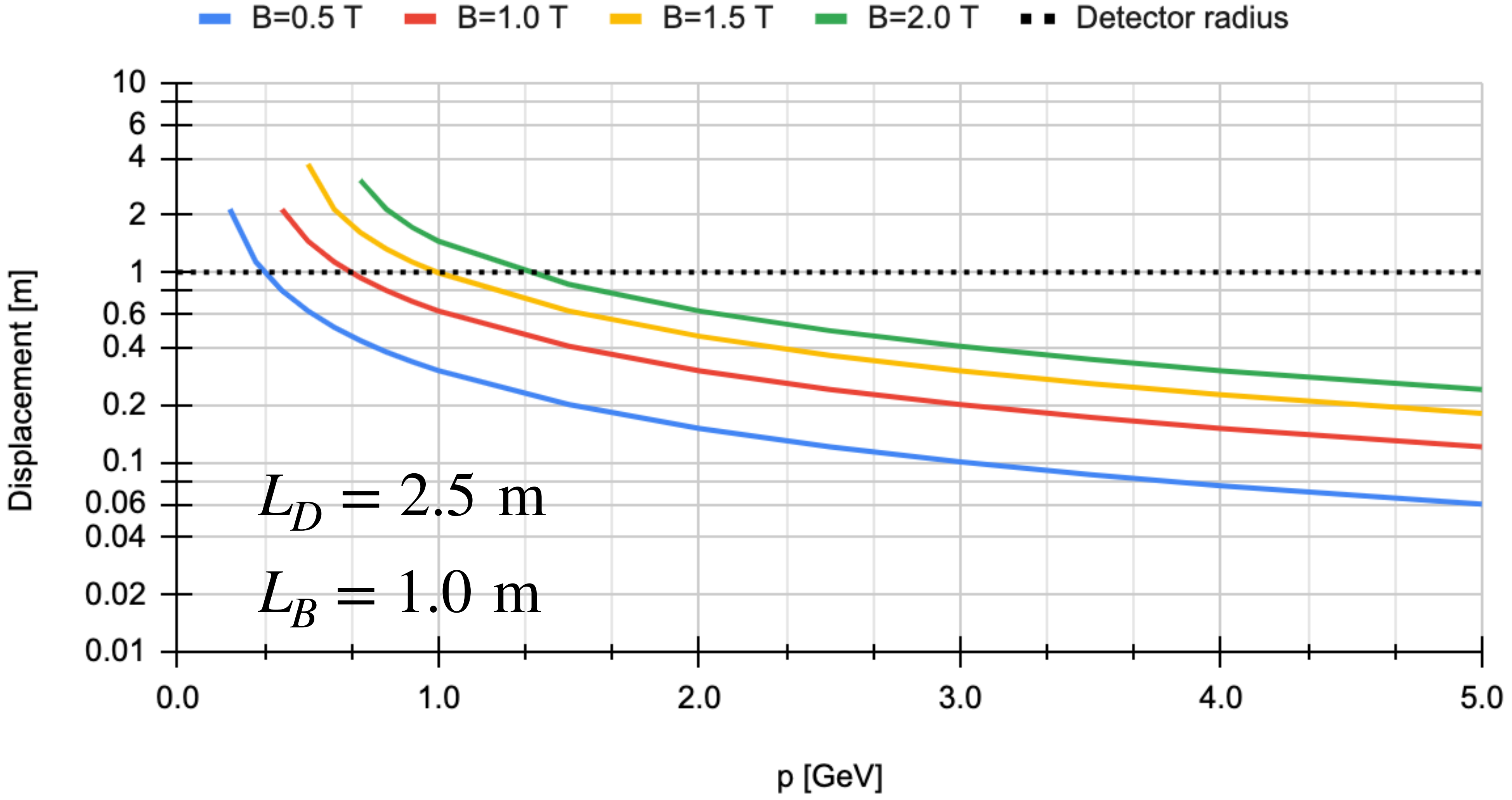
Using the point $\left(Z_{\rm exit}, X_{\rm exit}\right)$ again we get the intersection of the tangent: $c_{\rm T} = Z - m_{\rm T} \cdot X$

$$c_{\rm T} = L_B - \left(-\sqrt{\frac{R^2}{L_B^2} - 1}\right) \cdot \sqrt{R^2 - L_B^2} = L_B + \frac{R^2 - L_B^2}{L_B} = \frac{R^2}{L_B}$$

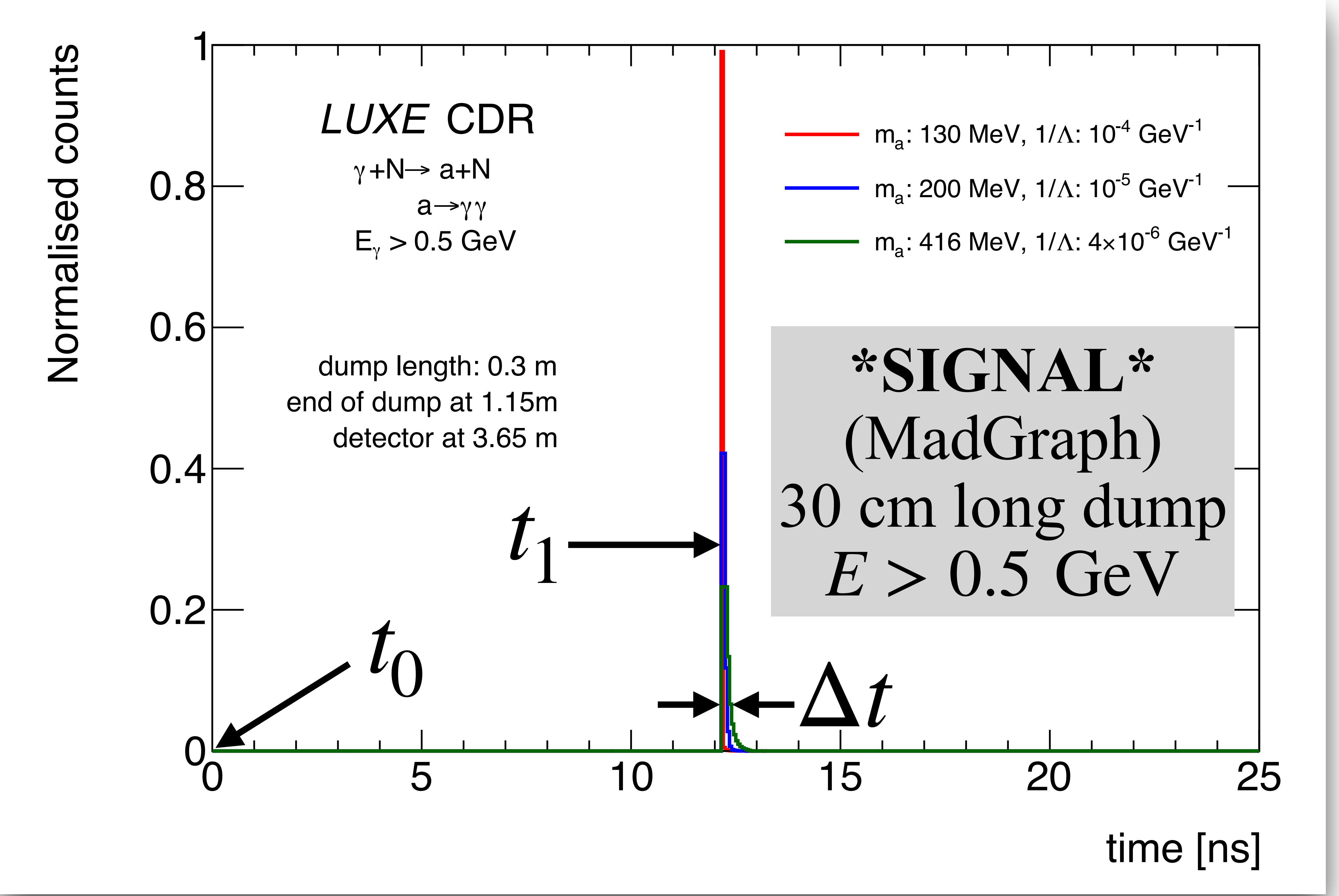
Hence, the prediction along the tangent at some point $Z_{\rm tangent}$ is: $X = \dfrac{Z - c_{\rm T}}{m_{\rm T}}$

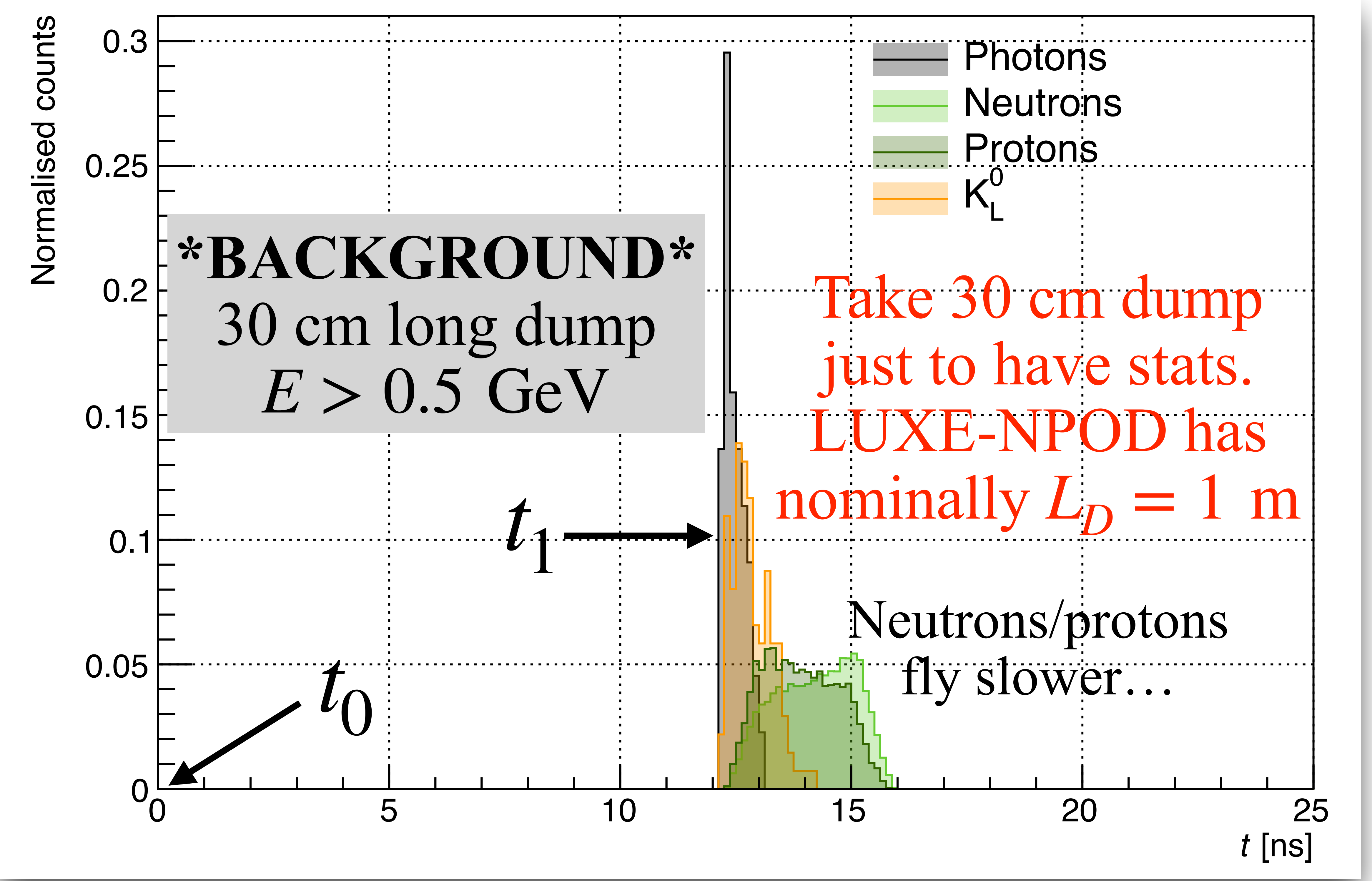
$$X_{\rm tangent} = \left(\frac{R^2}{L_B} - Z_{\rm tangent}\right) \frac{L_B}{\sqrt{R^2 - L_B^2}}$$ and so putting $Z_{\rm tangent} = Z_{\rm det} = L_D - L_0 \simeq L_D$

we get that $$X_{\rm tangent} \simeq \left(\frac{(p/0.3B)^2}{L_B} - L_D\right) \frac{L_B}{\sqrt{(p/0.3B)^2 - L_B^2}}$$



Timing cut





- The time it takes a bkg photon to fly from $z_0 = 0$ to the calorimeter face at $z_1 = z_D + L_D/2 + L_V = 3.65$ m, is $t_1 = t_0 + (12 + \Delta t)$ ns
  - with $z_D = 1$ m, $L_D = 0.3$ m and $L_V = 2.5$ m and $t_0 = 0$
- We trigger at t_0 (Eu.XFEL clock) and open a short time window Δt
  - most signal (and bkg) photons will arrive within $\Delta t \simeq 0.5$ ns
  - almost all bkg hadrons will arrive after that - need ~0.1 ns resolution

	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**
0.5	~16	~96	~94	~52	~99.9	~99.8	~95
1.0	~0	~80	~70	~13	100	~99.9	100

Background estimation

- Assuming
  - one year of running with $T \sim 10^7$ live seconds, i.e. recorded BXs
  - rejection is $R_{\mathrm{sel}} \lesssim 10^{-3}$ based on kinematic cuts & timing (see backup)
  - neutron-to-photon fake rate is $f_{n\to\gamma} \lesssim 10^{-3}$ (see backup)

- Number of background two-photon events is $\boldsymbol{N_{\mathrm{bkg}} = P_{\mathrm{bkg}} R_{\mathrm{sel}} T_{\mathrm{operation}}}$
  - $\mathrm{bkg} = 2\gamma$
  - $\mathrm{bkg} = 2n \to 2\gamma$
  - $\mathrm{bkg} = \gamma + n \to 2\gamma$

- See backup for
  - the calculation of the probabilities P_{bkg}
  - the rejection details and possible technologies

Assumptions	Value
T_{op}	1E+07
R_{sel}	1E-03
$f_{n\to\gamma}$	1E-03

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

Max N_{bkg}	LUXE NPOD	Electrons on dump
$N_{2\gamma}$	0.8	267.8
$N_{2n\to2\gamma}$	0.5	8.7
$N_{\gamma+n\to2\gamma}$	1.2	82.8

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 $\Gamma_{a\to\gamma\gamma} = m_a^3/(64\pi\Lambda_a^2)$

Scalar and Naturalness

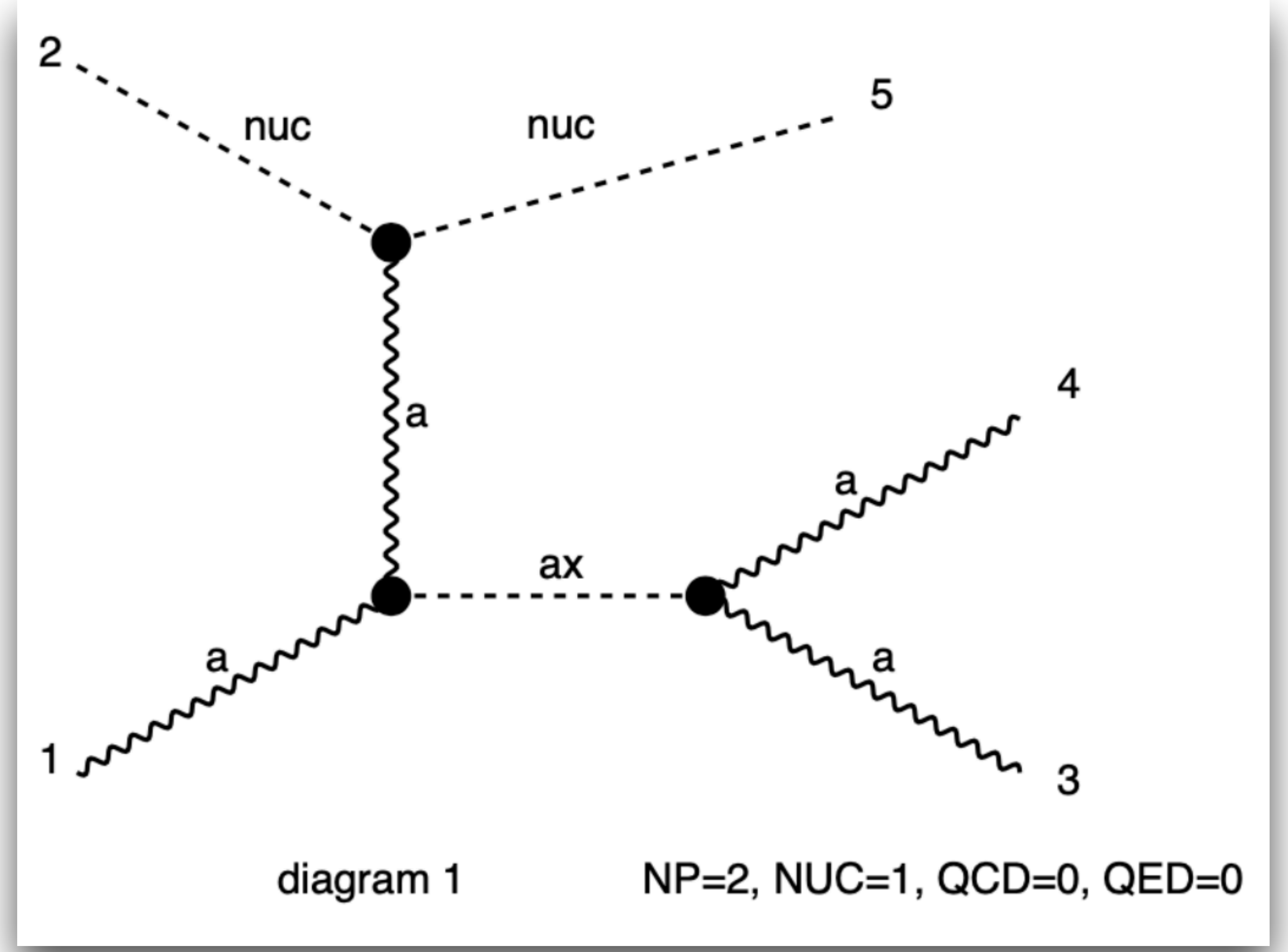
- The $\phi - \gamma$ coupling induces quadratically divergent, additive contribution to the scalar mass-square, $\delta m_\phi^2 \sim \Lambda_{\mathrm{UV}}^4/(16\pi^2\Gamma_\phi^2)$
  - Λ_{UV} is the scale in which NP is required to appear in order to cancel the quadratic divergences
  - This leads to a naturalness bound:

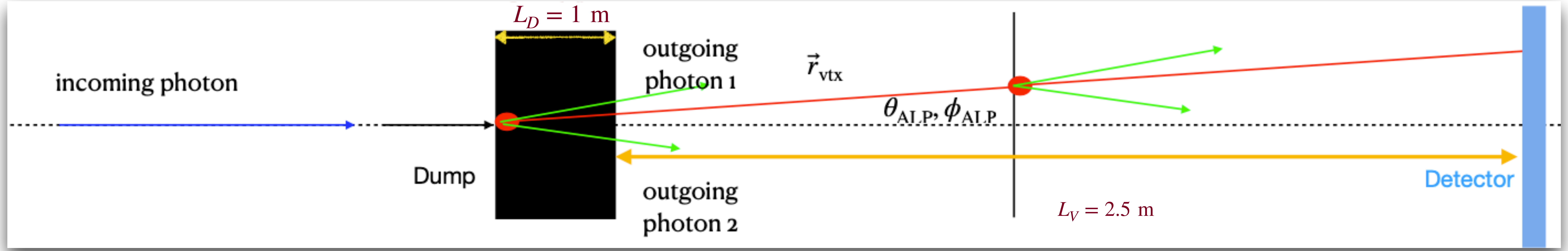
$$\Gamma_\phi \gtrsim 4 \times 10^5\ \mathrm{GeV} \left(\frac{\Lambda_{\mathrm{UV}}}{\mathrm{TeV}}\right)^2 \frac{200\ \mathrm{MeV}}{m_\phi}$$

- LUXE-NPOD is expected to reach the sensitivity required to probe the edge of the parameter space of natural models in its phase-1

Signal MC prod. with MadGraph

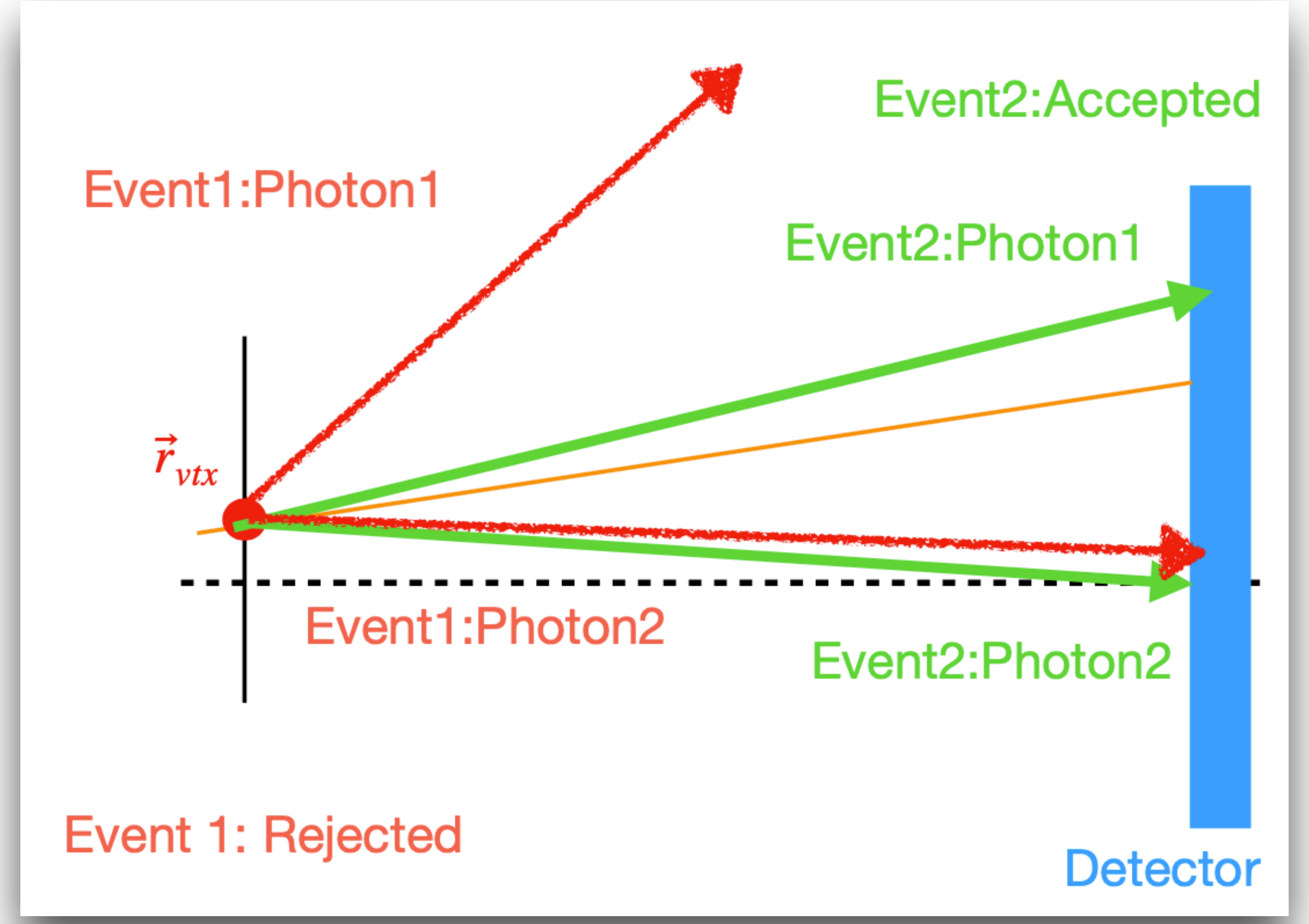
- Generate this process: a nuc -> ax nuc where a is photon, nuc is the nucleus of the tungsten dump and ax is the ALP (Primakoff production)
- The nuclear form factor was obtained from Iftah Galon and implemented in the model
- MadGraph does not smear the vertex position, so all collisions happen at z=0, t=0
- Moreover MadGraph decays the ALP instantaneously
- The 2 photons are produced at z=0 and hence we need to displace them according to the ALP's lifetime

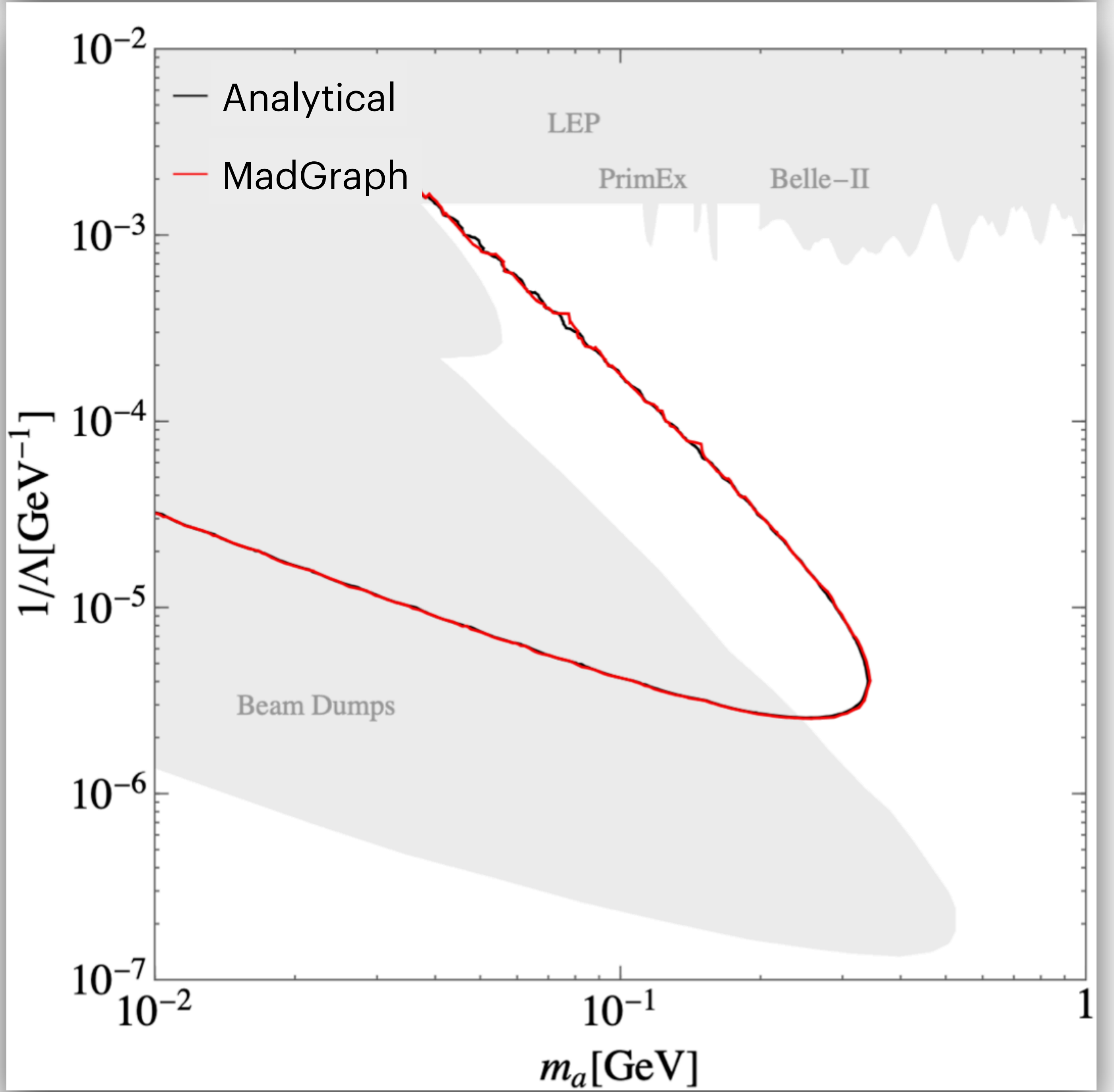




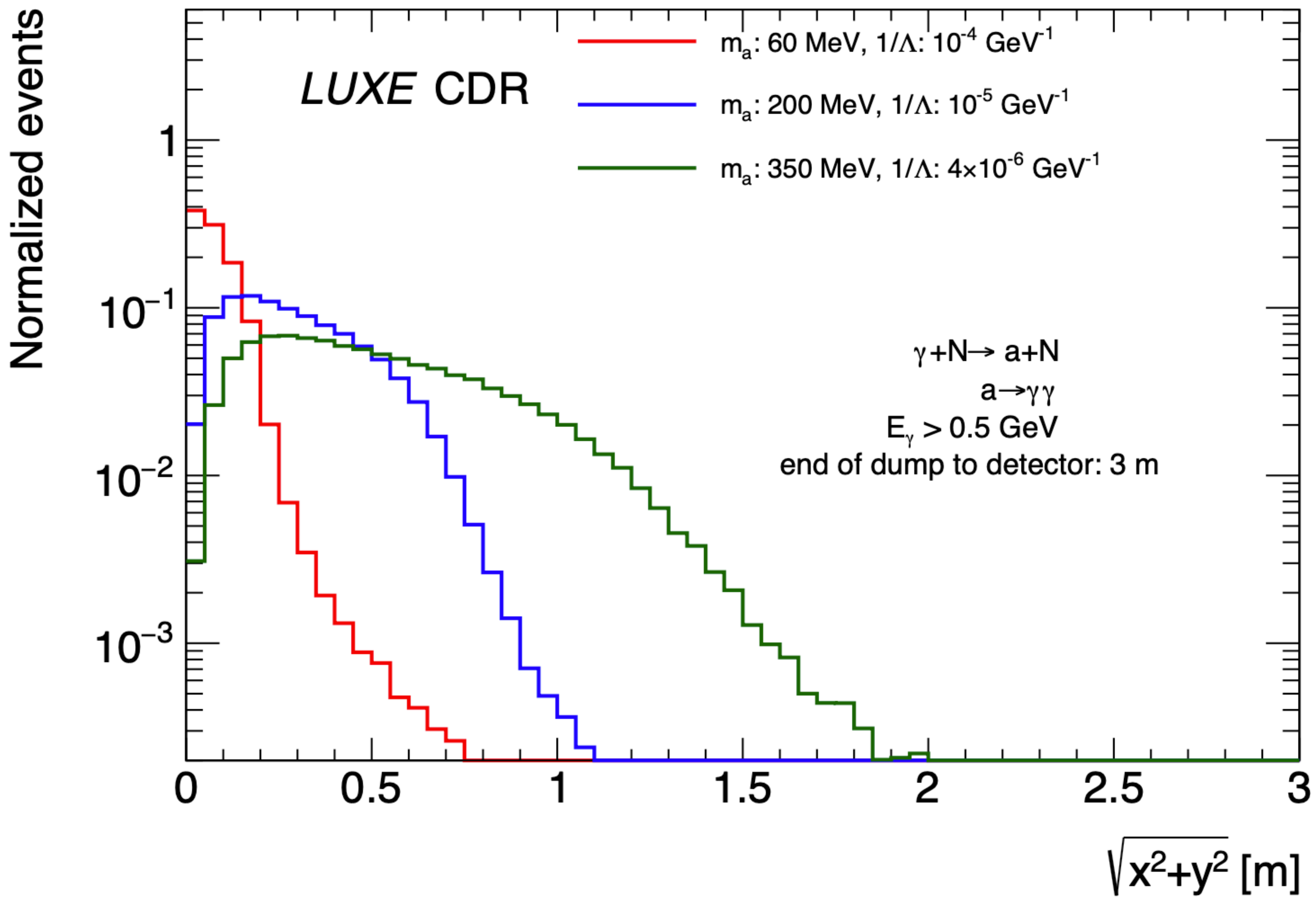
Signal MC prod. with MadGraph

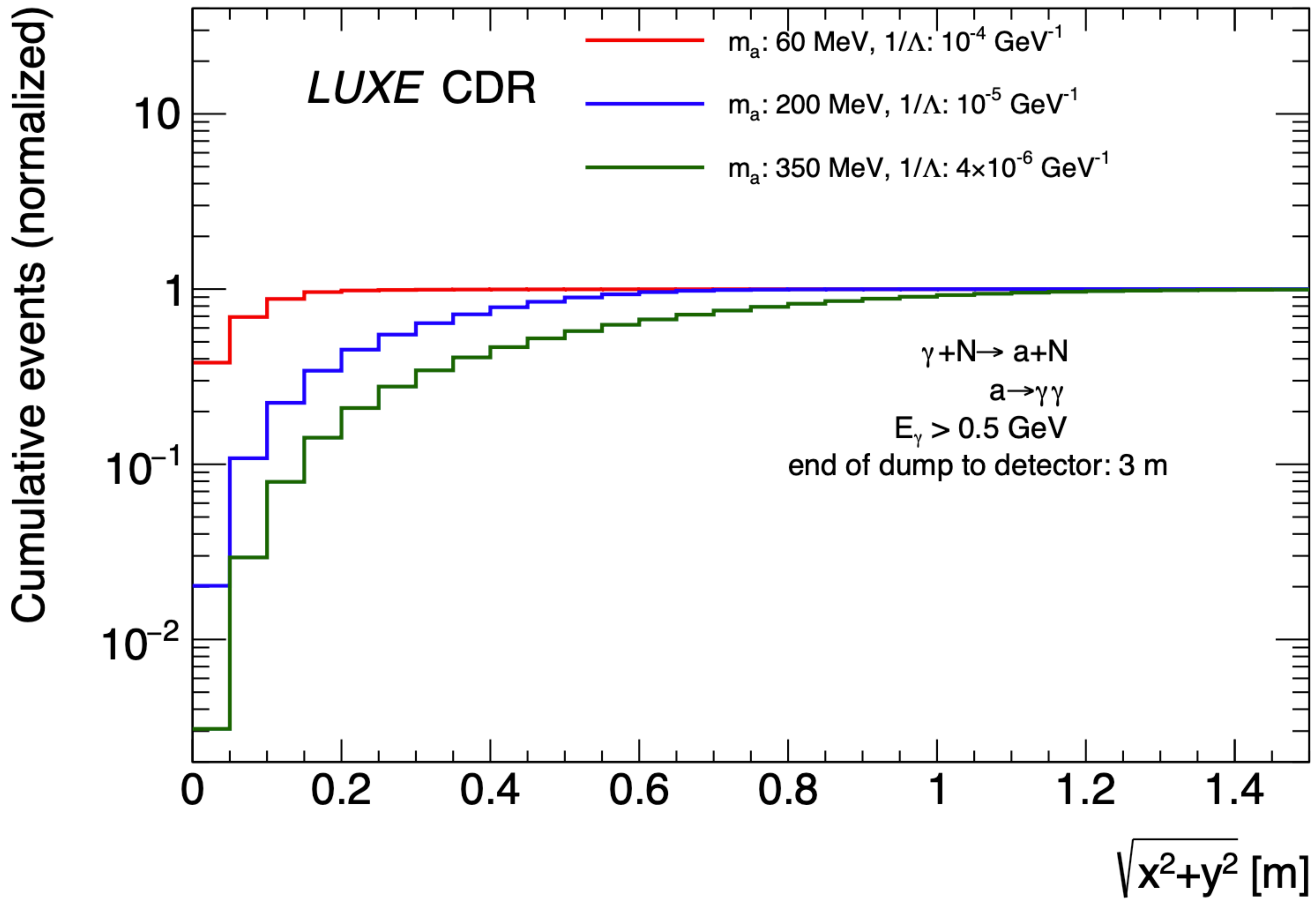
- The distance of decay ($r_{\rm vtx}$) for each ALP is obtained by randomly drawing a length from the decay length distribution of the ALP, where:
  - the decay length is $L_a = c\tau_a p_a / m_a$
  - the direction is determined by the momentum of ALP
  - $r_{\rm vtx}$ is randomly drawn number from e^{-L_a}
- Once $\vec{r}_{\rm vtx}$ is obtained, the two photons are shifted to that position
  - if $L_D < r_{\rm vtx} \cos\theta_a < L_D + L_V$ we proceed to next stage, otherwise the event is rejected
  - given the opening angle of the photons and the distance they still need to travel to detector, we check if the photons impinge the detector or not.
  - if both photons impinge the detector and $E_\gamma > 0.5\ \text{GeV}$, then that event is accepted
- The acceptance $\mathscr{A}$ is the number of events with both photons passing the energy cut and geometric constraints divided by the total number of events generated
- Once the geometric acceptance is obtained, the factor is multiplied by the effective luminosity and the cross-section of production to get the number of ALP events (see earlier slide) where $N_a = \mathscr{L}_{\rm eff} \sum_i \sigma_i \mathscr{A}_i N_{\gamma,i}$ and where the sum is over sum over the incoming photon beam energy distribution $N_{\gamma,i}$





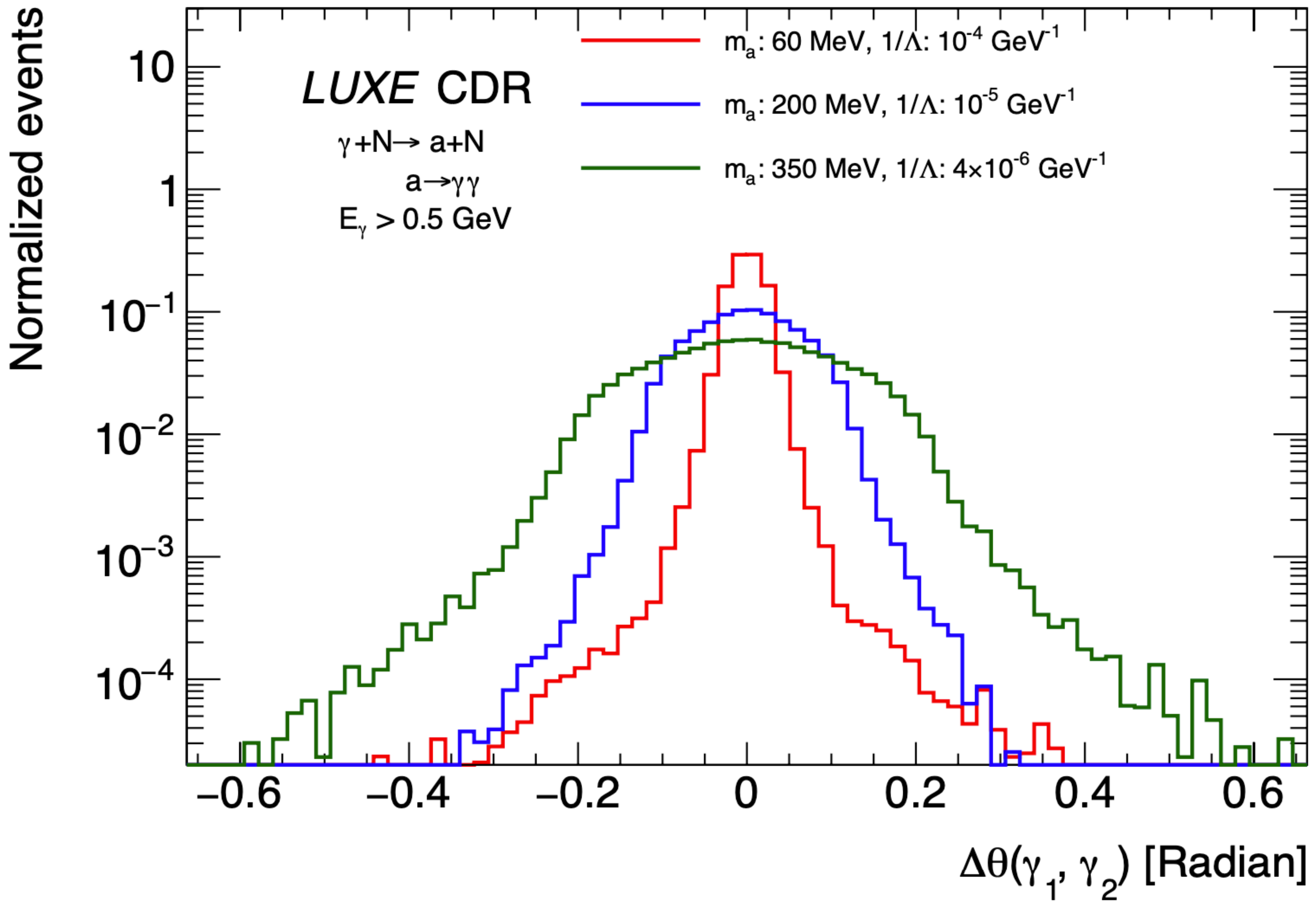
Signal MC prod. with MadGraph

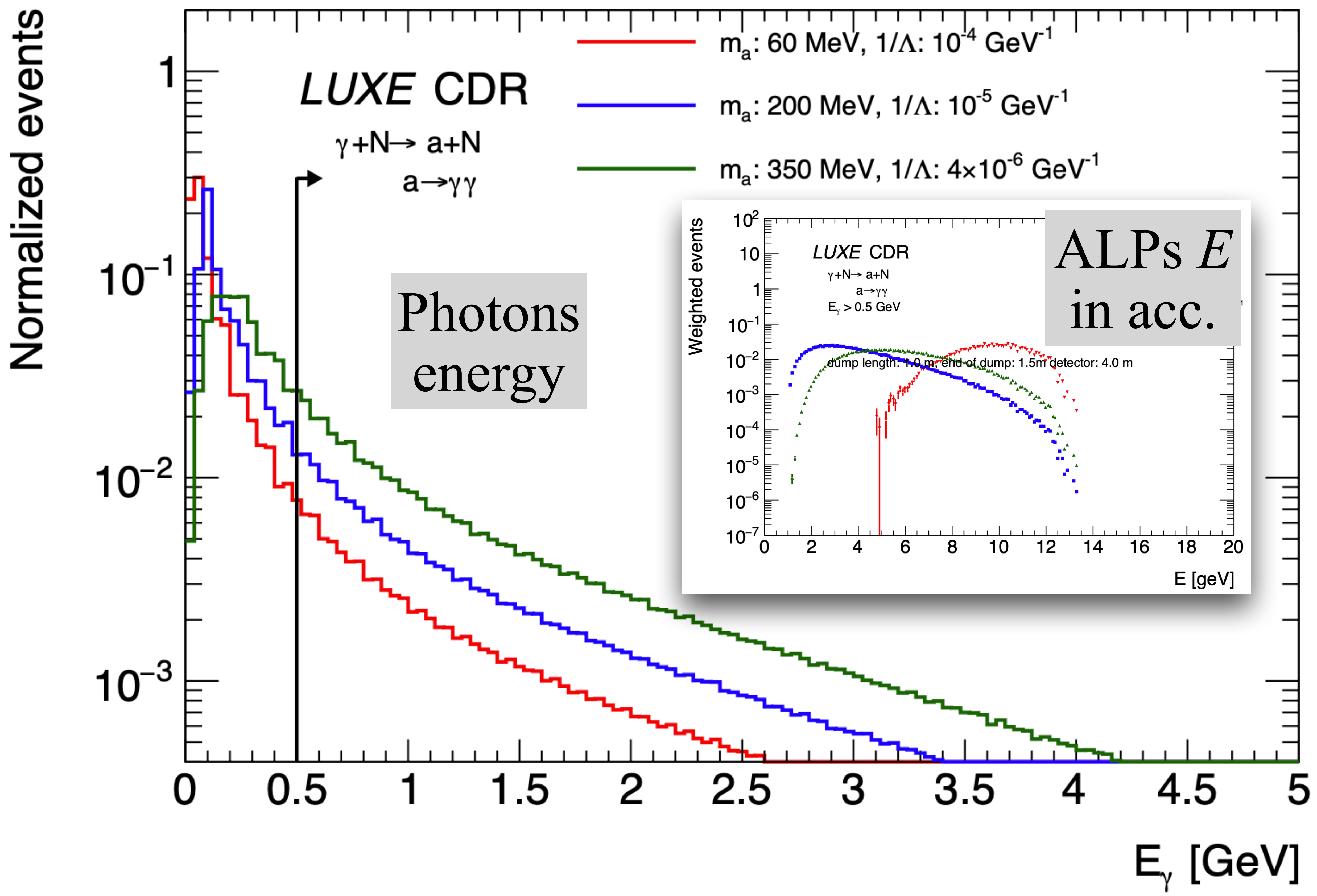




More than 90% of the photons are captured by a detector with radius of 1 m

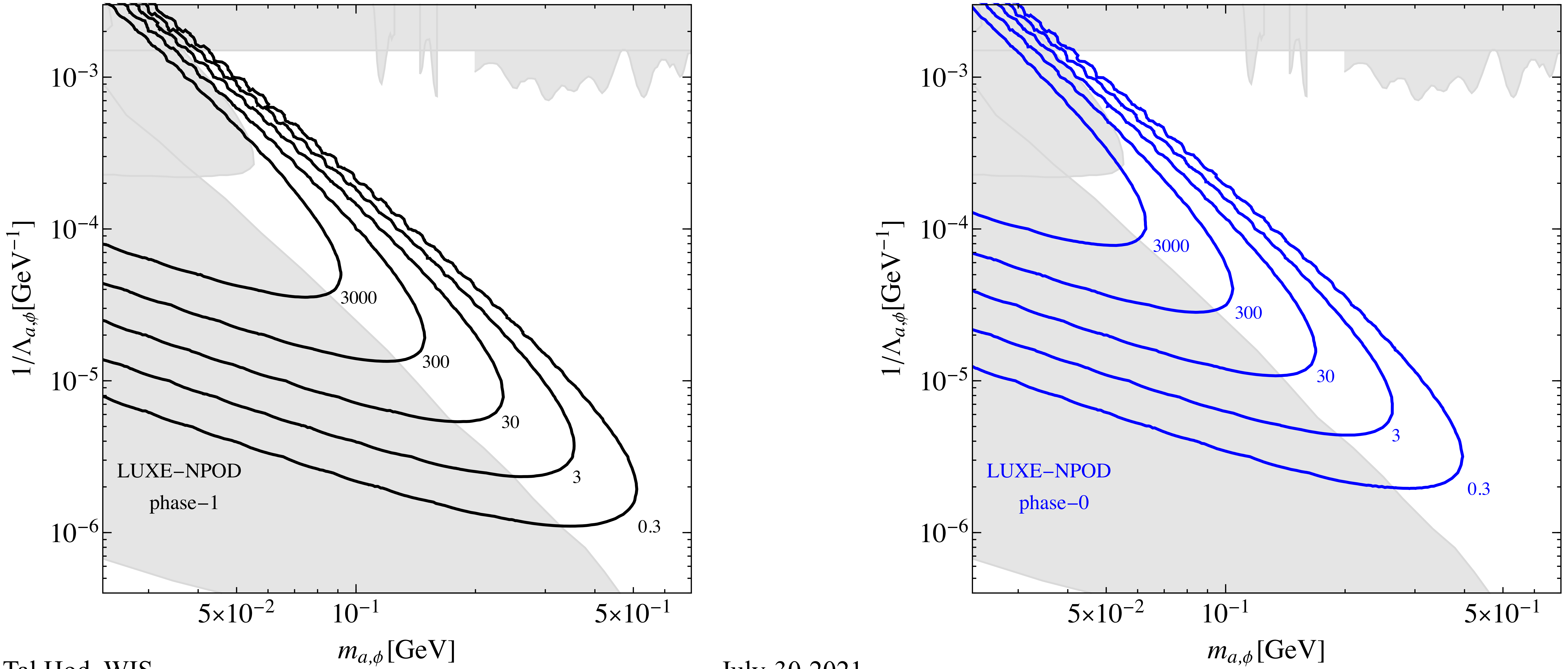
Signal MC prod. with MadGraph





Contours of the expected number of $a, \phi \to 2\gamma$ events, $N_{a,\phi}$, for phase-0 and phase-1

The lines correspond to 1 year of data taking.
The nominal curve is for $N_{a,\phi} = 3$ which is the 95 % CL equivalent for background free search



New Physics production at the IP

- Axion-like particles (ALPs)
  - or scalars ($X = a, \phi$)

- Milli-charged particles (mCPs)
  - $m_\psi \ll m_e$ and $q_\psi \equiv qe \ll e$