



LUXE: A new experiment to study non-perturbative QED in electron-LASER and photon-LASER collisions

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On behalf of the LUXE Collaboration

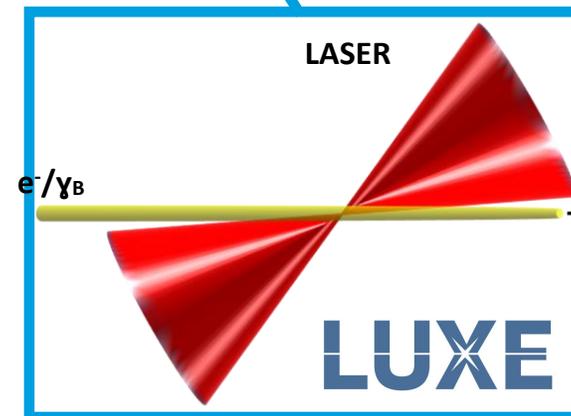
LUXE

Overview



What is the LUXE experiment?

- proposed new experiment at DESY and EU.XFEL in Schenefeld & Hamburg, Germany
- collisions of XFEL electron beam and high-power LASER
- synergy between particle physics and LASER physics
- (growing) international collaboration
→ 88 members (26 institutes)

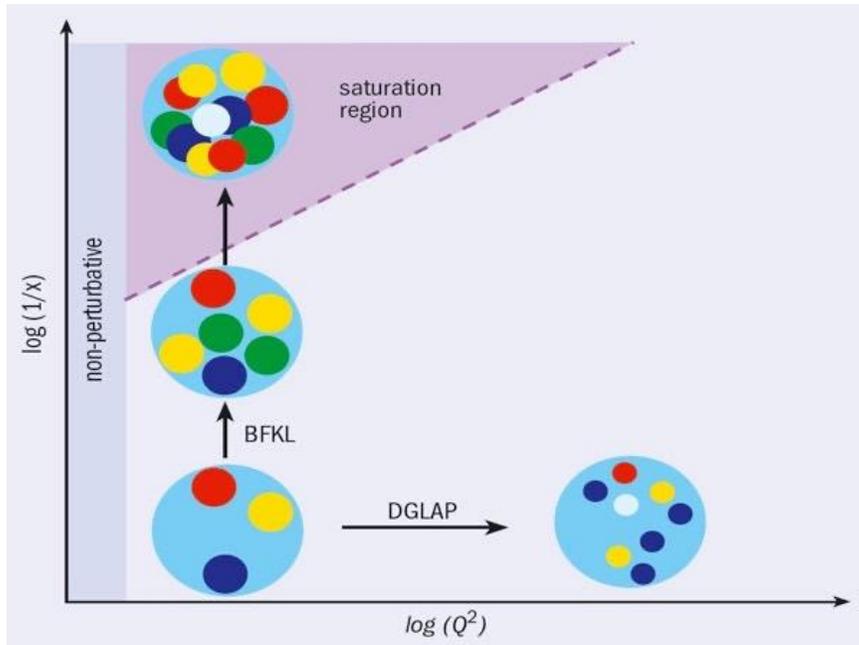


More documentation?

- LUXE CDR: [H. Abramowicz et al., Eur. Phys. J. Spec.Top. 230 \(2021\) 2445](#)
- LUXE website: <https://luxede.desy.de>

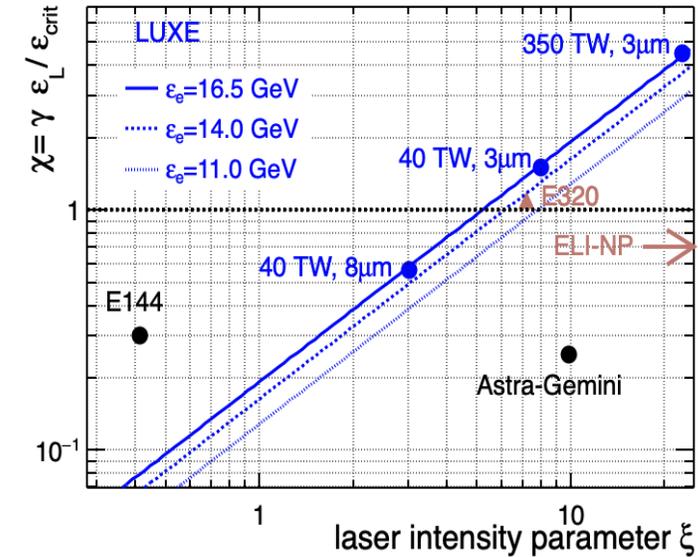
Synergy between particle physics and LASER physics

Particle Physics – non-perturbative QCD



Can not calculate in non-perturbative region. α_s too big.

Laser Physics – non-perturbative QED



ϵ_{crit} – Schwinger field (Schwinger limit)

ϵ_L - Laser field

χ - work done over λ_e in units of $m_e c^2$ (when $\chi=1$, the laser can do work over the electron wavefunction to create a pair).

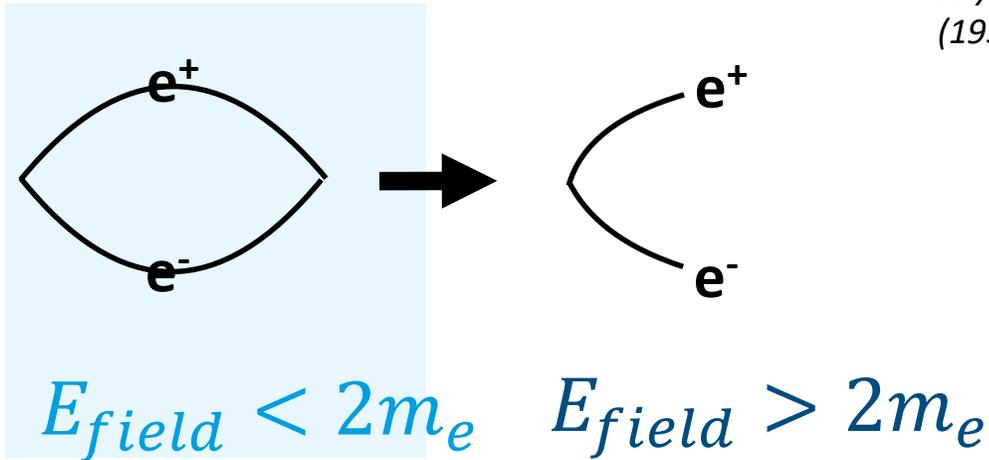
ξ - work done over λ_e in units of $\hbar\omega_L$ (gives a measure of the number of laser photons interacting with the electron at a given time. ξ^2 is a measure of the photon density of the laser beam)

Know how to calculate. Need to sum all contributions in charge-field coupling, ξ .

Schwinger limit - $\mathcal{E}_{\text{crit}}$



Schwinger
Phys. Rev. 82
(1951), 664



Field energy:

$$E_{\text{field}} = \frac{\mathcal{E}}{m_e}$$

Fluctuation time $> \lambda_e$
so do not annihilate
but use energy
supplied by strong
field to become real

$$\mathcal{E}_{\text{crit}} = \frac{m_e^2 c^3}{e \hbar} = 1.32 \times 10^{18} \text{ V/m}$$

Fluctuating vacuum is stimulated by high field
to produce real pair-creation

Synergy between particle physics and LASER physics

Particle Physics – variables

x, Q^2, y, s

$$Q^2 = s x y$$

Laser Physics – variables

ξ, X, η

$$\chi = \eta \xi$$

η – cm energy square (s) in units of $m_e c^2$

χ - work done over electron Compton wavelength λ_e in units of $m_e c^2$

ξ - work done over λ_e in units of $\hbar\omega_L$ (ξ^2 is a measure of the photon density of the laser beam)

$$\eta = \frac{E_e E_L}{m_e^2} (1 + \cos\vartheta)$$

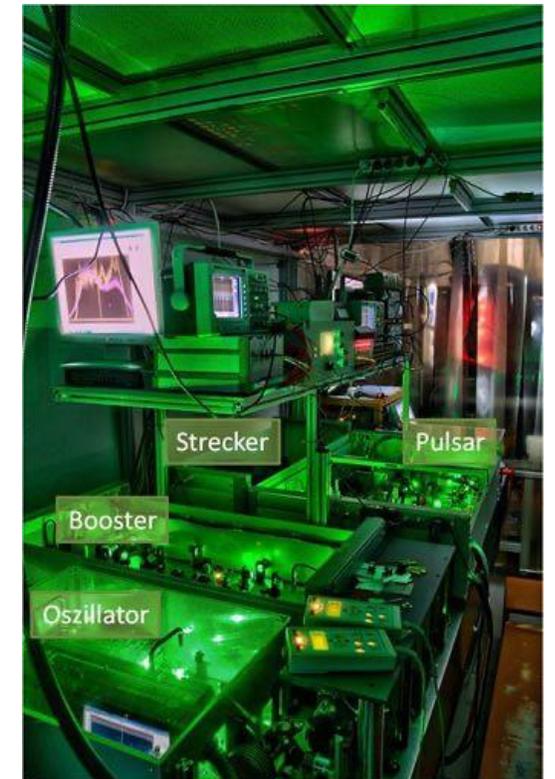
η (LUXE, $E_e=16.5$ GeV, $E_L=1.55$ eV) = 0.192

$\left\{ \begin{array}{l} \xi - \text{Classical non-linearity parameter} \\ \chi - \text{Quantum non-linearity parameter} \\ \eta - \text{Energy parameter} \end{array} \right\}$

Experimental specs: laser

- High power CPA Ti:Sapphire laser from HI Jena (JETI-40) and 350TW commercial laser
- Laser repetition rate at 1 Hz
- High precision laser diagnostics: less than 5% uncertainty on peak intensity & 1% shot-to-shot uncertainty
- Development & Installation in 2021-2025

	Phase 0		Phase 1
Power @ waist radius	40 TW @ 8 μm	40 TW @ 3 μm	350 TW @ 3 μm
wavelength	800 nm red laser (1.55 eV)		
Duration	30 fs (10 cycles)		
Peak intensity	$0.19 \times 10^{20} \text{ W cm}^{-2}$	$1.33 \times 10^{20} \text{ W cm}^{-2}$	$12 \times 10^{20} \text{ W cm}^{-2}$
Peak ξ	3.0	7.9	23.6
Peak χ (16.5 GeV)	0.56	1.5	4.5
Collision angle	17.2° (angular coefficient = 0.978)		



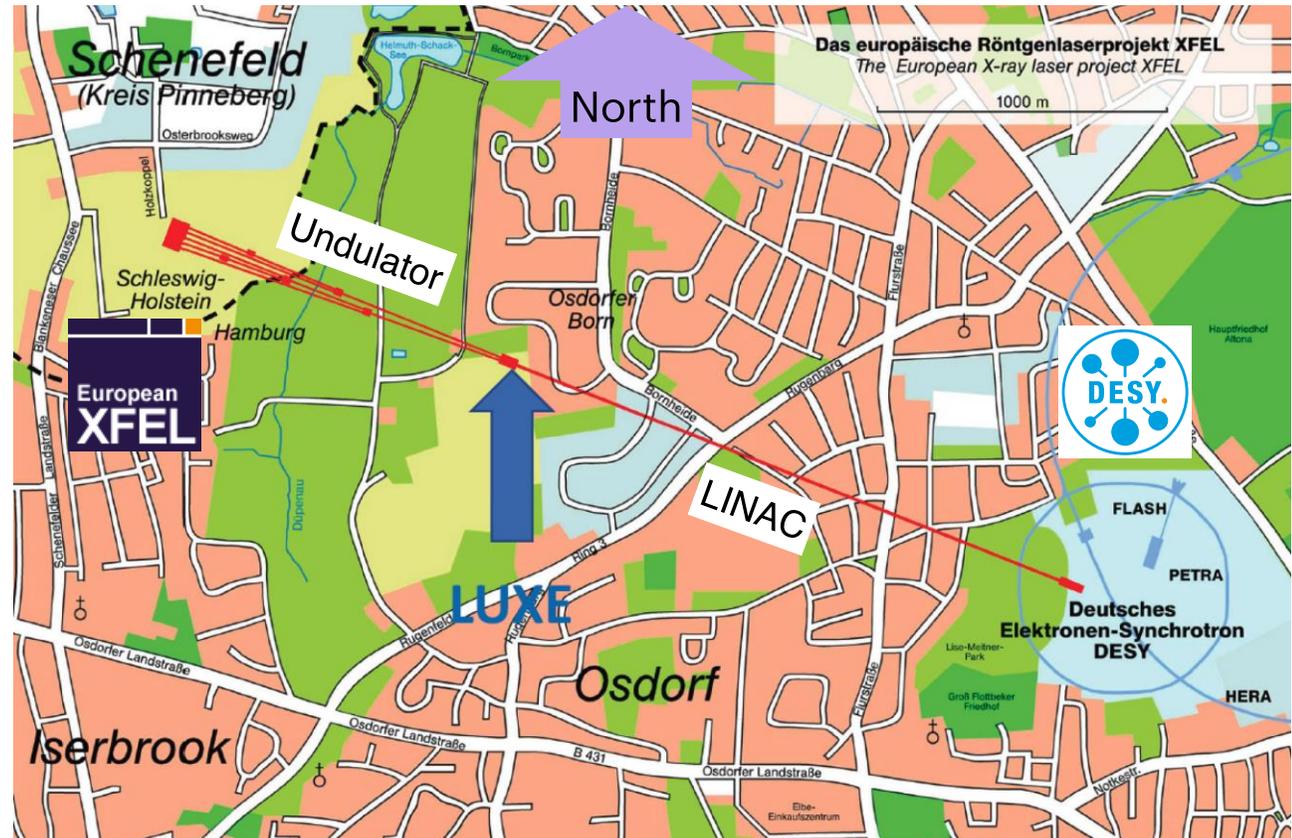
Experimental specs: EU.XFEL

European X-ray Free-Electron Laser

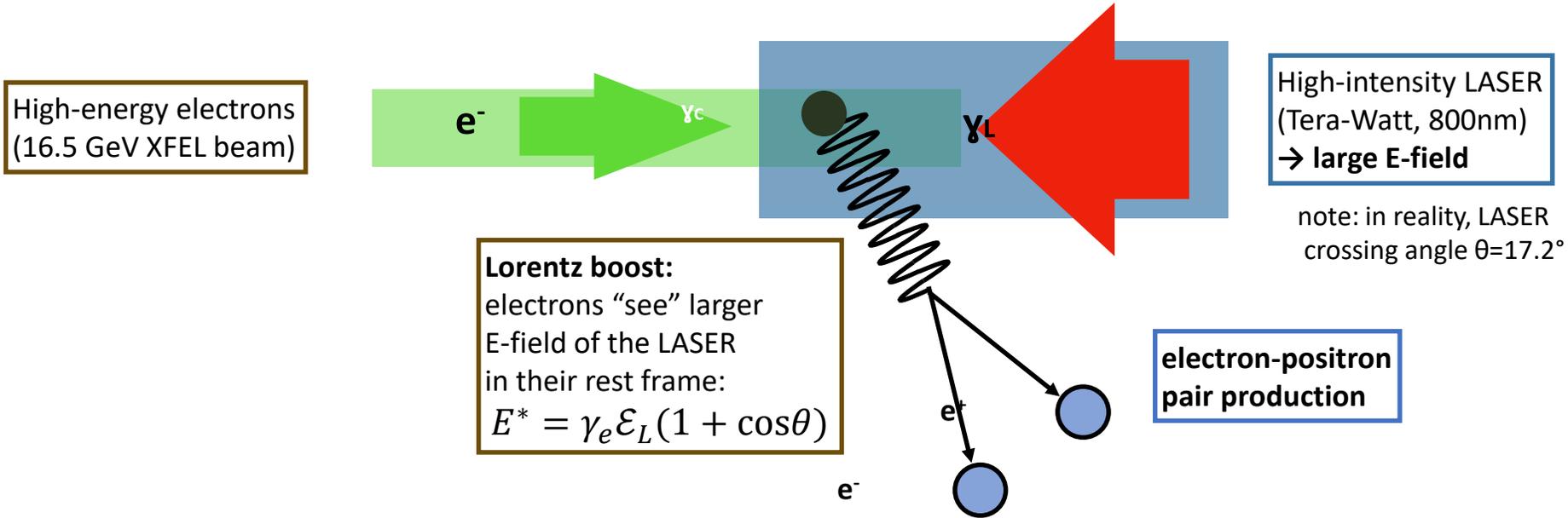
- Electron beam injected at DESY campus
- Accelerated in a 1.9-km LINAC to a 17.5 GeV beam, and then turned into X-ray

LUXE will use 1/2700 bunches from one EU.XFEL train

- Bunch: 16.5 (14) GeV @ 10 Hz
- Laser: 1 Hz
- 9 bunches for backgrounds + 1 bunch for signal data taking
- each bunch includes 1.5×10^9 electrons
- convertible into photons via Bremsstrahlung

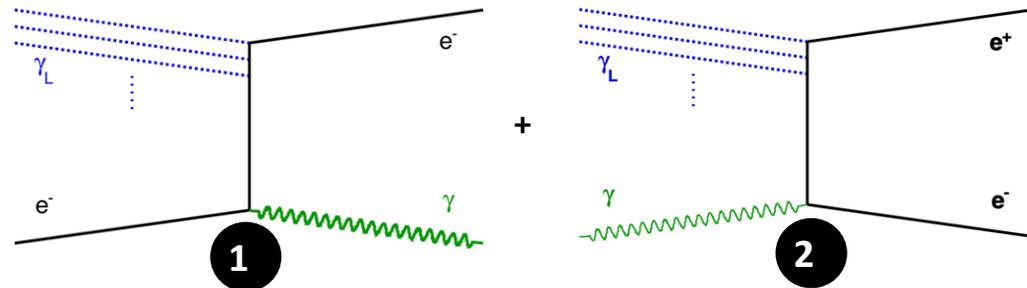


LUXE: Electron + LASER collisions

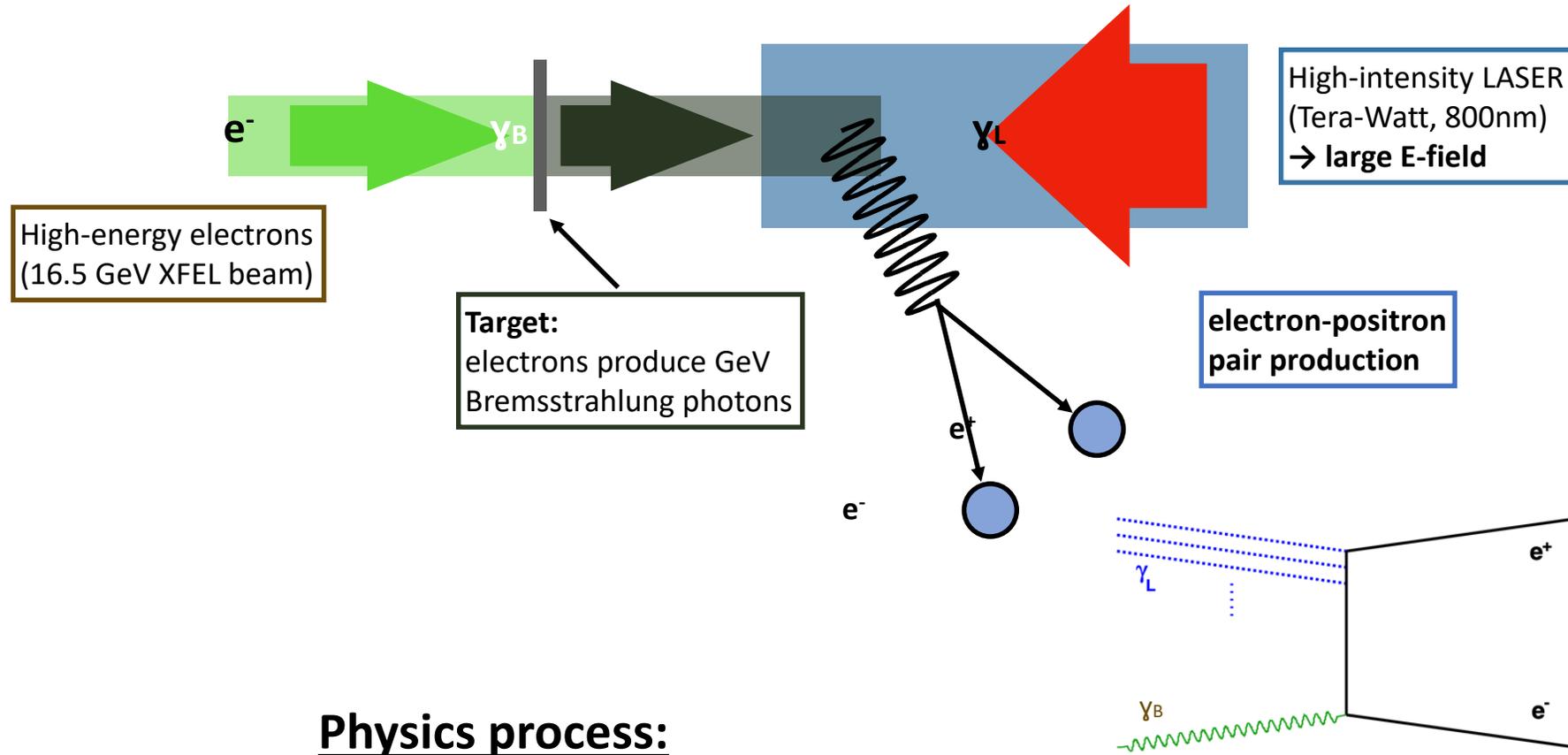


Physics processes:

- 1 Non-linear Compton Scattering: $e^- + n\gamma_L \rightarrow e^- + \gamma_C$
- 2 Non-linear Breit-Wheeler pair production: $\gamma_C + n\gamma_L \rightarrow e^+ + e^-$



LUXE: Photon + LASER collisions



Physics process:

Non-linear Breit-Wheeler pair production : $\gamma_B + n\gamma_L \rightarrow e^+ + e^-$

LUXE: first SF-QED experiment to probe directly photon-photon interaction

Non-perturbativity at small coupling

- Electron-laser mode -

$$P \left(\begin{array}{c} \gamma_L \\ \vdots \\ \text{---} \\ \vdots \\ \gamma \end{array} \right) \sim \xi^2$$

(Laser) photon number density, ξ^2

$$\xi = \frac{m_e c^2}{\hbar \omega} \frac{E}{E_{cr}}$$

$$P \left(\begin{array}{c} n\gamma_L \\ \vdots \\ \dots \\ \vdots \\ \gamma \end{array} \right) \sim \xi^{2n}$$

n laser photons

$$\sum_n \left(\begin{array}{c} n\gamma_L \\ \vdots \\ \dots \\ \vdots \\ \gamma \end{array} \right) \equiv \left(\begin{array}{c} \text{---} \\ \text{---} \\ \vdots \\ \gamma \end{array} \right)$$

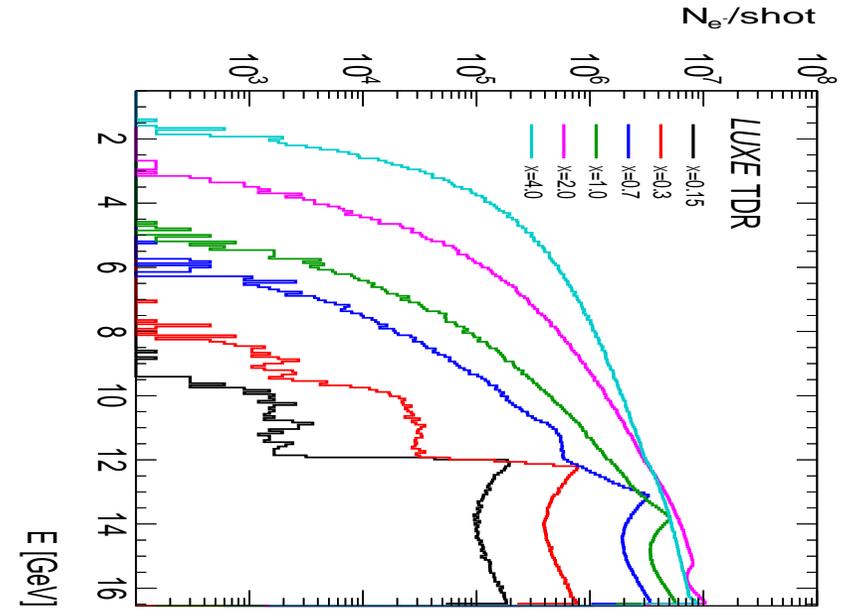
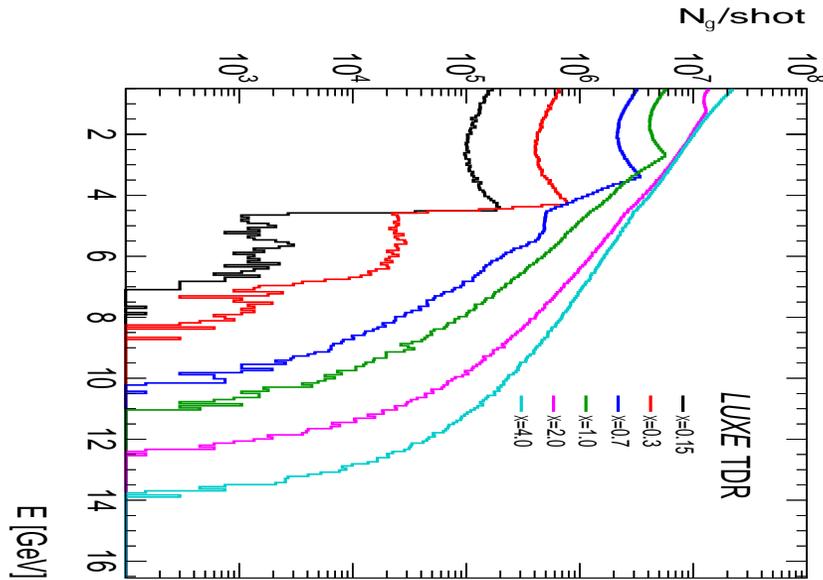
Nonlinear Compton scattering

$$e^\pm + n\gamma_L \rightarrow e^\pm + \gamma$$

'Non-perturbativity at weak coupling'

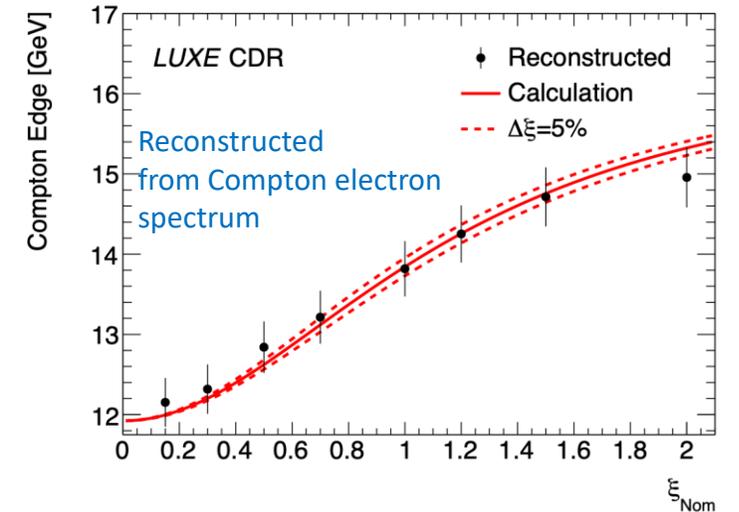
'Effective mass' $m_e \rightarrow m_e \sqrt{1 + \xi^2}$

Compton edge



in strong fields, electron acquires ξ – dependent effective mass m_*
 $= m_e \sqrt{1 + \xi^2}$
 \rightarrow Compton edge shifts as function of ξ

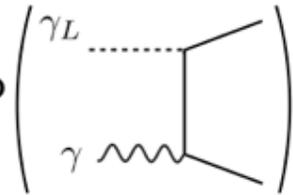
Theory: $E^{\gamma}_{edge}(\xi) = E_e \frac{2n\eta}{2n\eta + 1 + \xi^2}$,
 with $\eta_{LUXE} = 0.192, n=1$



$$E^e_{edge}(\xi) = E_e - E^{\gamma}_{edge}(\xi)$$

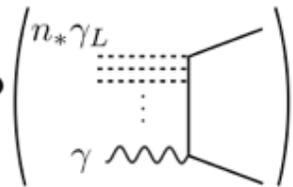
Schwinger-type non-perturbativity

- Photon-laser mode -

$$P \left(\begin{array}{c} \gamma_L \text{ (dashed)} \\ \gamma \text{ (wavy)} \end{array} \right) \sim \xi^2$$


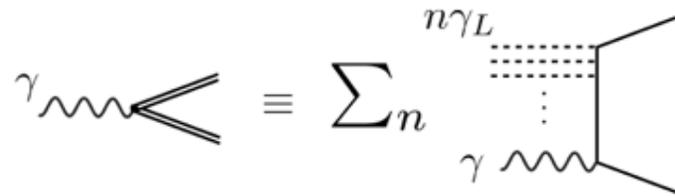
Linear Breit-Wheeler, CM energy:

$$2m_e^2 \eta_\gamma \geq 4m_e^2 (1 + \xi^2)$$

$$P \left(\begin{array}{c} n_* \gamma_L \text{ (dashed)} \\ \vdots \\ \gamma \text{ (wavy)} \end{array} \right) \sim \xi^{2n_*}$$


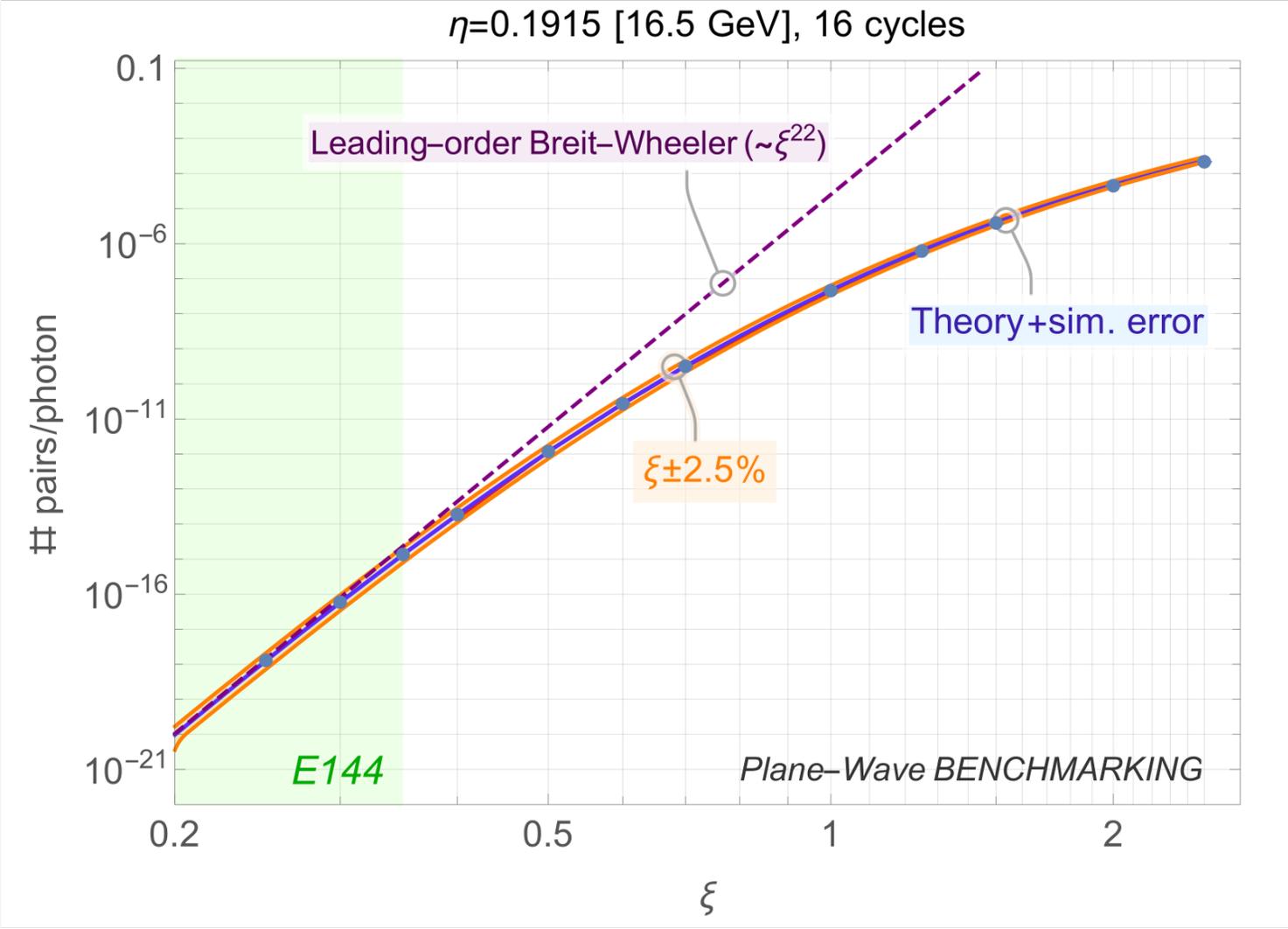
(Multiphoton) **Nonlinear** Breit-Wheeler:

$$n_* = \left\lceil \frac{2(1 + \xi^2)}{\eta_\gamma} \right\rceil$$

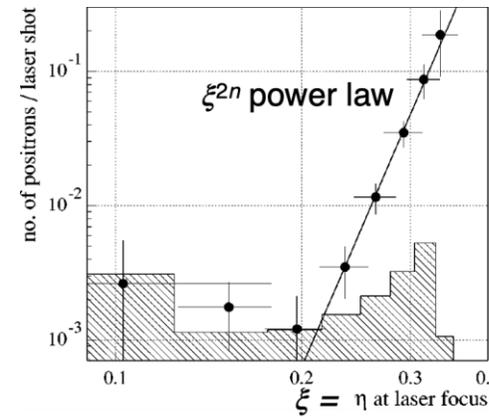
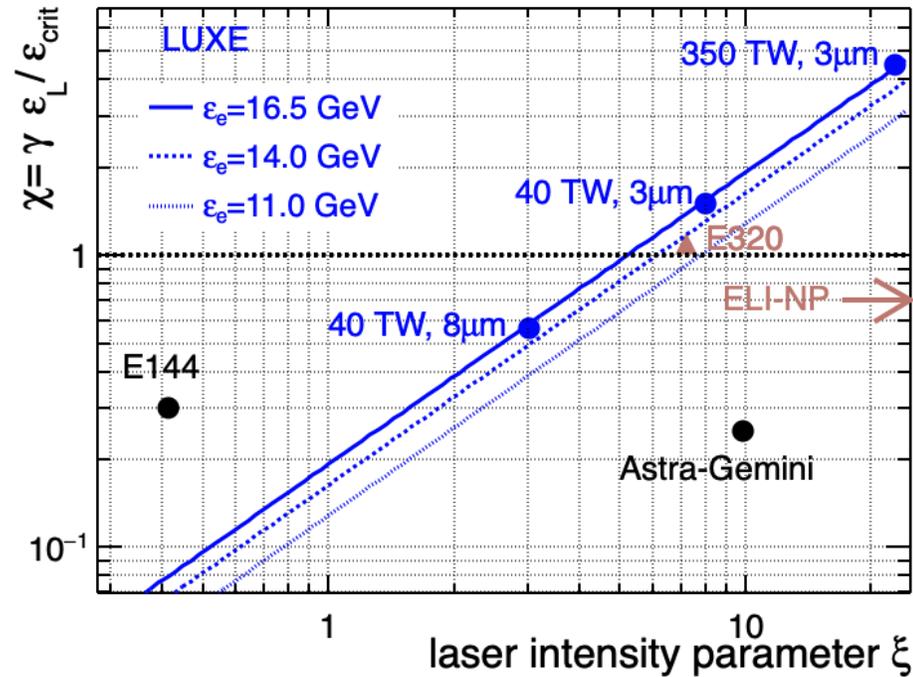
$$\gamma \text{ (wavy)} \text{ meeting two lines} \equiv \sum_n \begin{array}{c} n \gamma_L \text{ (dashed)} \\ \vdots \\ \gamma \text{ (wavy)} \end{array}$$


(Non-perturbative) **Nonlinear** Breit-Wheeler

$$\gamma + n \gamma_L \rightarrow e^+ e^-$$

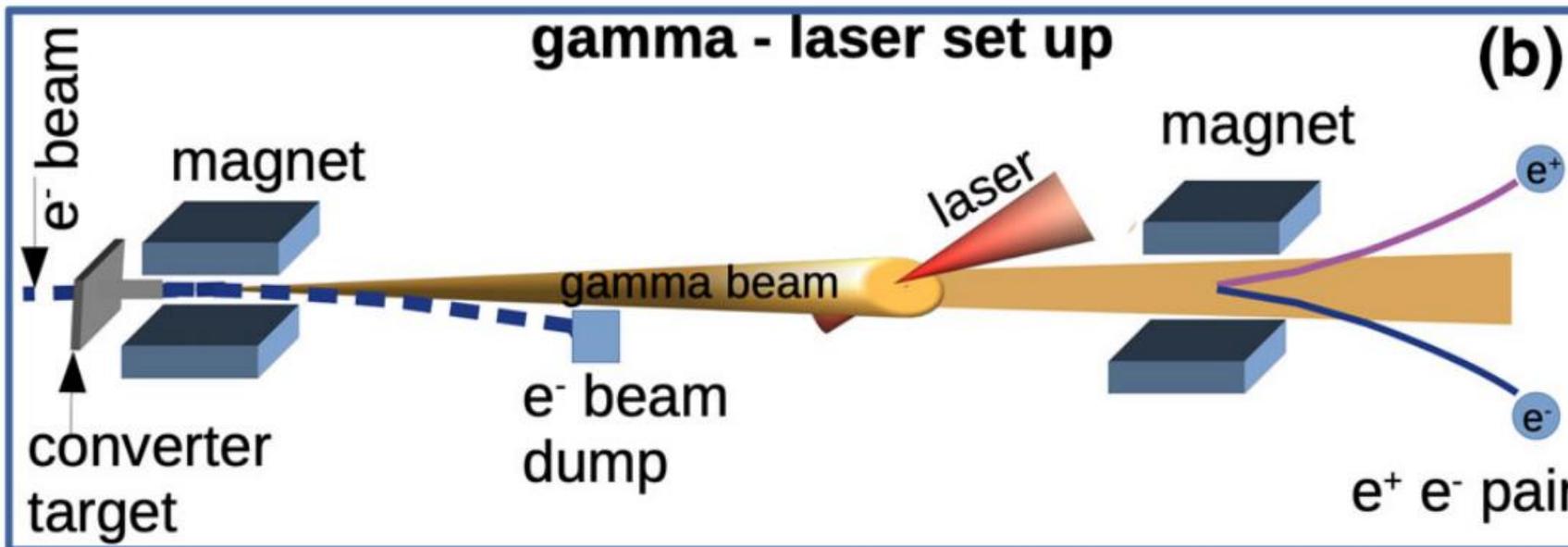
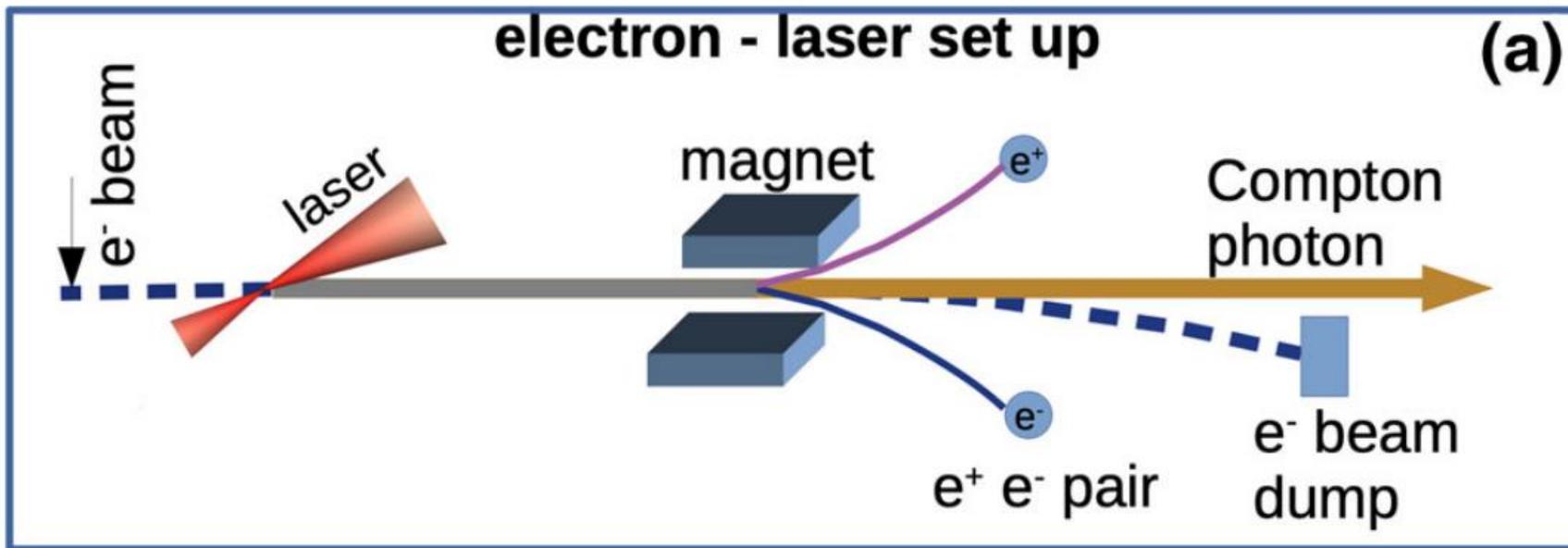


LUXE in Strong-Field QED Parameter Space

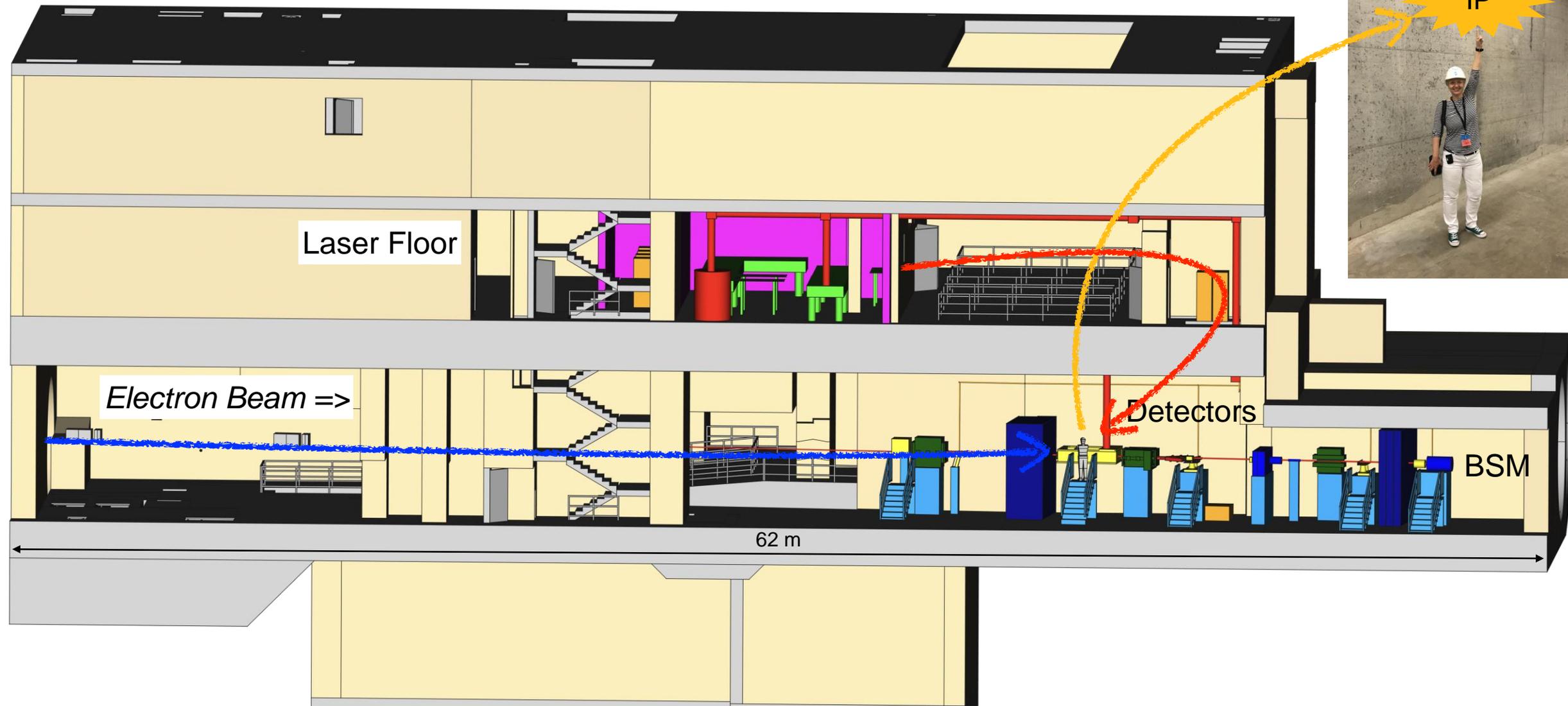


PRD 60 092004 (1999)
 E144 experiment: collision between
 46.6 GeV electron and sub-TW laser beams
 photon num. equivalent to $n \approx 5$

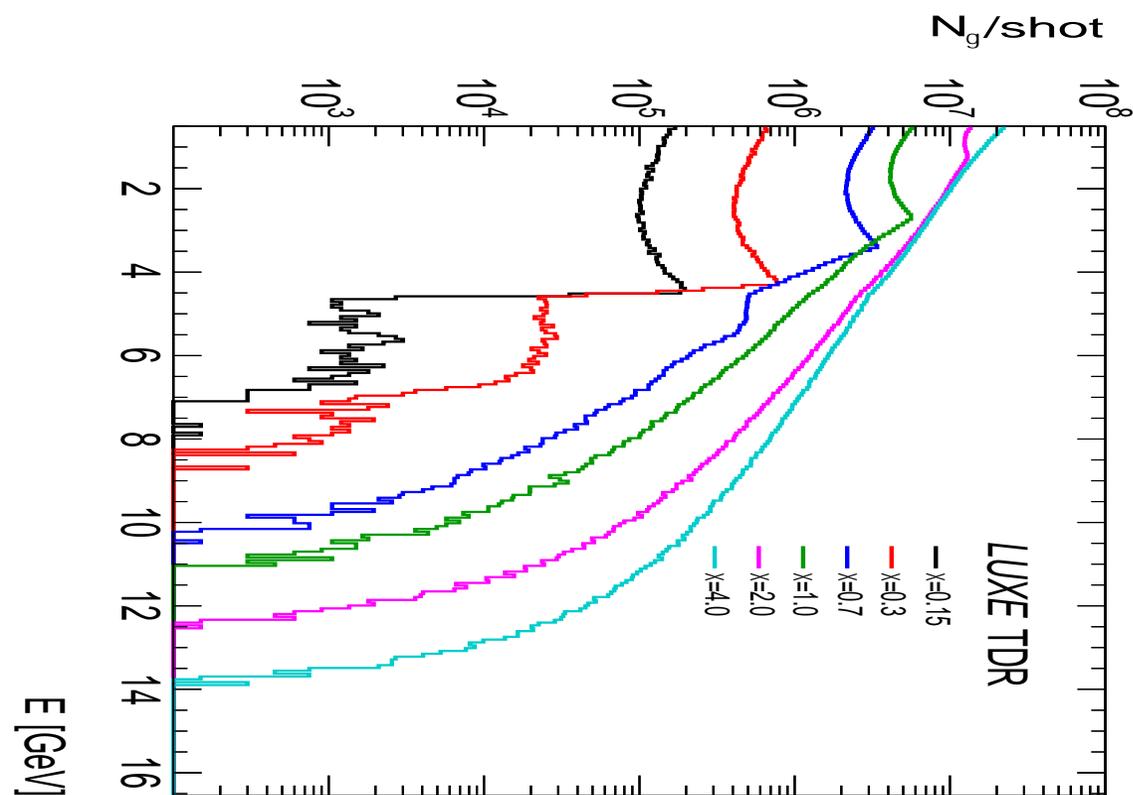
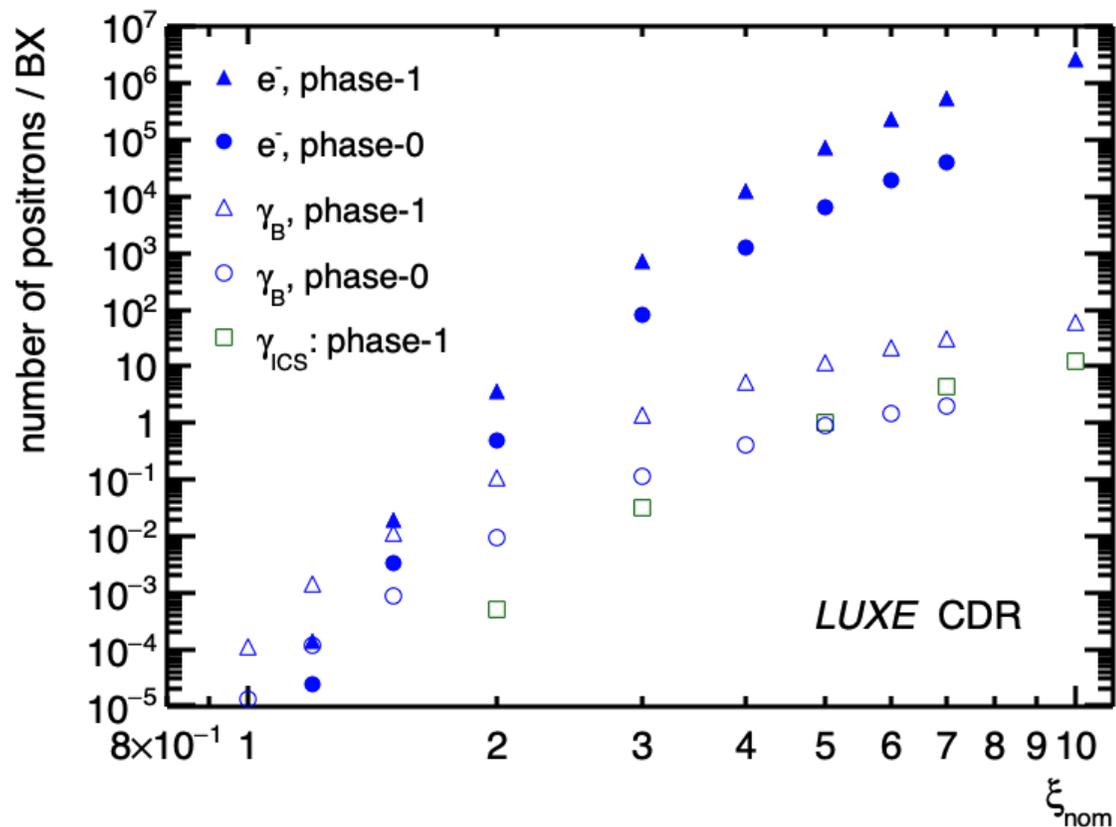
- E144: SLAC experiment in 1990's, using 46.6 GeV electron beam [Bamber et al. (SLAC 144) '99]
 → reached $\chi \leq 0.25$, $\xi < 0.4$, observed $e^- + n\gamma_L \rightarrow e^- e^+ e^-$ process
 → observed start of the ξ^{2n} power law
- LUXE: - good chance to be first to enter $\xi > 1$ and $\chi > 1$ regime!
 - directly study collisions between LASER and real GeV photons



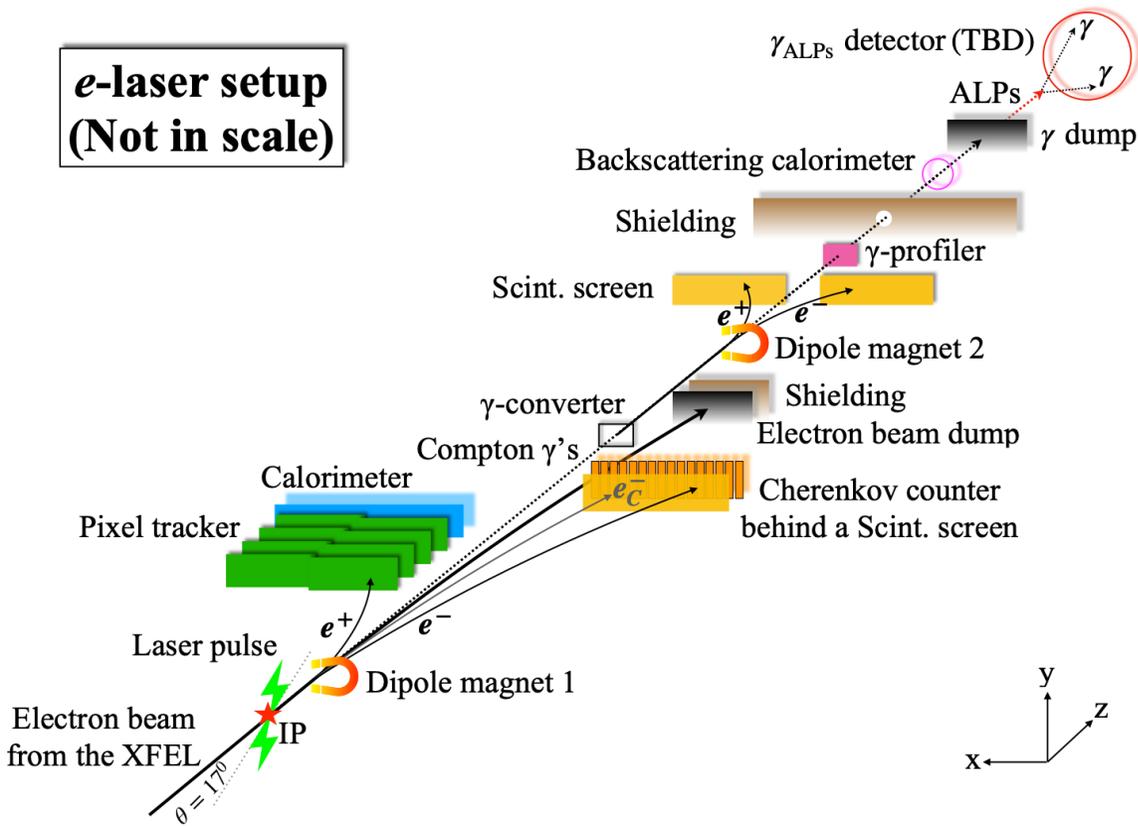
Experimental specs.: LUXE setup



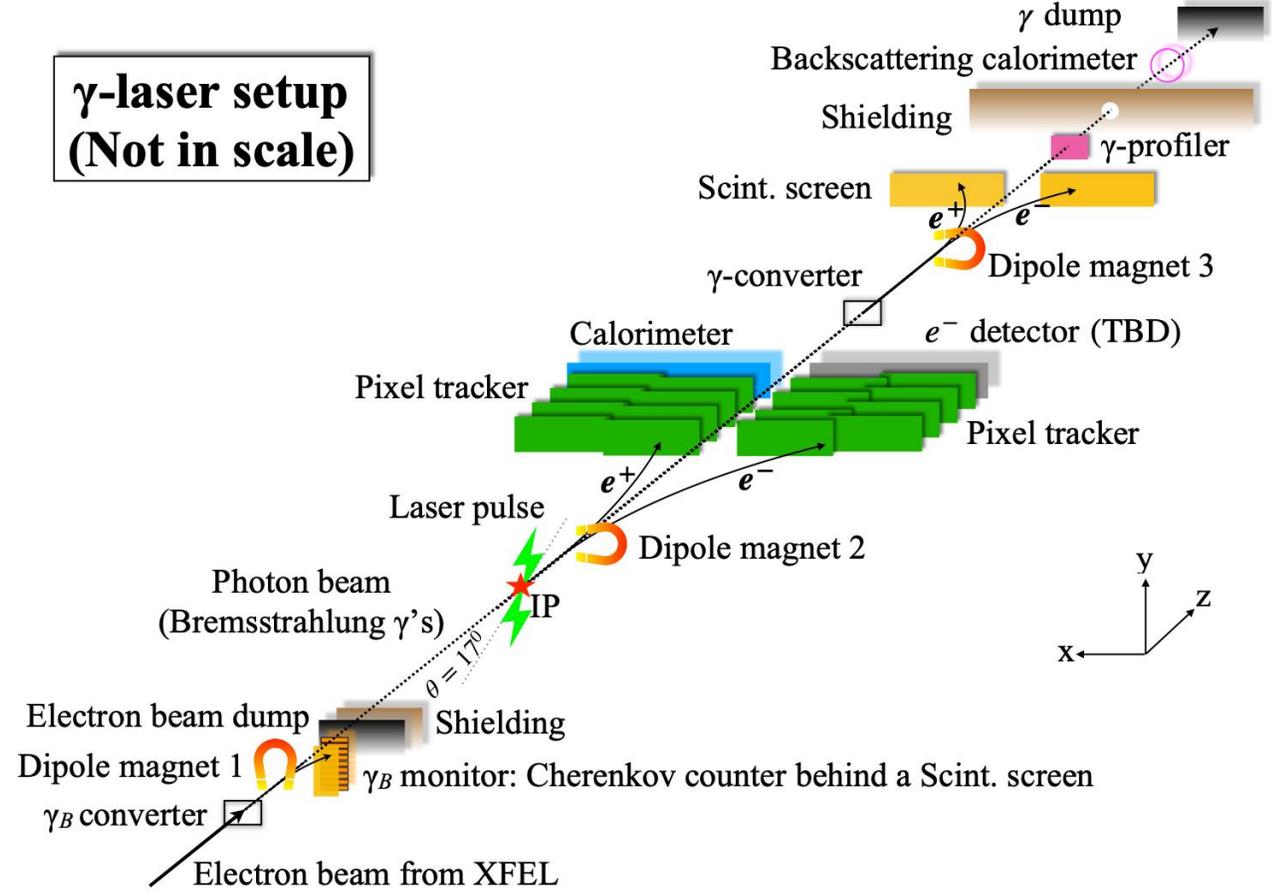
Challenges



**e-laser setup
(Not in scale)**

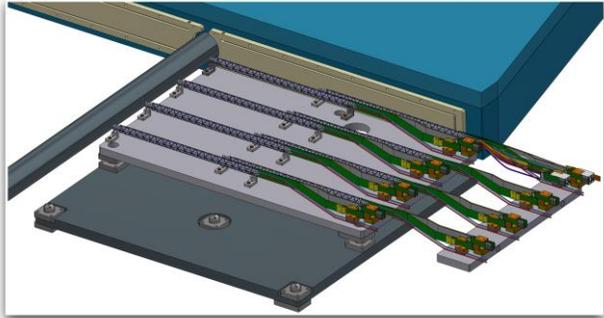


**gamma-laser setup
(Not in scale)**

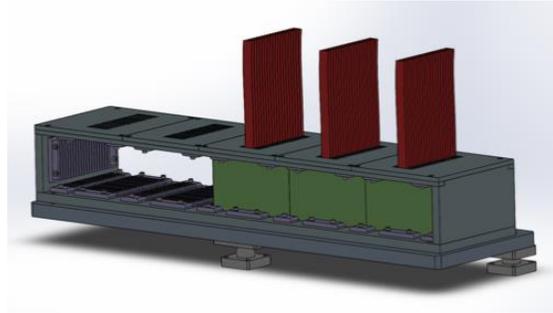


Detectors for LUXE

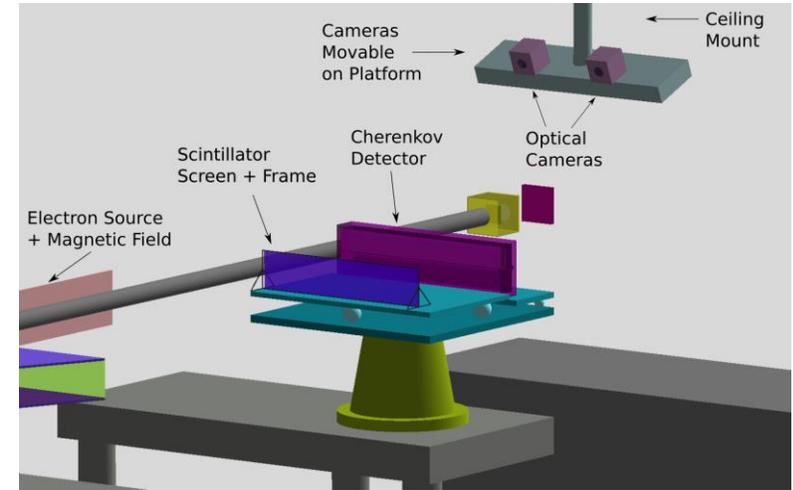
Tracker, Calorimeter, Cherenkov, Scintillator screens,
Gamma-Ray Spectrometer, Gamma-Ray Profiler, Gamma-flux Monitor



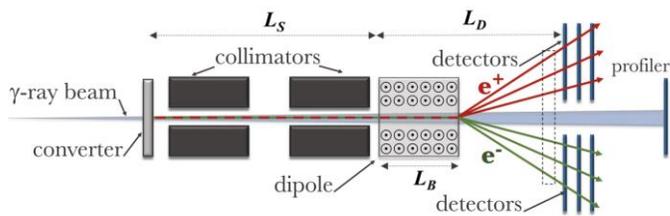
Tracker



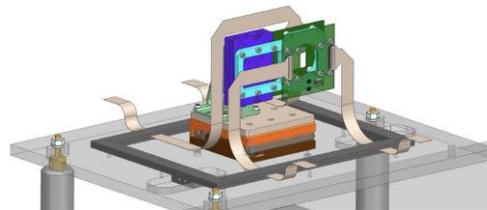
Calorimeter



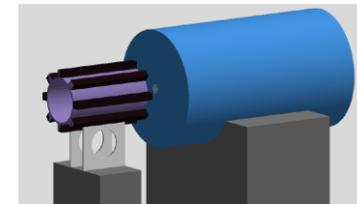
Cherenkov, Scintillator screens



Gamma-Ray Spectrometer



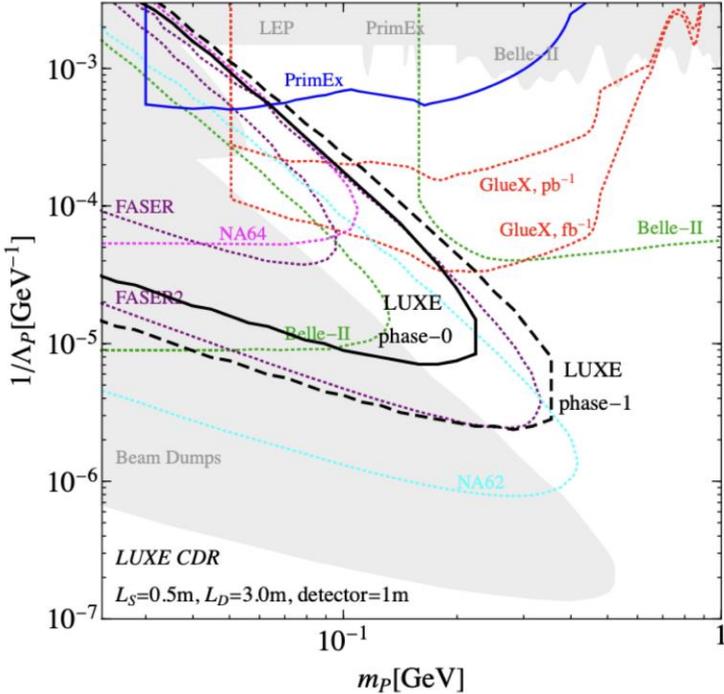
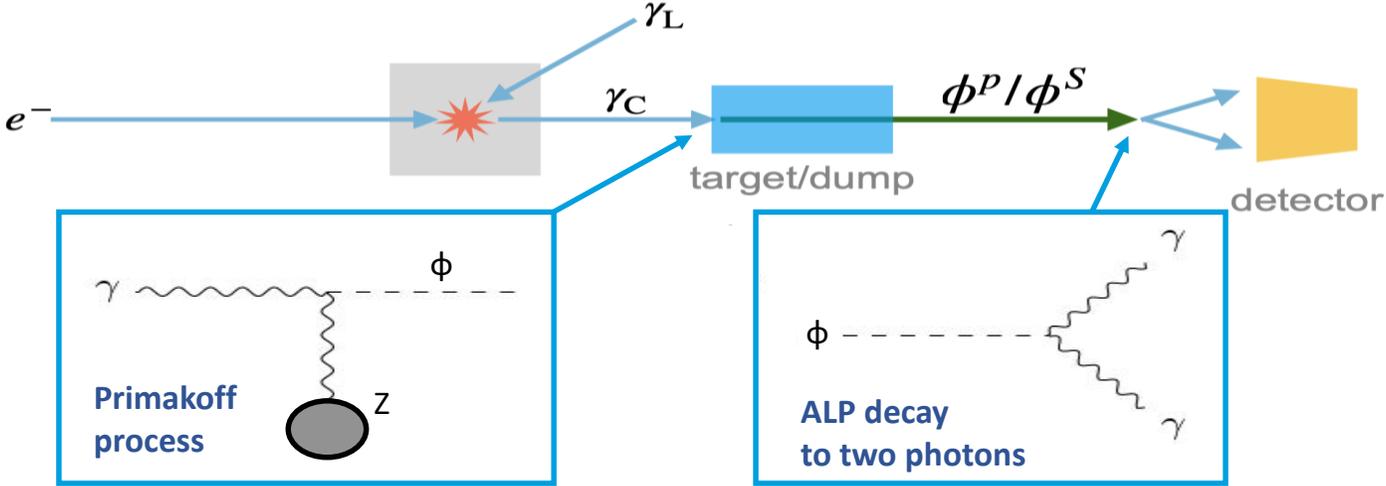
Gamma-Ray Profiler



Gamma-flux Monitor

Bonus: Searching for BSM Physics with LUXE

- LUXE will produce a high-intensity photon beam
 - produce ALPs or milli-charged particles (MCP) in photon beam-dump



Sensitivity could be competitive with other experiments ongoing and in planning

Conclusions and outlook

- Exciting opportunity to explore QED in a new regime using EU.XFEL electrons and high power laser.
- Observe transition from perturbative to non-perturbative QED.
- Parasitically use for BSM physics.

- CDR received CD0 approval by DESY.
- TDR is presently under review by DESY PRC.
If approved, installation could happen in about 3 years.
- Results – still in this decade!

- **Come and join us in a breakthrough experiment!!**

Backup

E_{critical} – Schwinger

2. PAIR CREATION IN QED

2.1. FLUCTUATIONS IN AN EXTERNAL ELECTRIC FIELD

Already in quantum mechanics we agree that the ground state displays fluctuations. In QFT the ground state is the vacuum of the theory, and vacuum fluctuations correspond to quanta appearing and disappearing. Yet, charge is conserved even for virtual processes, consequently electron-positron *pairs* are constantly created and annihilated in the QED vacuum, waiting for an external source of energy to allow them out into the real world. When a pair emerges the electron and the positron initially separate, then reunite into annihilation. In the "fluctuation time" Δt before the electron-positron loop closes, enough energy ($\Delta E \geq 2m_e c^2$) should be imparted to the pair to ensure the energy conservation of a real process. Consistency with the time-energy uncertainty relation requires

$$\Delta E \Delta t \geq \hbar. \quad (1)$$

Above, Δt is the time interval of brief 'existence' of the pair, whereas ΔE gives the degree of energy non-conservation implied by the virtual process,

$$\Delta E = 2mc^2, \quad (2)$$

where m is the electron mass. Again, Δt is the time before the $e^- - e^+$ loop closes. If an external electric field is applied, it will tend to separate the electron and the positron. To achieve the break-up of the pair, it must convey the energy $\Delta E = 2mc^2$ to the pair during the time Δt , *i.e.* before annihilation takes place. An electron of charge e is imparted the mechanical work $eE\Delta x$ upon being displaced by Δx in an electric field E , and similarly but with displacement in the opposite direction for the positron. Assuming displacement with velocity close to the speed of light, one thus

requires

$$\Delta x \cdot (e E) \sim \Delta t c (e E) \simeq mc^2 \quad (3)$$

for the pair to break. Applying (1), (2) and dropping a factor of 2 from this qualitative argument leads to a minimal break-up field E_{cr} given by

$$\frac{\hbar}{mc^2} \cdot c \cdot (e E_{cr}) = mc^2. \quad (4)$$

Note that $\Delta x = \frac{\hbar}{mc}$ is the Compton wavelength. All in all

$$E_{\text{critical}} \equiv E_{cr} = \frac{m^2 c^3}{e \hbar} \sim 10^{18} \frac{V}{m} = 10^{16} \frac{V}{cm}. \quad (5)$$

This quantity, called the critical electric field, is a useful unit of comparison. In a region with electric fields even remotely close to E_{cr} , the vacuum would become a conductor.

C.R. Acatrinei, *QED in Strong Electromagnetic Backgrounds – Effective Action Methods*, Romanian Journal of Physics **64** (2019) 113.