Proposal for a new experiment using a Laser and XFEL to test quantum physics in the strong-field regime

Beate Heinemann (DESY and University of Freiburg)

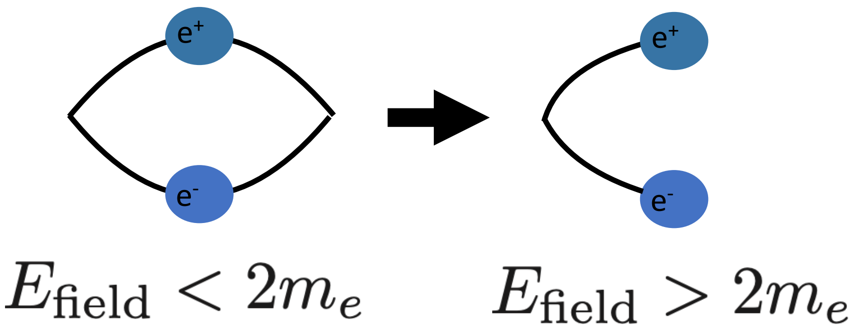
DMLab Scientific Kick-off Meeting, December 9th 2021

THE CRITICAL FIELD

Presence of strong external field => cannot use perturbative expansion:

- work by field over Compton wavelength > than two rest masses of particles→ critical field (aka “Schwinger limit”)

$$\varepsilon_{crit} = \frac{m_e^2 c^3}{\hbar e} \simeq 1.3 \cdot 10^{18}\ \mathrm{V/m}$$



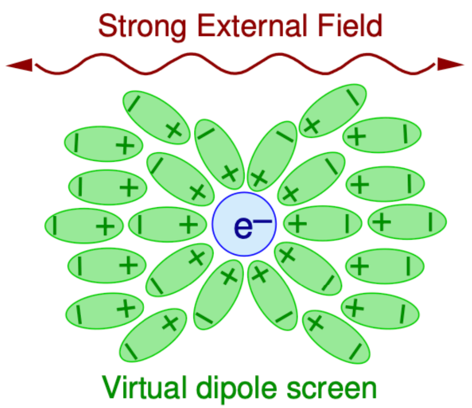
1) Field-Induced Pair Creation:

- pair production from vacuum $P \propto exp\left(-\pi \frac{\varepsilon_{crit}}{\varepsilon}\right)$

Schwinger 1951

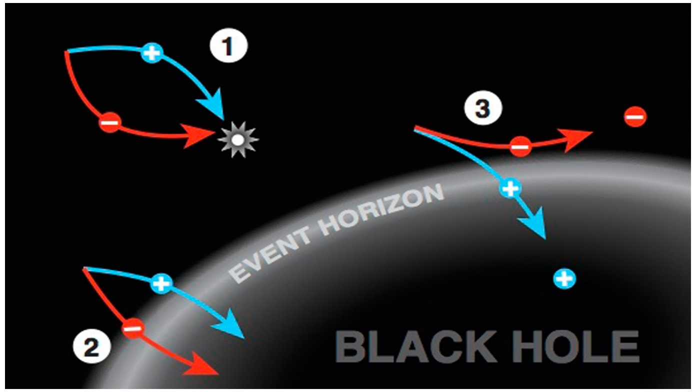
2) Modified Compton Spectrum:

- electron becomes “dressed” => larger effective m_e



ANALOGY TO HAWKING RADIATION

- **Energy needed to create on-shell e^+e^- pair:** $\Delta E = 2mc^2$
- **Grav. Field near the event horizon:** $F = \frac{G_N M m}{r_s^2}$
- **Schwarzschild radius** $r_s = \frac{2G_N M}{c^2}$**. =>** $F = \frac{mc^4}{4G_N M}$
- **Energy to separate pair:** $E = F d_{min} = \frac{mc^4}{4G_N M} \times \frac{\hbar}{mc} = \frac{\hbar c^3}{4G_N M}$



=> Hawking radiation possible if virtual pair becomes real, i.e. $\frac{\hbar c^3}{4G_N M} > 2mc^2$

- **Analogous to pair production in EM field if $E > E_{crit}$**
  - Critical fields appear e.g. on surface of neutron stars (magnetars), at high-energy accelerators, in heavy nuclei,…

H. Murayama:
“Seeing this in the electromagnetic field might be the closest we ever get to observing Hawking radiation”

HEISENBERG AND EULER: THE CRITICAL FIELD

Folgerungen aus der Diracschen Theorie des Positrons.

Von **W. Heisenberg** und **H. Euler** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 22. Dezember 1935.)

Aus der Diracschen Theorie des Positrons folgt, da jedes elektromagnetische Feld zur Paarerzeugung neigt, eine Abänderung der Maxwellschen Gleichungen des Vakuums. Diese Abänderungen werden für den speziellen Fall berechnet, in dem keine wirklichen Elektronen und Positronen vorhanden sind, und in dem sich das Feld auf Strecken der Compton-Wellenlänge nur wenig ändert. Es ergibt sich für das Feld eine Lagrange-Funktion:

$$\mathfrak{L} = \frac{1}{2}(\mathfrak{E}^2 - \mathfrak{B}^2) + \frac{e^2}{hc}\int_0^\infty e^{-\eta}\frac{d\eta}{\eta^3}\left\{ i\eta^2(\mathfrak{E}\mathfrak{B})\cdot\frac{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)+\text{konj}}{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)-\text{konj}} + |\mathfrak{E}_k|^2 + \frac{\eta^2}{3}(\mathfrak{B}^2-\mathfrak{E}^2)\right\}.$$

($\mathfrak{E}, \mathfrak{B}$ Kraft auf das Elektron.

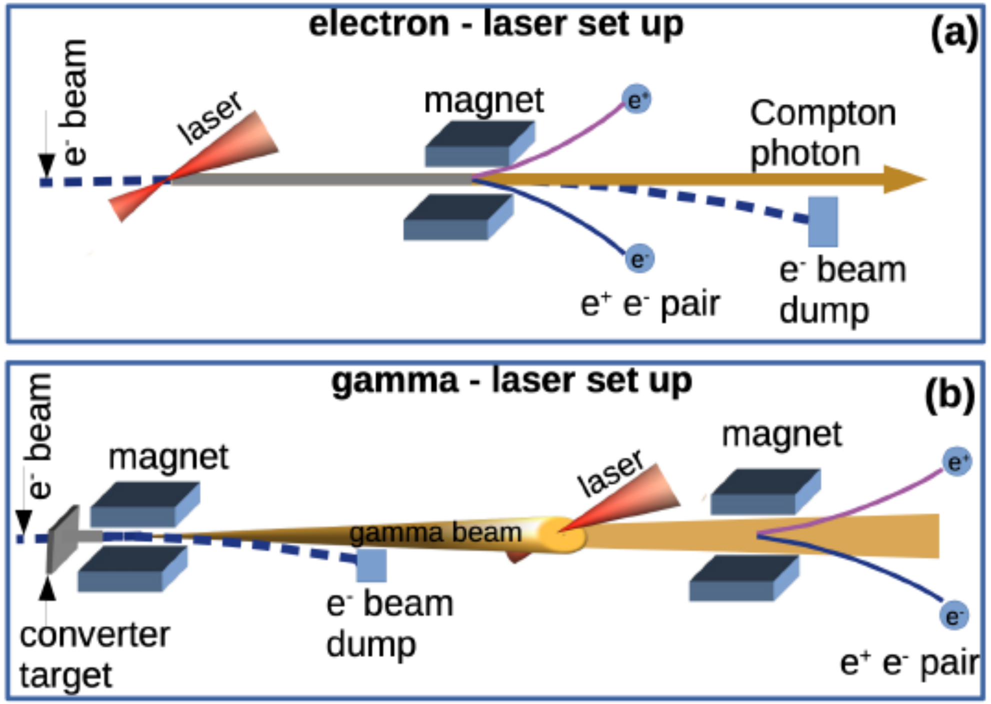
$|\mathfrak{E}_k| = \frac{m^2c^3}{e\hbar} = \frac{1}{„137“}\frac{e}{(e^2/mc^2)^2}$ = „Kritische Feldstärke“.)

Z.Phys. 98 (1936) no.11-12, 714-732
(translation at arXiv:physics/0605038

PARTICLE BEAM AND LASER

- **Use laser to generate electric field**
- **Use high energy electron beam** $\gamma = E_{beam}/m_e$

$$\xi = \frac{e\varepsilon_L}{m_e\omega_L c} \propto \sqrt{I_{Laser}} \qquad \chi \approx \gamma\frac{\varepsilon_L}{\varepsilon_{crit}} \propto \sqrt{I_{Laser}E_{beam}}$$



- **Laser intensity required to reach Schwinger field (χ~1):**

Beam energy	I_{Laser} [W/cm2]
1 eV	2×10^{29}
1 GeV	$\sim10^{22}$
10 GeV	$\sim10^{20}$

=> Much beyond currently achievable values

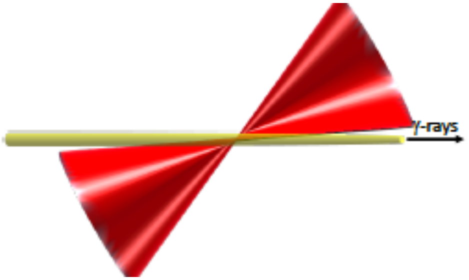
=> State-of-the-art laser needed (~10 PW)

=> Can use well-tested laser technology (~100 TW)

With ~10 GeV beams can reach Schwinger limit in rest frame with current laser technology

LASER PARAMETERS

- **Repetition rate: 1 Hz**
- **Pulse length 30 fs**
- **Collision angle: 17.2 degrees**



Parameter	Phase-0	Phase-I
Laser energy after compression [J]	1.2	10
Percentage of laser in focus [%]	50	
Laser focal spot size w_0 [µm]	>3	
Peak intensity [10^{19} W/cm^2]	**13.3**	**120**
Peak intensity parameter ξ	**7.9**	**23.6**
Peak quantum parameter χ:		
E_{beam}=16.5 GeV	**1.5**	**4.5**
E_{beam}=14.0 GeV	**1.3**	**3.8**

Laser intensity:

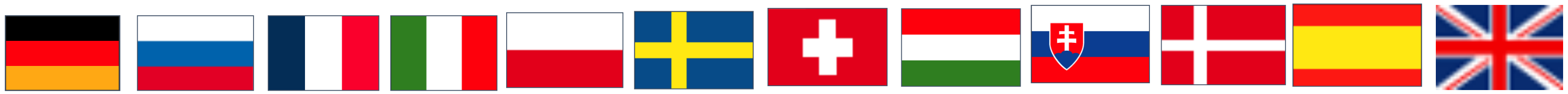
$$I = \frac{E_L}{\Delta t \pi d^2}$$

with

E_L: energy (J)
Δt: pulse length (s)
πd^2: focus area (m^2)

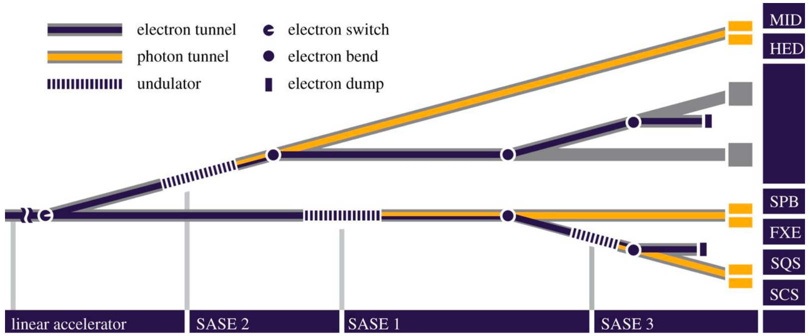
Lower intensities achieved by de-focussing laser or stretching pulse

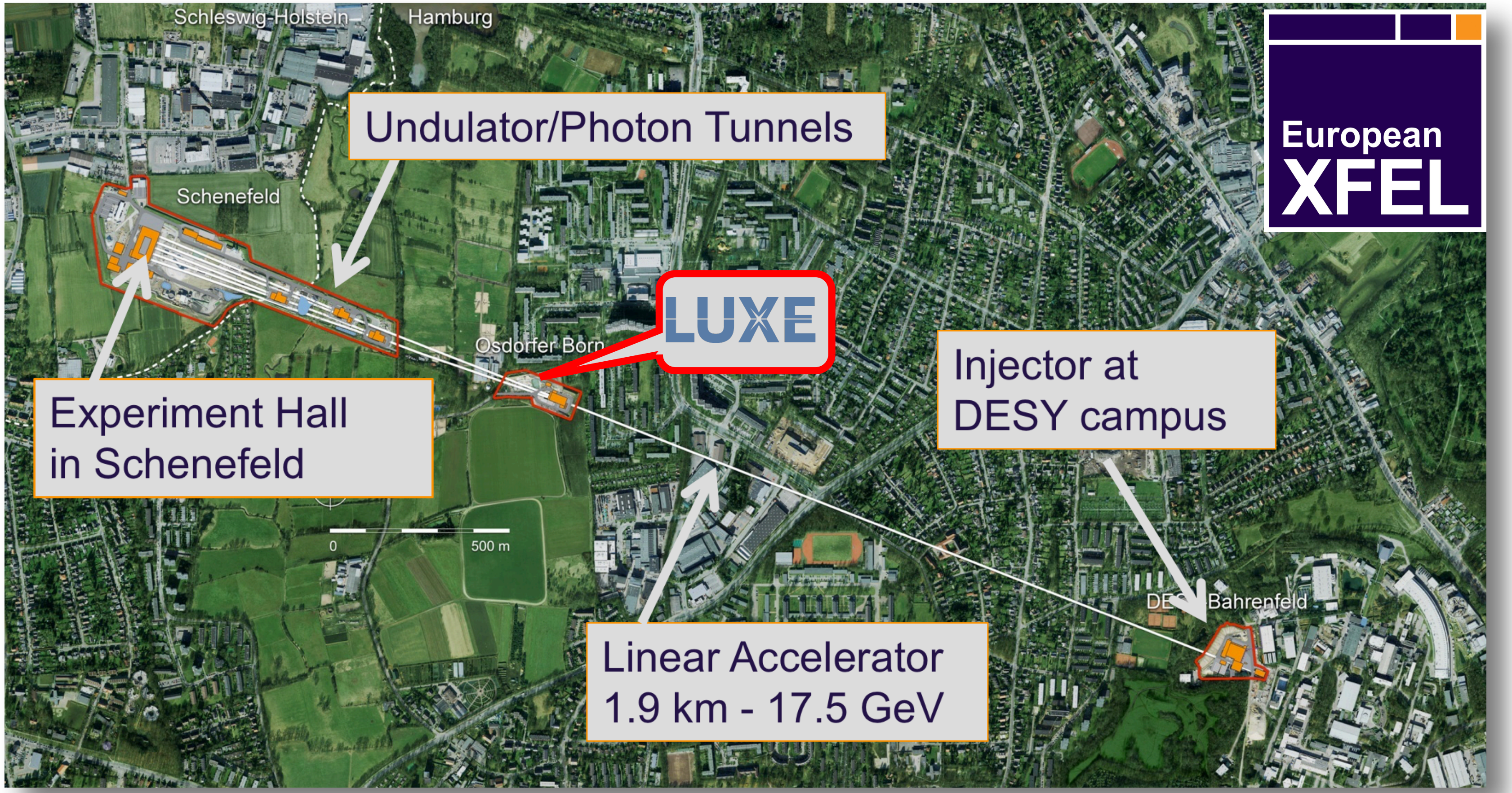
THE EUROPEAN XFEL



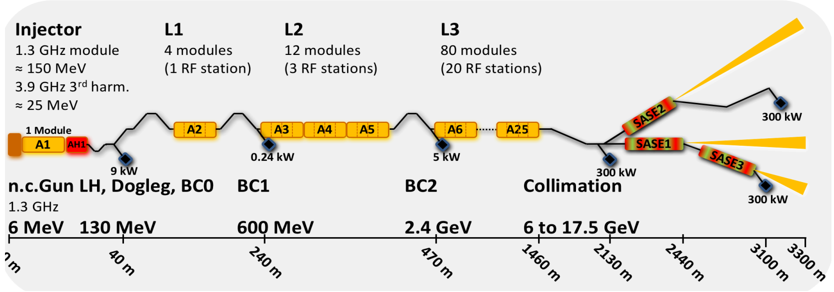
Electron accelerator:

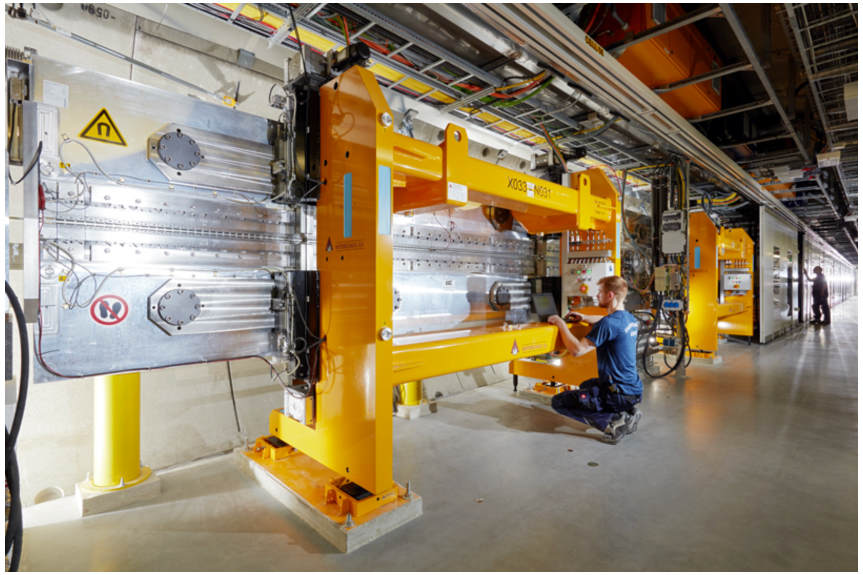
- 2.1 km 17.5 GeV SCRF linear accelerator
- 2700 electron bunches at rate of 10 Hz
- X-ray photons produced in undulators
- Experiments for physics, material science, chemistry, biology, …

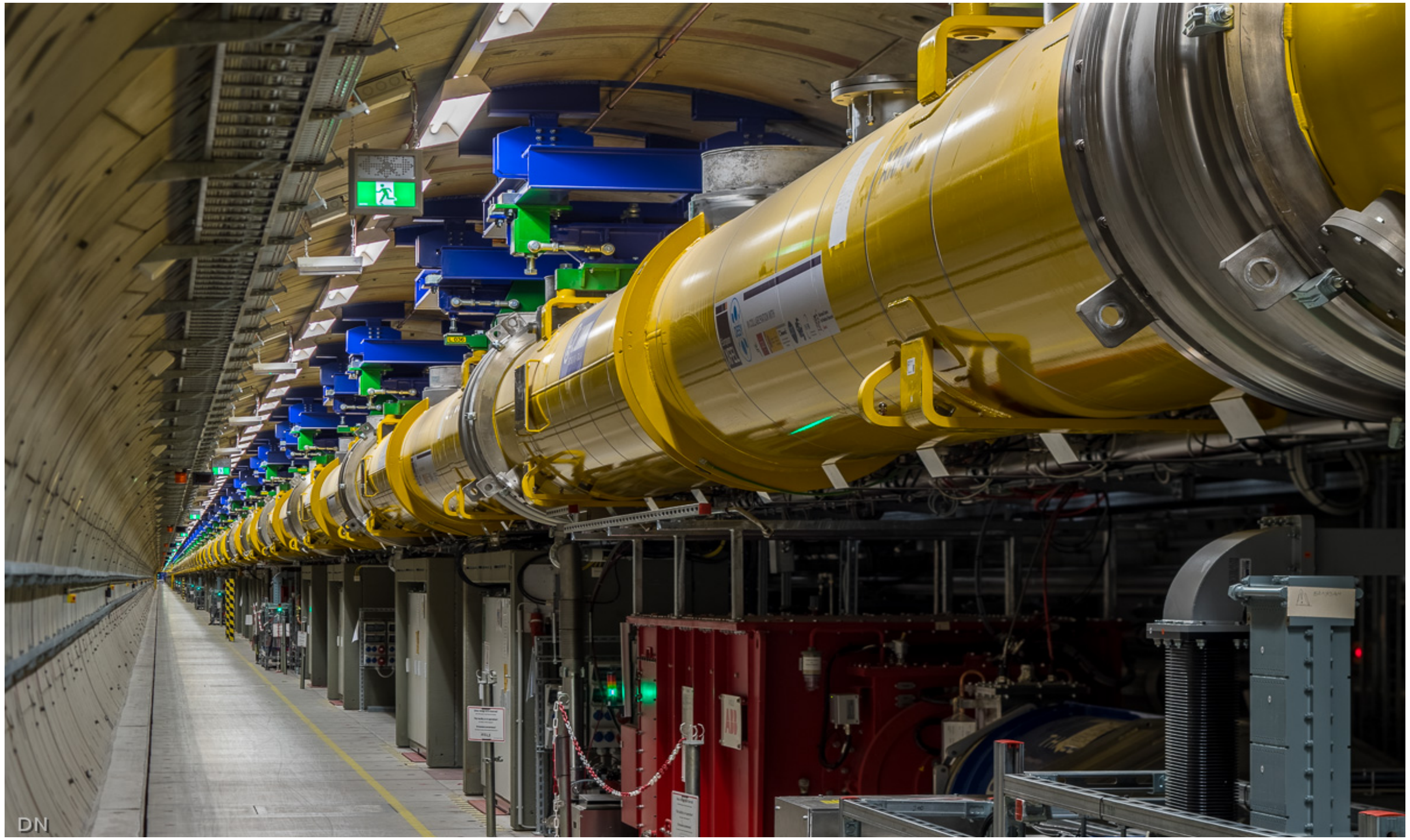




View along L3 accelerator section and undulator

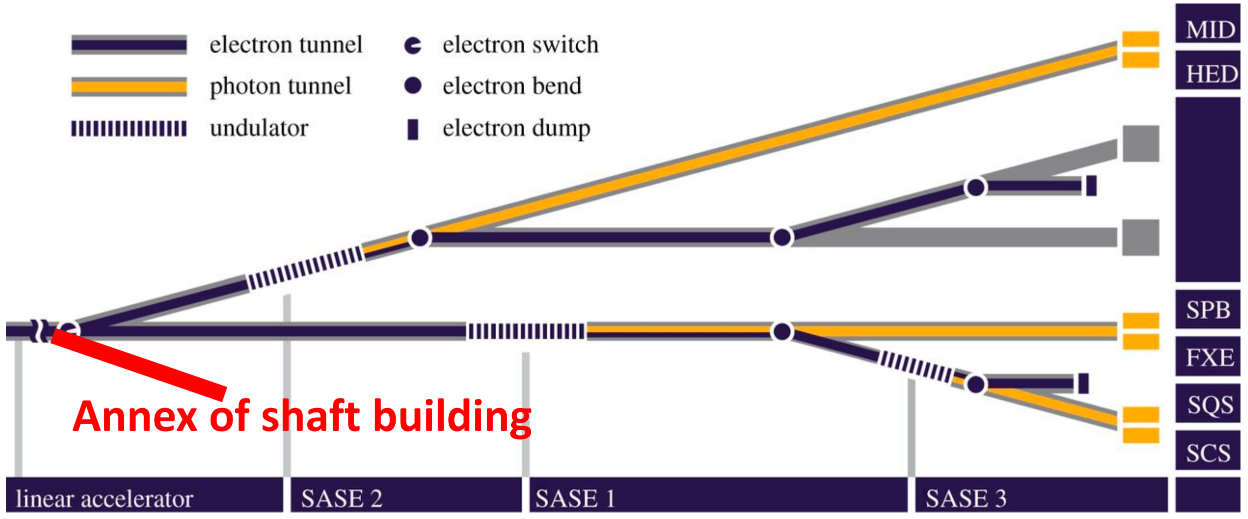


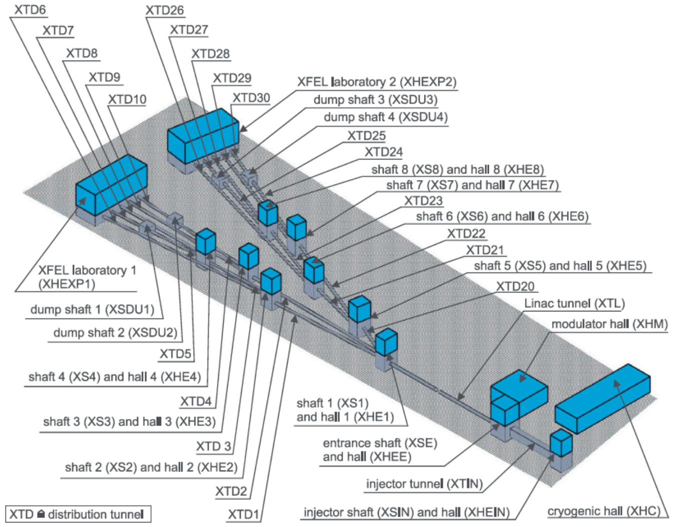




LOCATIONS IN EU.XFEL TUNNEL

- **Location at EU.XFEL:**
  - Annex of shaft building XS1: at end of electron accelerator
  - Was build for 2nd EU.XFEL fan foreseen for later (>2029)
- **Design aims to have no impact on photon science programme**
  - Use only 1 of the 2700 bunches in bunch train (kicked out by fast kicker magnet)





Contributors to LUXE CDR

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Technische Universität Dresden

AGH
AGH University of Science and Technology

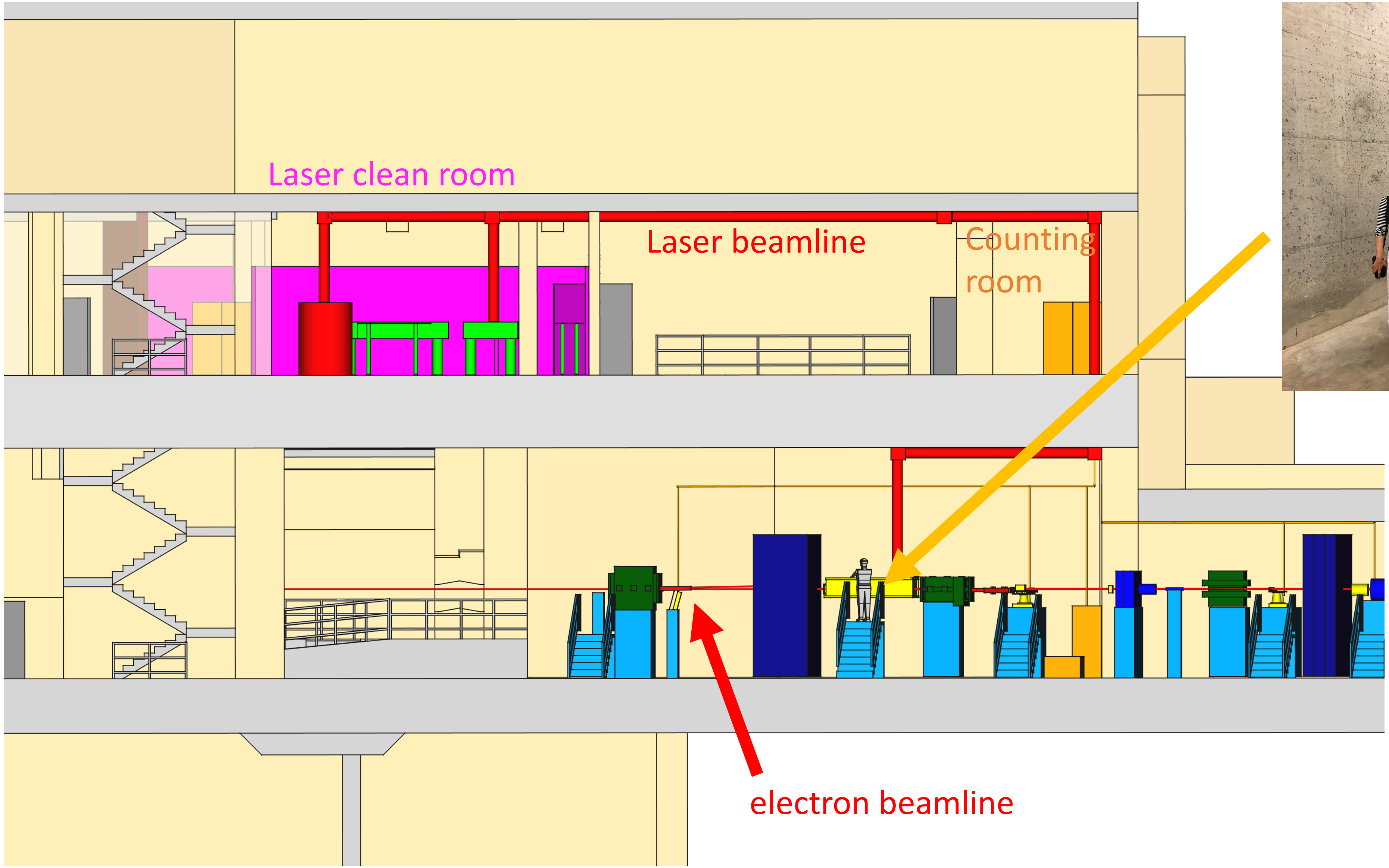
Національна Академія Наук України 1918

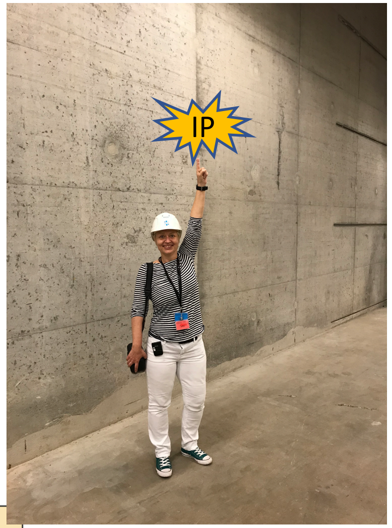
Technion
Israel Institute of Technology

Tel Aviv University

מכון ויצמן למדע
Weizmann Institute of Science

CAD DRAWING OF INSTALLATIONS IN XS1 BUILDING



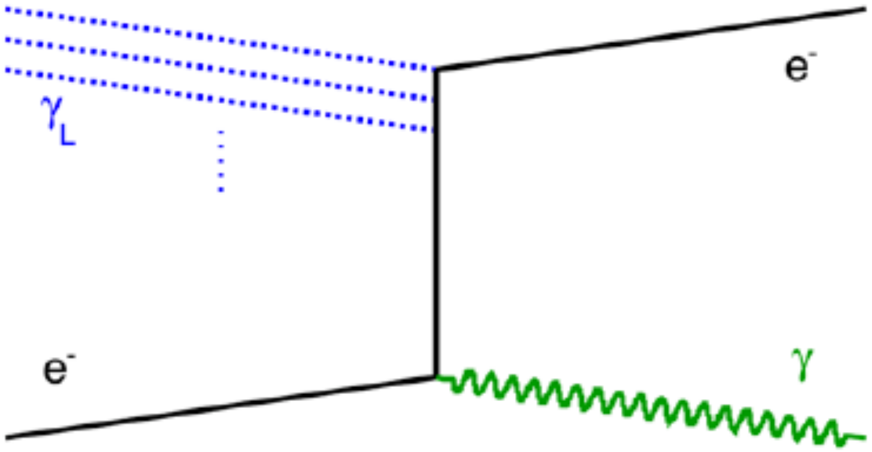


MAIN PROCESSES OF INTEREST

Non-linear Compton

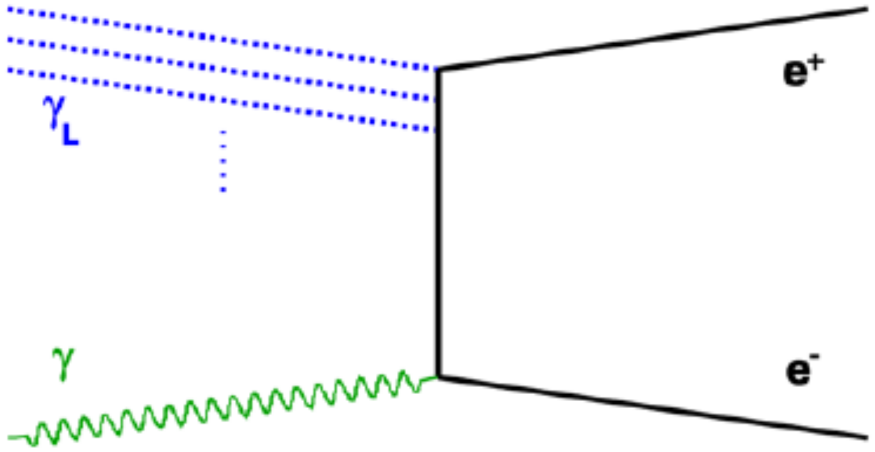
$$e^- + n\gamma_L \rightarrow e^- + \gamma$$

Low-energy ph
from laser
(E=1.5 eV)



Non-linear Breit-Wheeler: pair production

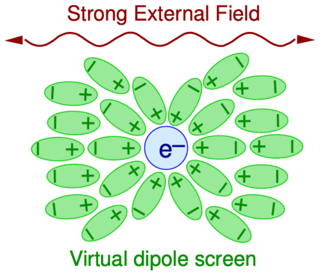
$$\gamma + n\gamma_L \rightarrow e^+e^-$$



High energy electron or photon interacts with laser

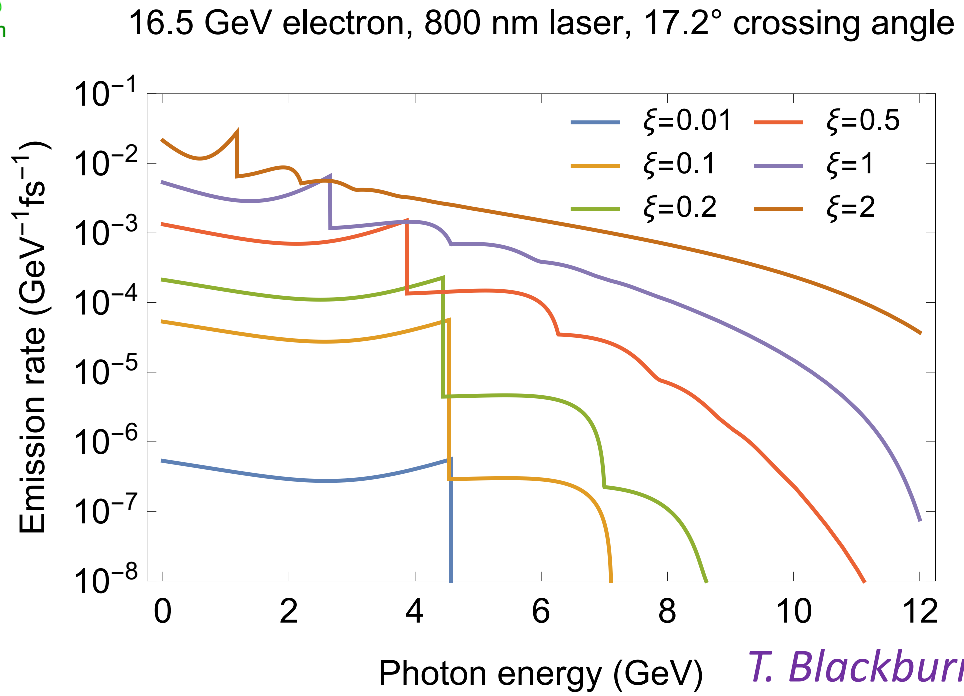
- Also higher order process “trident” $e^- + n\gamma_L \rightarrow e^-e^+e^-$
- LUXE first to directly probe $\gamma + n\gamma_L \rightarrow e^+e^-$

NON-LINEAR COMPTON PROCESS: COMPTON EDGE

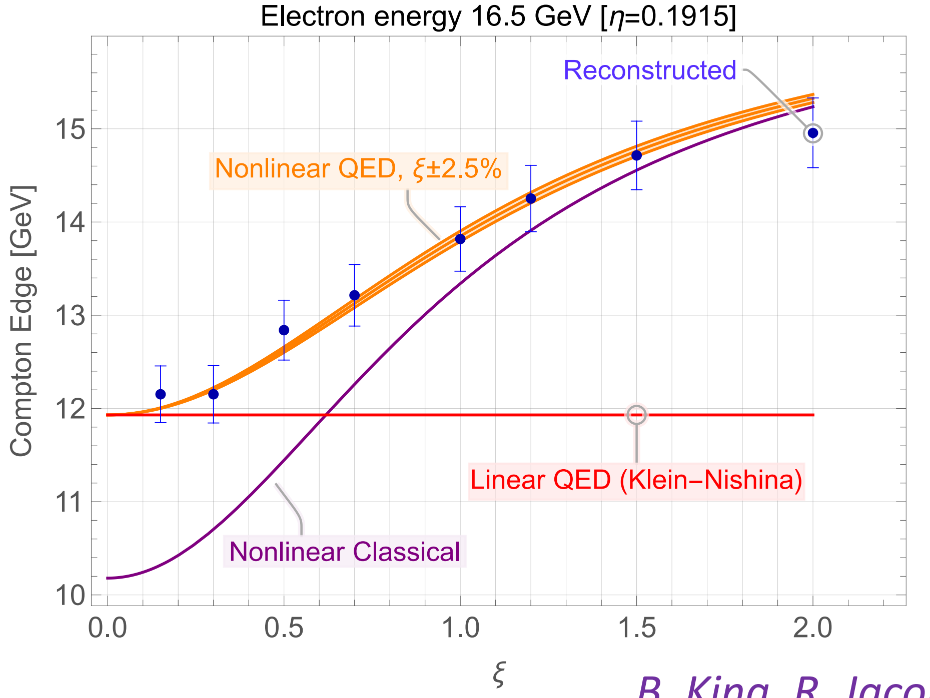


Compton edges shifted to lower energies as electrons acquires an effective mass in strong field: $m_* = m\sqrt{1+\xi^2}$

$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1-\cos\theta)}$$



T. Blackburn, arXiv:2102.02032



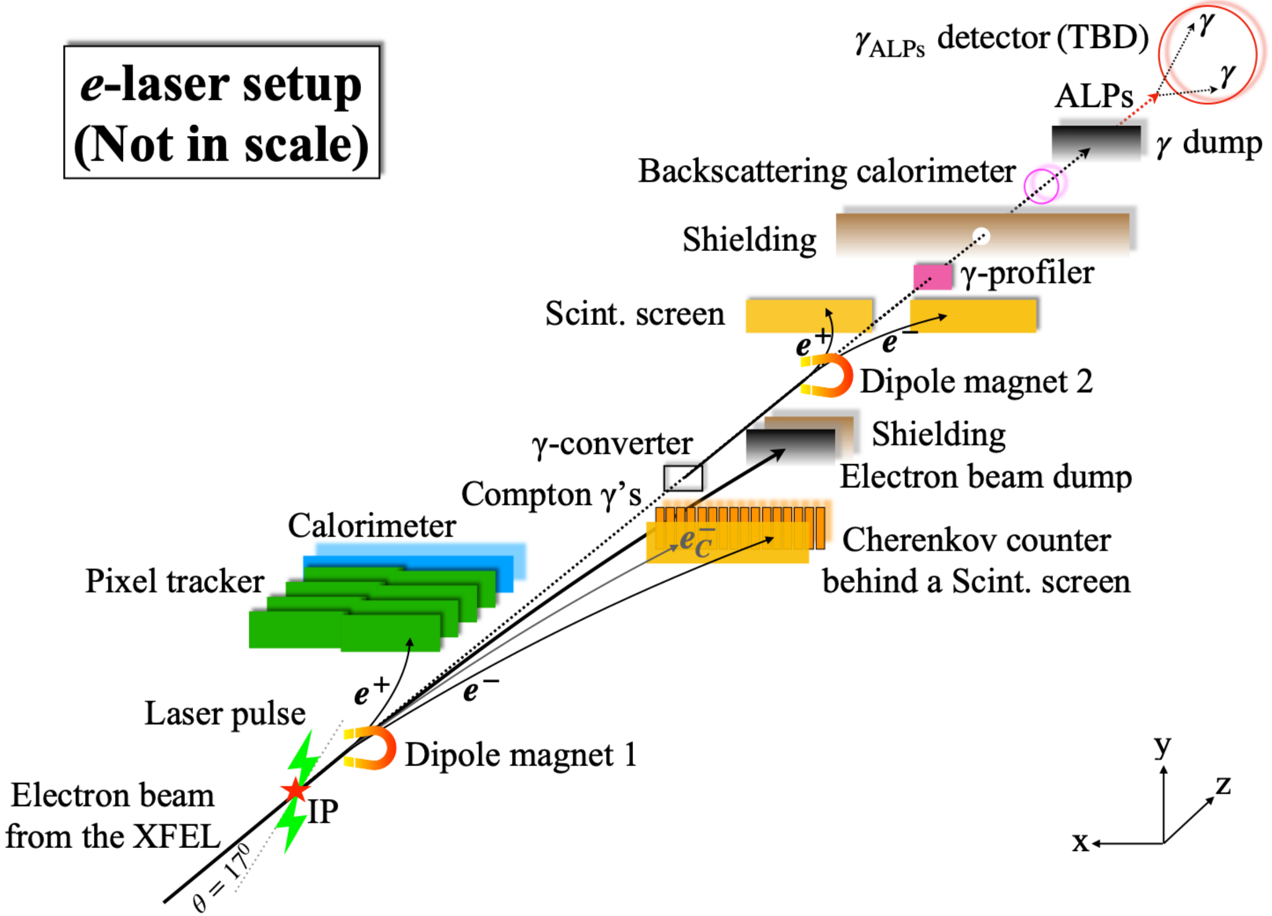
B. King, R. Jacobs

=> Goal: direct observation of screening of electron inside a field

DETECTORS FOR ELECTRON-LASER INTERACTIONS

Detection of electrons, positrons and photons

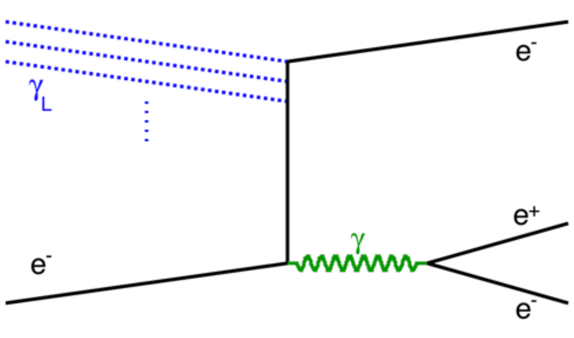
- Electron rates: 10^6-10^9 particles
  - Cherenkov detectors & scintillators
- Photon rates: 10^6-10^9 particles
  - Sapphire detector & backscatter calorimeter
- Positrons: 10^{-4}-10^4
  - Pixel tracker (ALPIDE) & EM calorimeter
  - About 50 cm long for full acceptance
- BSM experiment at back
  - Detect axion-like particles



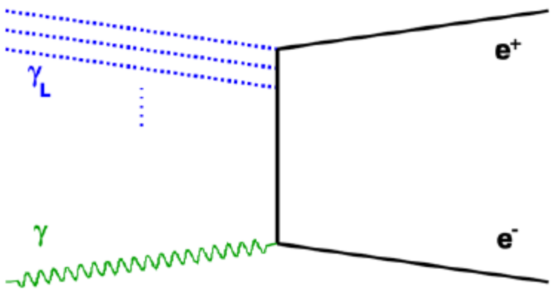
(Slightly different setup for gamma-laser interactions, see backup)

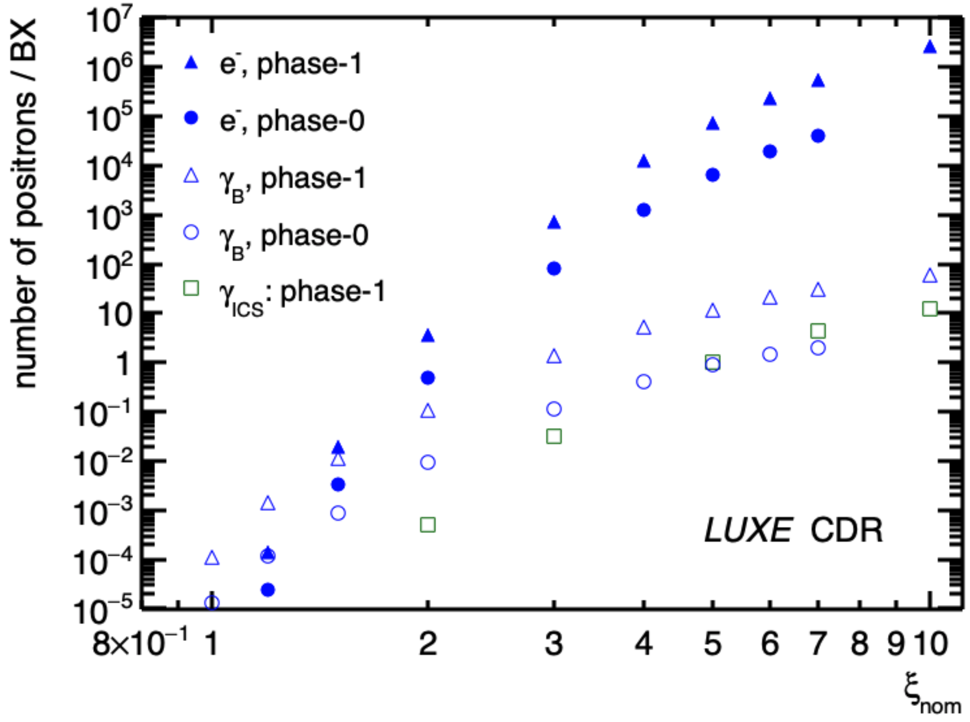
BREIT WHEELER PROCESS: e^+e^- PAIRS

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



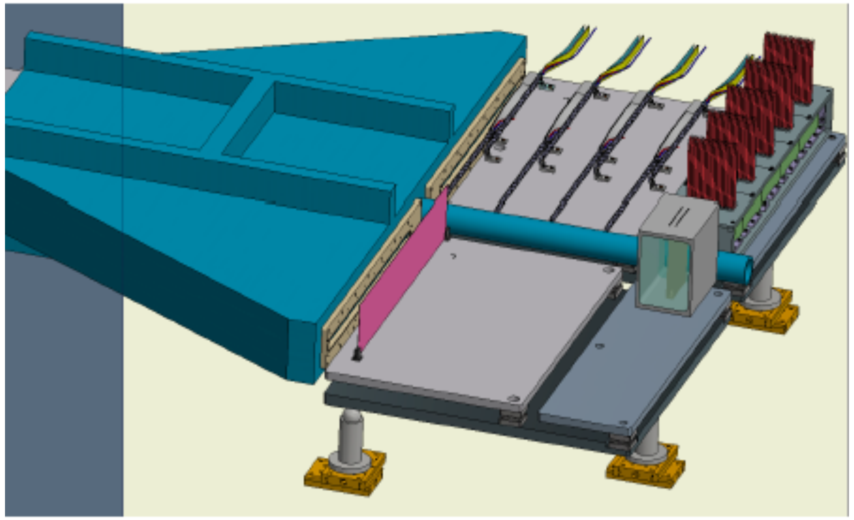
$\gamma + n\gamma_L \rightarrow e^- + e^+$





- **Expected event rates**
  - Electron-laser mode: 10^{-4}-10^{6} e^+e^- pairs
  - Photon-laser mode: 10^{-5}-10^{2} e^+e^- pairs
- **Need good background rejection and good linearity**
  - Silicon pixel tracker and high granularity calorimeter

COUNTING POSITRONS: TRACKER AND EM CALORIMETER

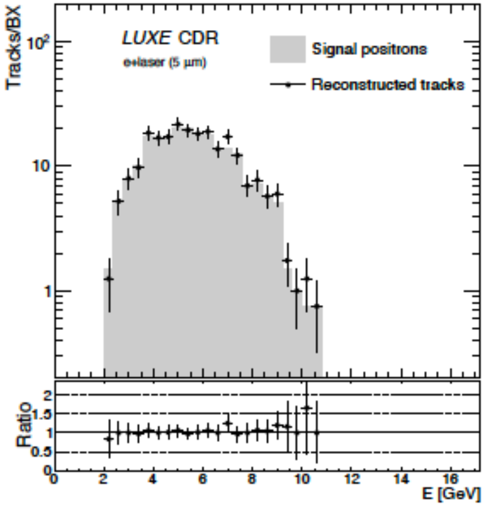


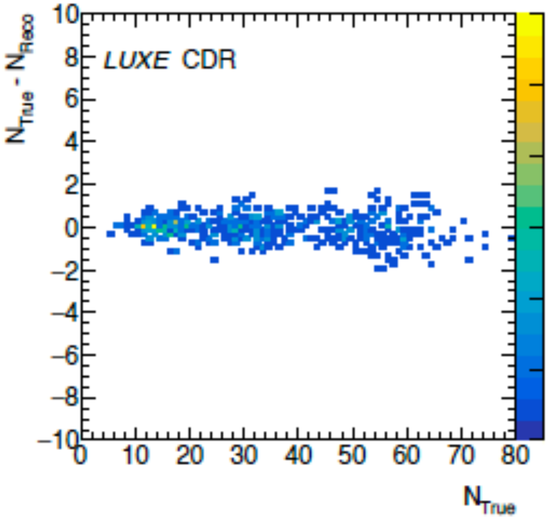
Calorimeter

- Based on FCAL developed for luminosity measurement at CLIC
  - GaAs (or Silicon) sensors interleaved with tungsten plates
  - Independently measures energy directly and via position => ratio gives N(e^+)

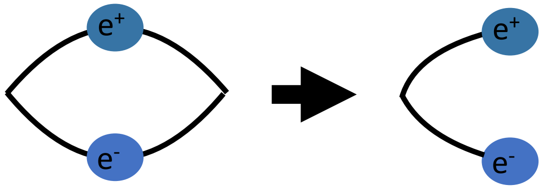
Tracker

- 4 layers of ALPIDE silicon pixel sensors
  - Pixel size 27 x 29 μm
  - Position measurement yields energy
- High background rejection and good performance up to multiplicities of ~10^4





BREIT-WHEELER PROCESS: BOIL THE VACUUM



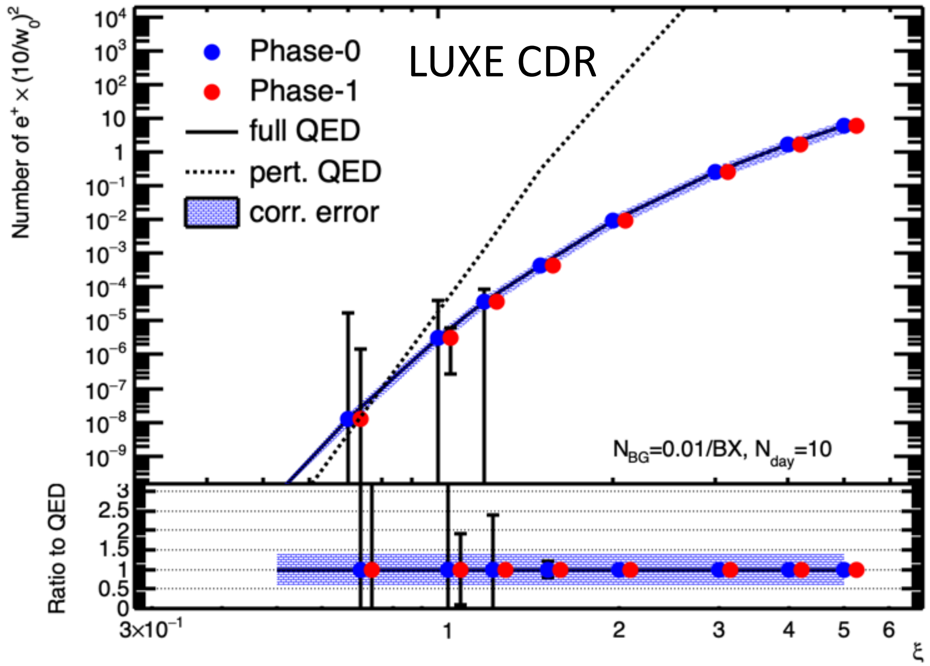
$E_{\text{field}} < 2m_e$ $\quad$ $E_{\text{field}} > 2m_e$

- **Prediction for rate of positrons per laser shot**
  - Perturbative regime: power-law

$$\xi \ll 1: \; R_{e^+} \propto \alpha^n \propto \xi^{2n}$$

  - Non-perturbative regime: departure from power-law

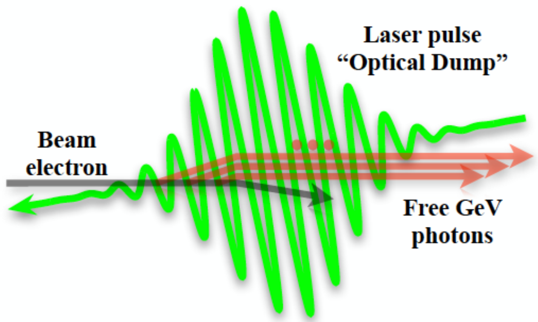
$$\xi \gg 1: \; R_{e^+} \propto \chi_\gamma \exp\left(-\frac{8}{3\chi_\gamma}\right)$$

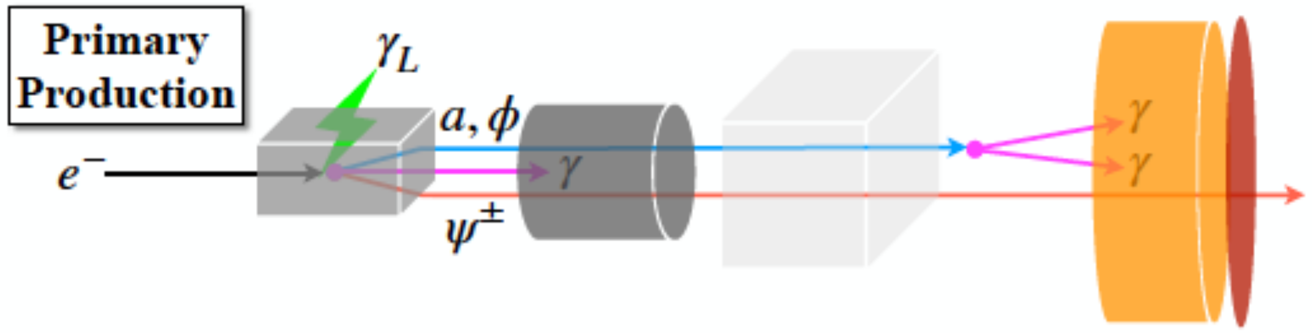


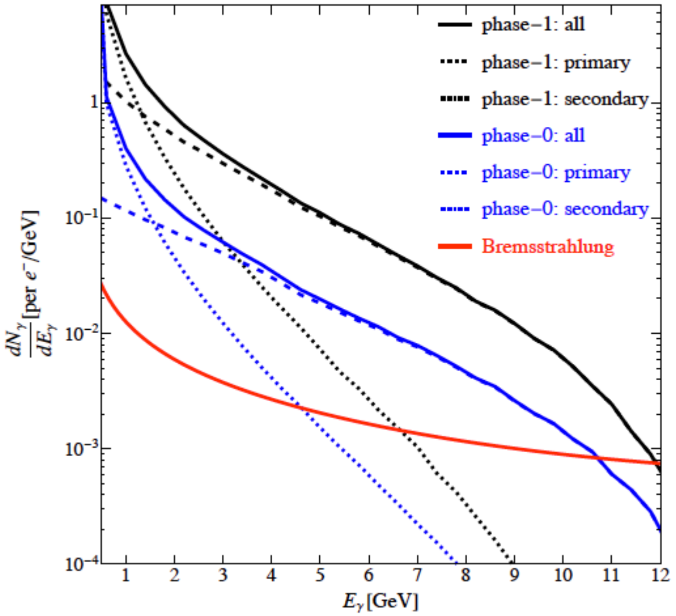
AND WHAT ABOUT DARK MATTER?

arXiv:0107.13554

- Non-Linear Compton process results in very high photon flux
  - Photon produced is “free”
- Idea: let those photons convert in beam dump to axion-like particle via Primakoff effect



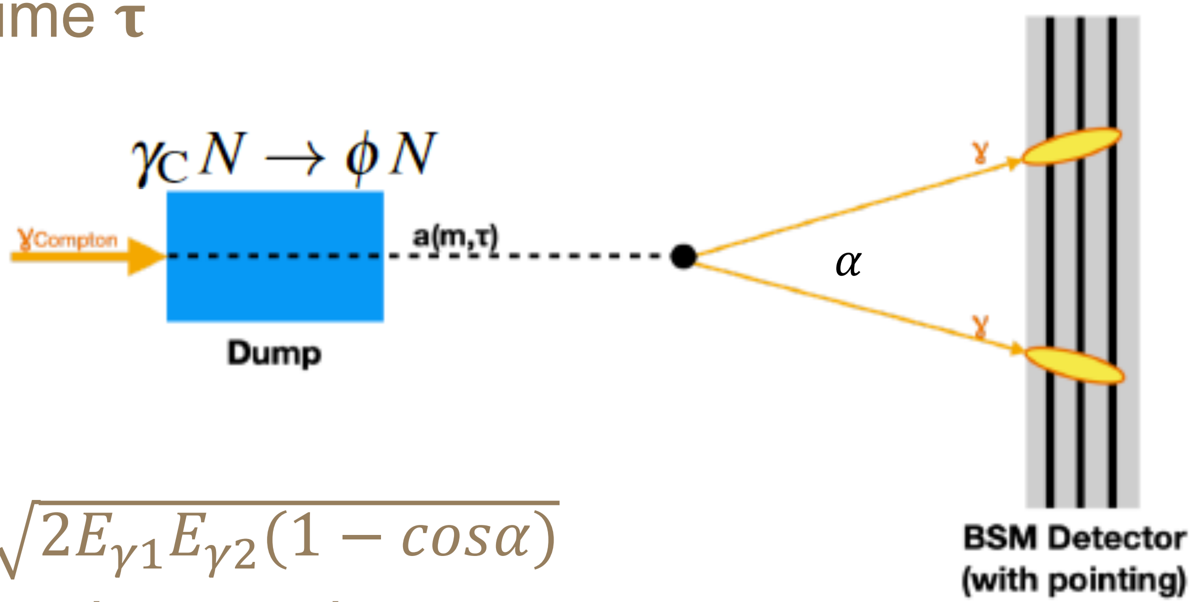




SENSITIVITY TO AXION-LIKE PARTICLES

Photons dumped on beam dump

- Converted to axion-like particles (ALP, ϕ) via Primakoff effect
  - Sensitivity to masses of m(a)~100 MeV
- ALPs decay to photons after some lifetime τ



Place detector behind dump

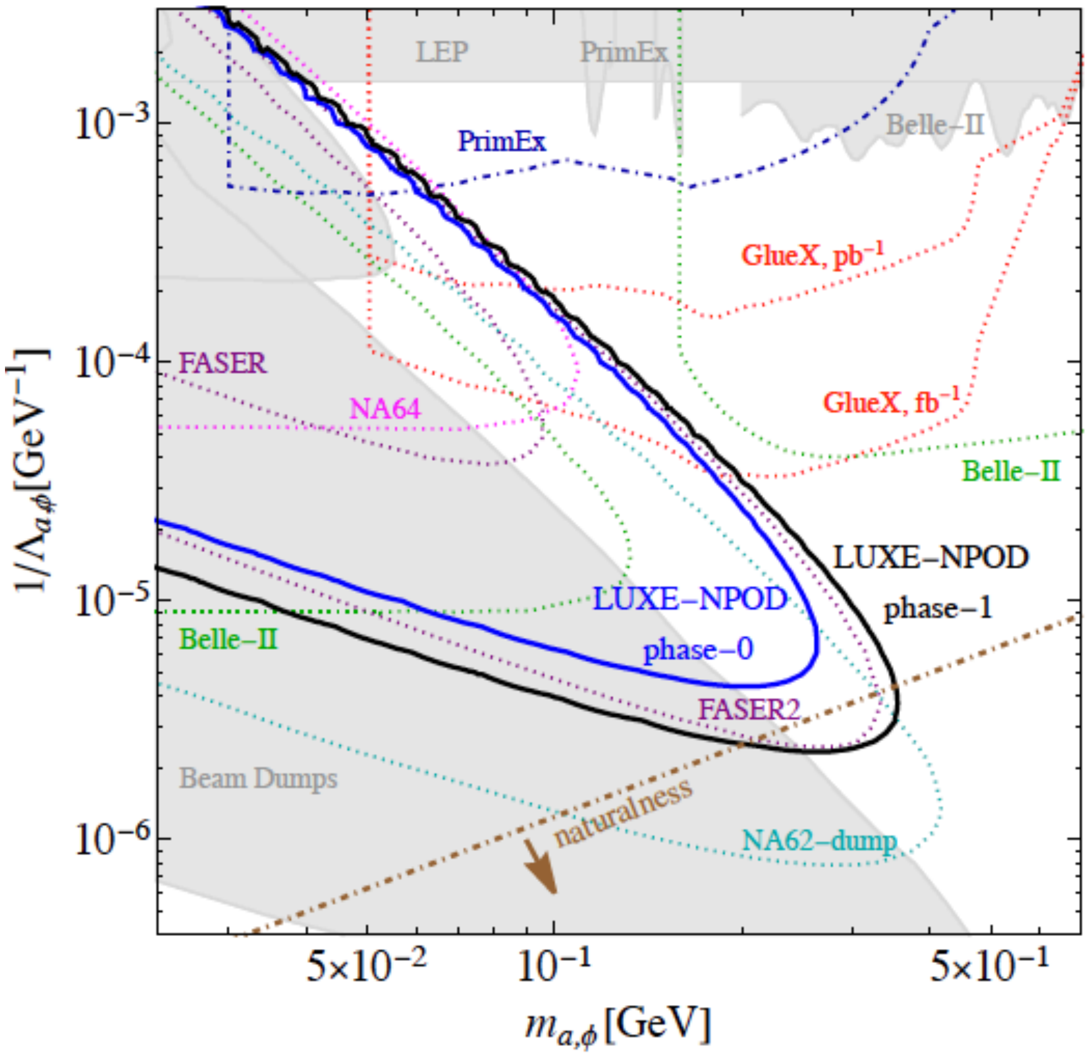
- Measure energies and angles => $M = \sqrt{2E_{\gamma 1}E_{\gamma 2}(1 - cos\alpha)}$
- Also determine lifetime by reconstructing decay point
- Need calorimeter with good rejection of neutrons and good pointing resolution
  - Reject background of neutrons/photons produced in dump and not much space available!

AXION-LIKE PARTICLES

Sensitivity estimated for 1 year assuming no background

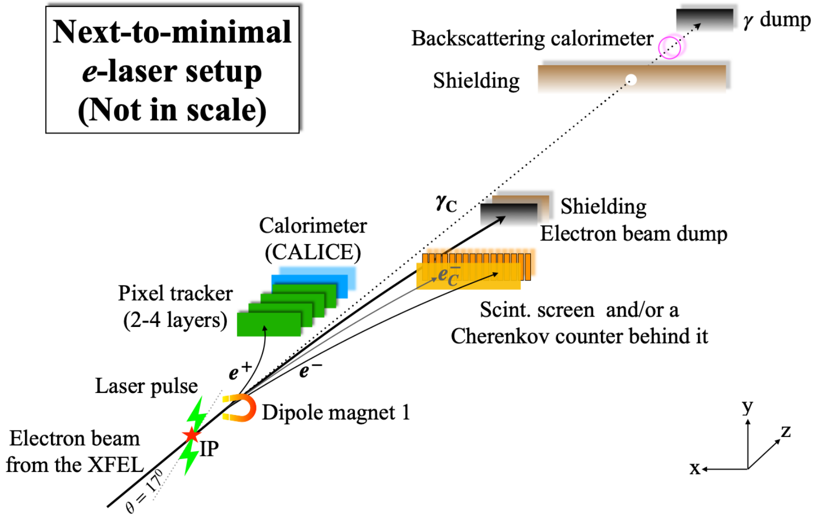
Competitive with other ongoing and planned experiments

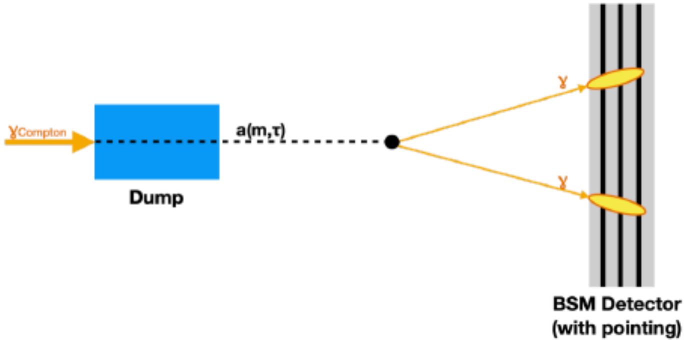
- Similar to e.g. FASER-2



OPPORTUNITIES FOR CONTRIBUTIONS AT DMLAB

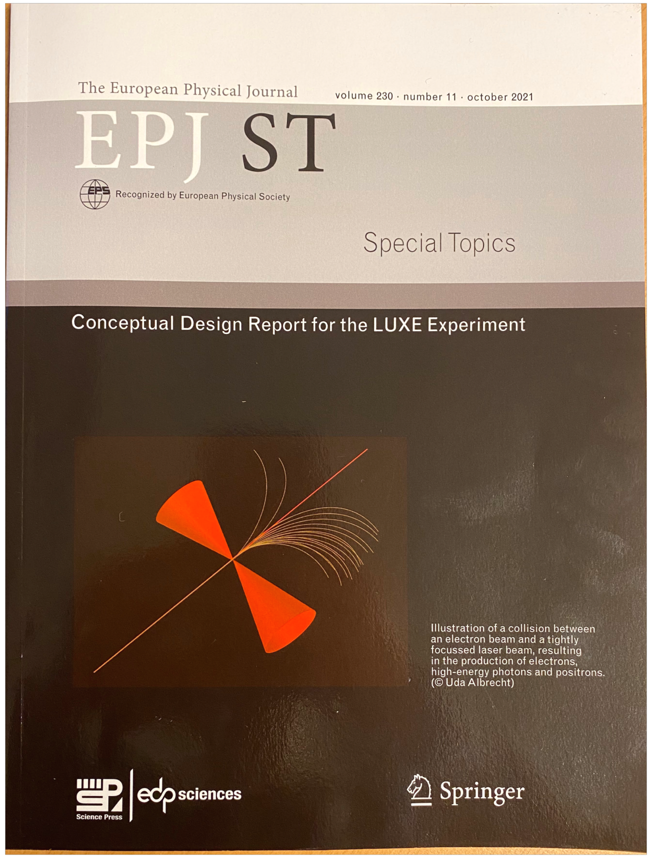
- **CALICE calorimeter with its high granularity and high resolution would be excellent contribution**
  - Discussions ongoing, could maybe use 18cm long CALICE prototype in a minimal initial version (see talk by R. Pöschl)
- **Design & construction of BSM detector**
  - Has only just started and ideas are needed
- **Many opportunities to contribute to simulation, software & analyses**
  - Simulation based on Geant4
  - Key4HEP envisaged for SW framework
- **High-power laser technology is a strongly developing research field**
  - Possibilities to contribute e.g. to diagnostics and operation





CONCLUSIONS & OUTLOOK

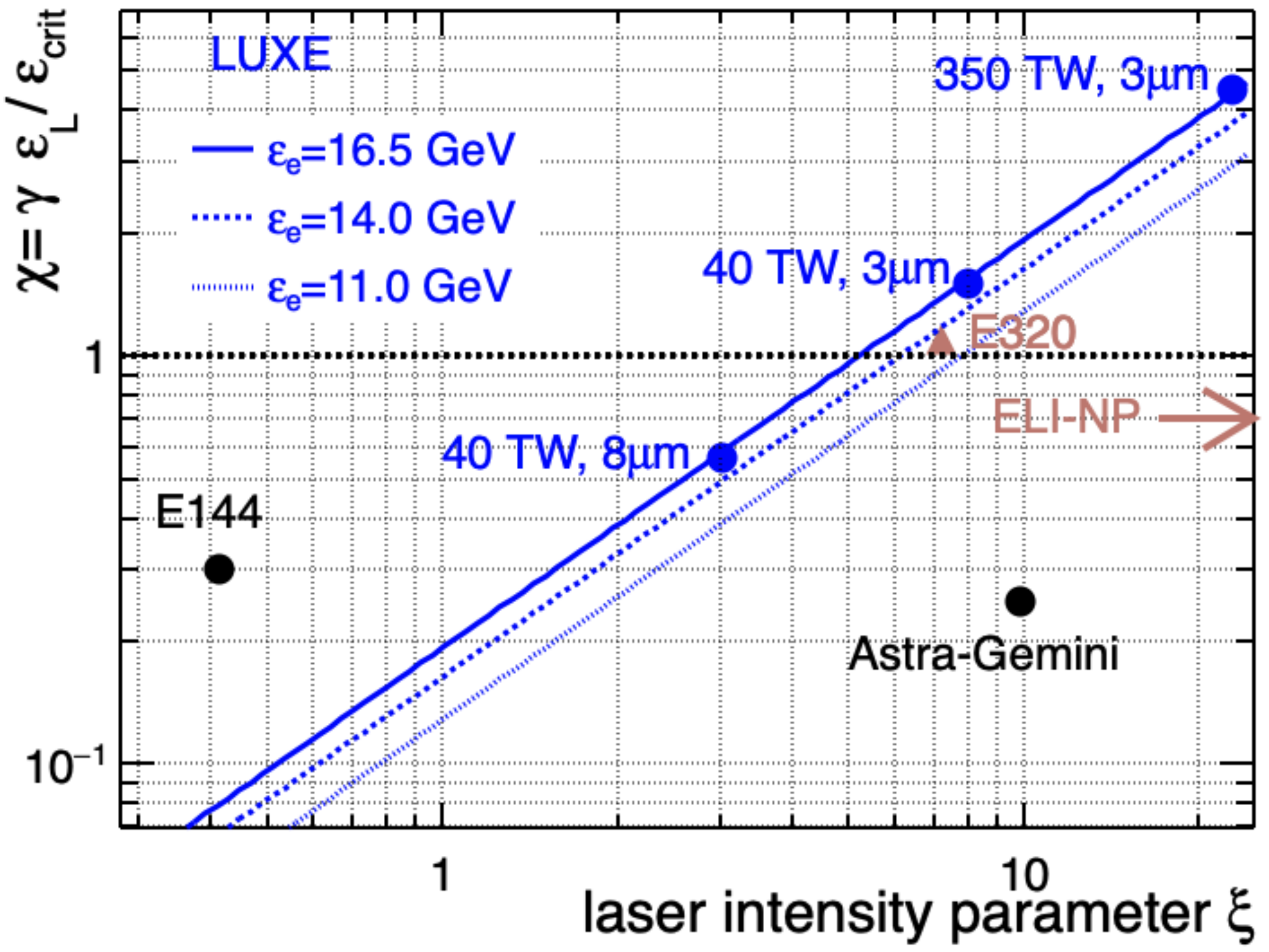
- **LUXE will probe a new regime of quantum physics!**
  - Electron-laser and photon laser modes
  - Parasitic search for axion-like particles
- **Opportunity to design, build and operate experiment & analyse data in this decade**
  - Planning for installation during 2024 shutdown planned by EU.XFEL
  - Physics running from 2025-2029
  - Multiple measurements can be performed
- **Hoping for approval at DESY in first half of 2022**



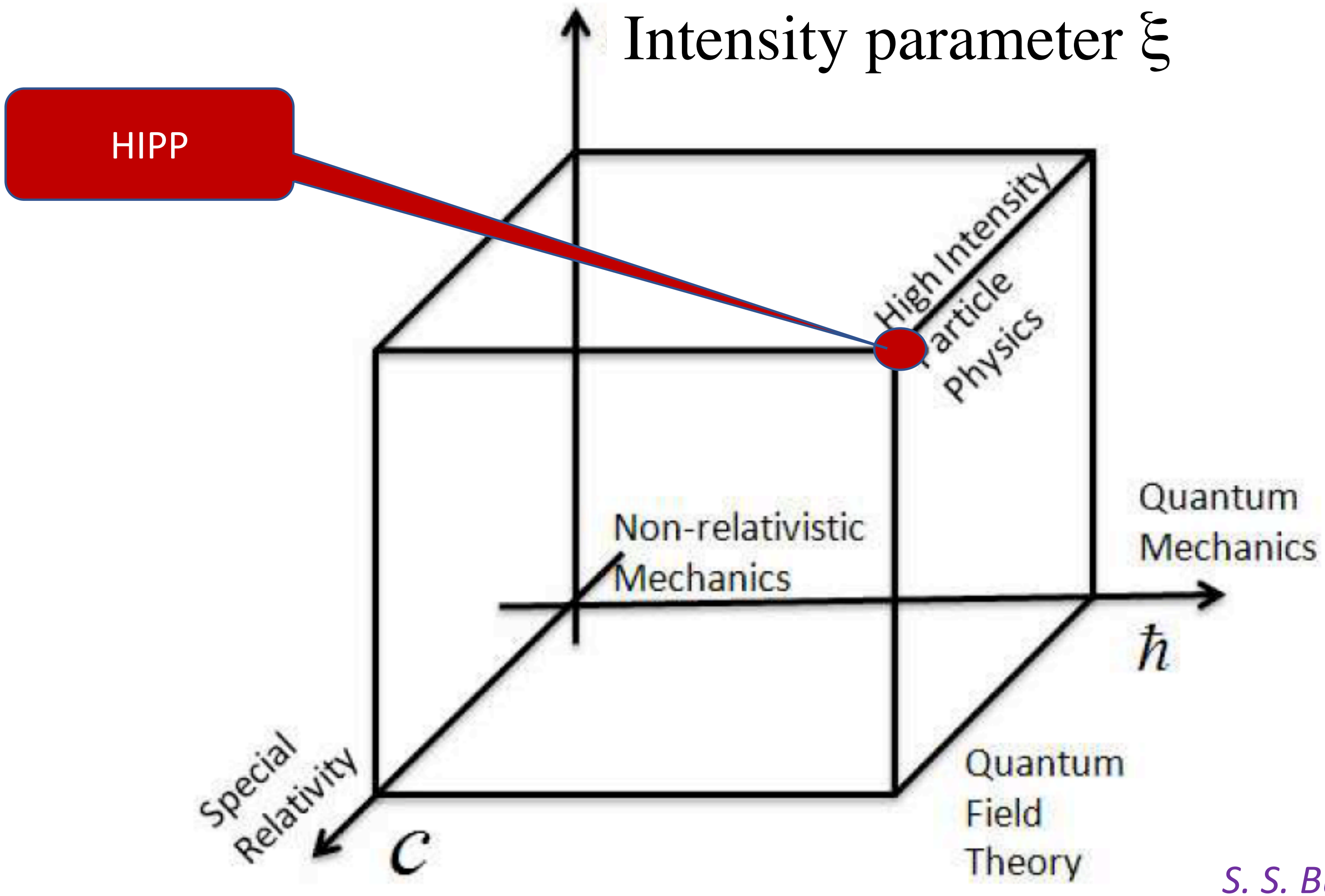
https://arxiv.org/abs/2102.02032

BACKUP

PARAMETER SPACE

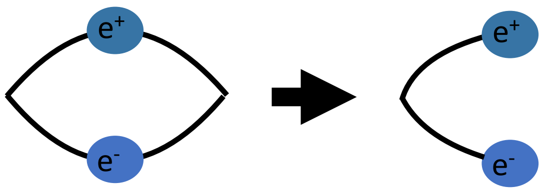


THEORIES ON A CUBE



S. S. Bulanov, W. Leemans et al.

BREIT-WHEELER PROCESS: BOIL THE VACUUM



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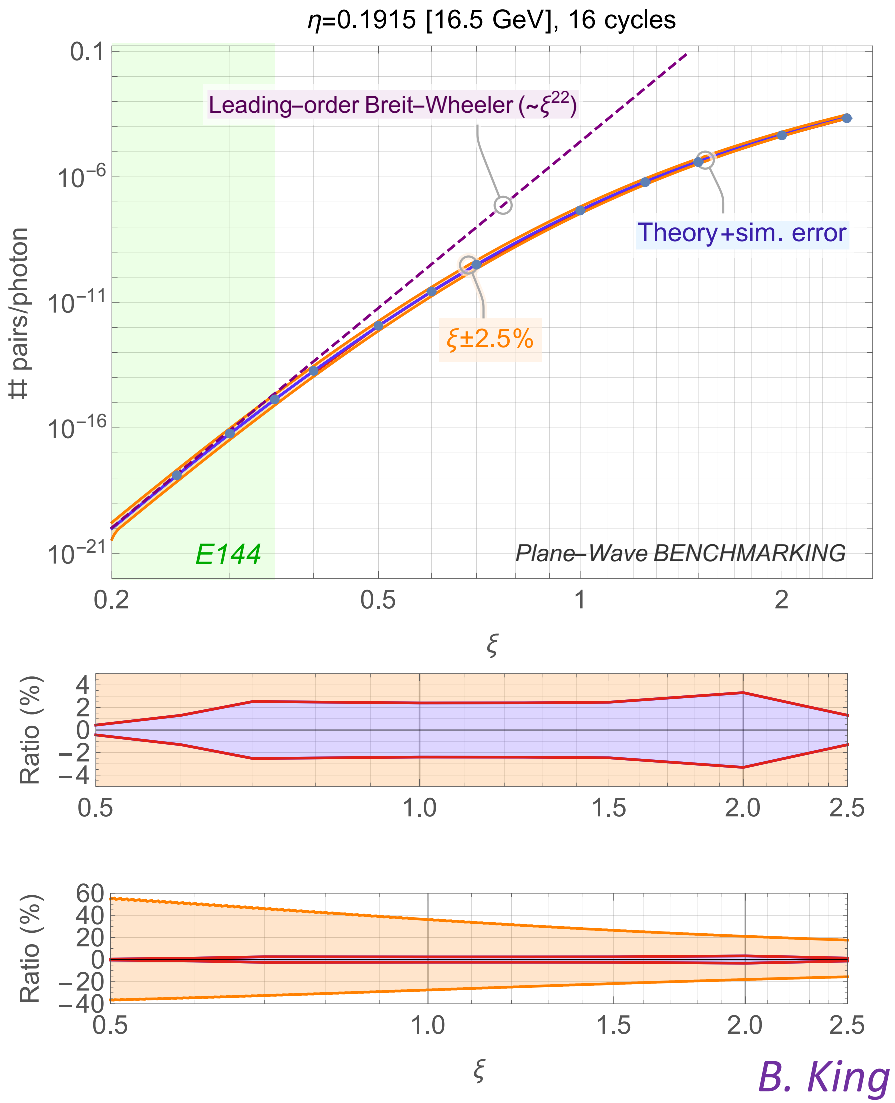
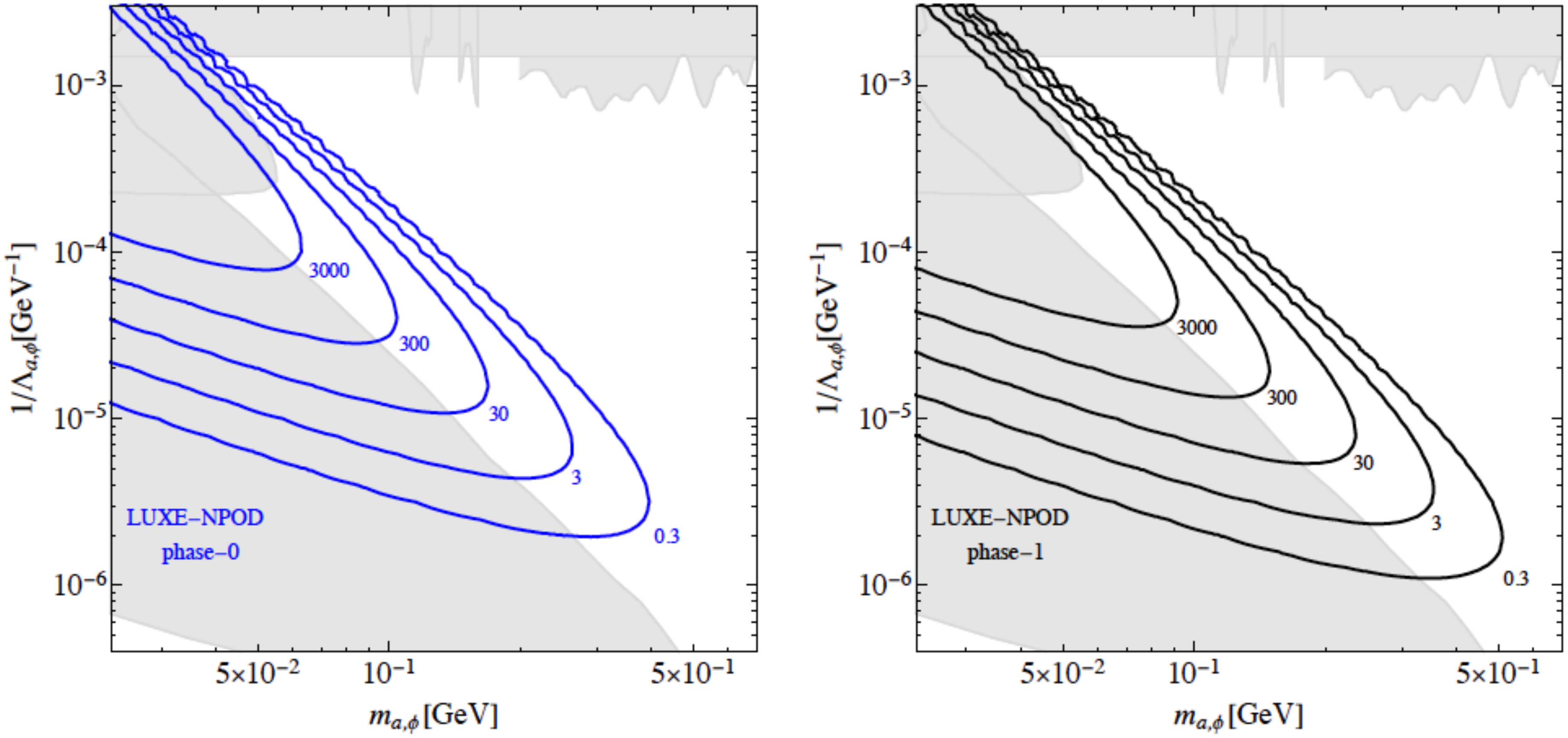


B. King

SENSITIVITY TO AXION-LIKE PARTICLES

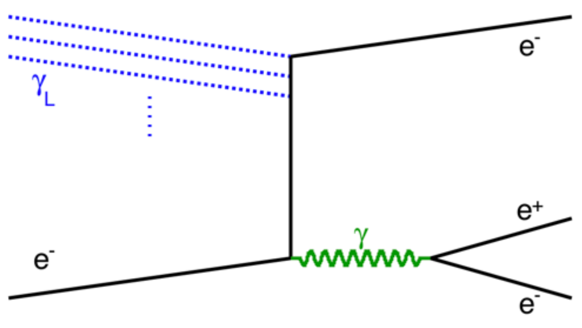


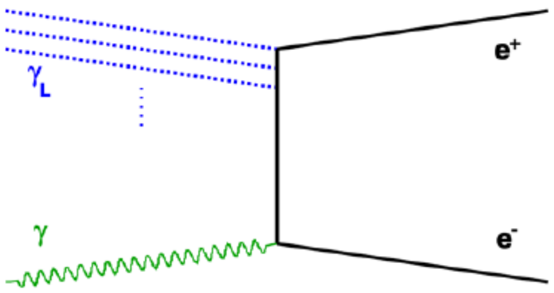
Contours indicate number of events observed: e.g. 3 are needed for ~95% CL exclusion if background is zero

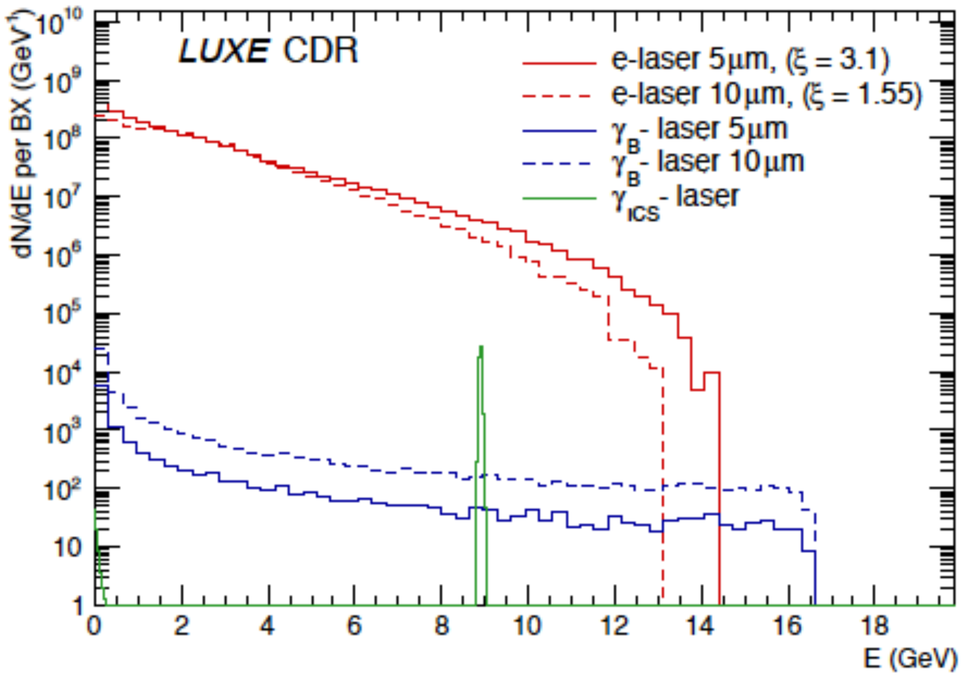
BREIT WHEELER PROCESS: e^+e^- PAIRS

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

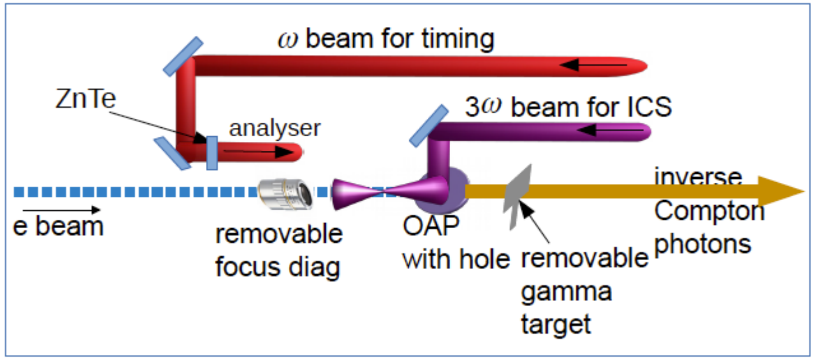
$\gamma + n\gamma_L \rightarrow e^- + e^+$







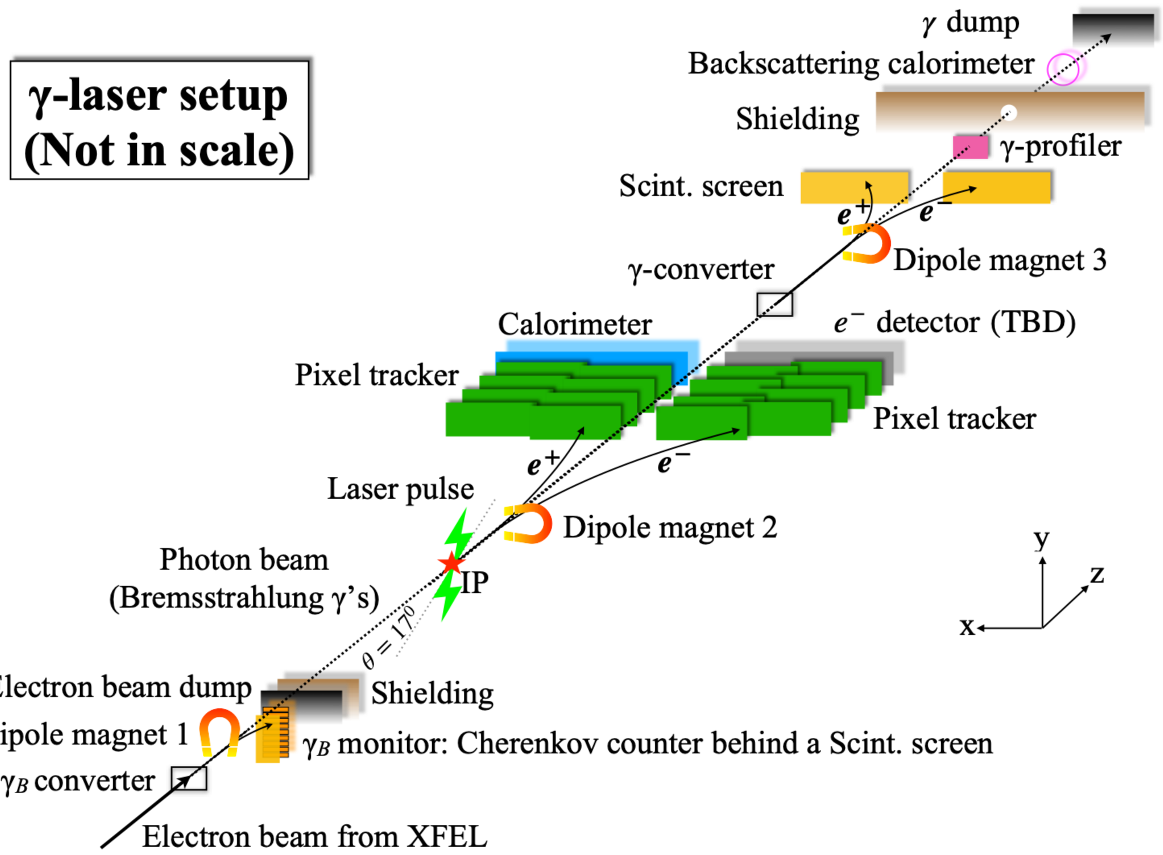
- Three methods for producing e^+e^- pairs
  - Compton photons inside same laser pulse => largest rate
  - Bremsstrahlung photons produced upstream => highest E
  - Compton photons produced upstream (E=9 GeV)



PHOTON-LASER INTERACTIONS

Detection of electrons, positrons and photons

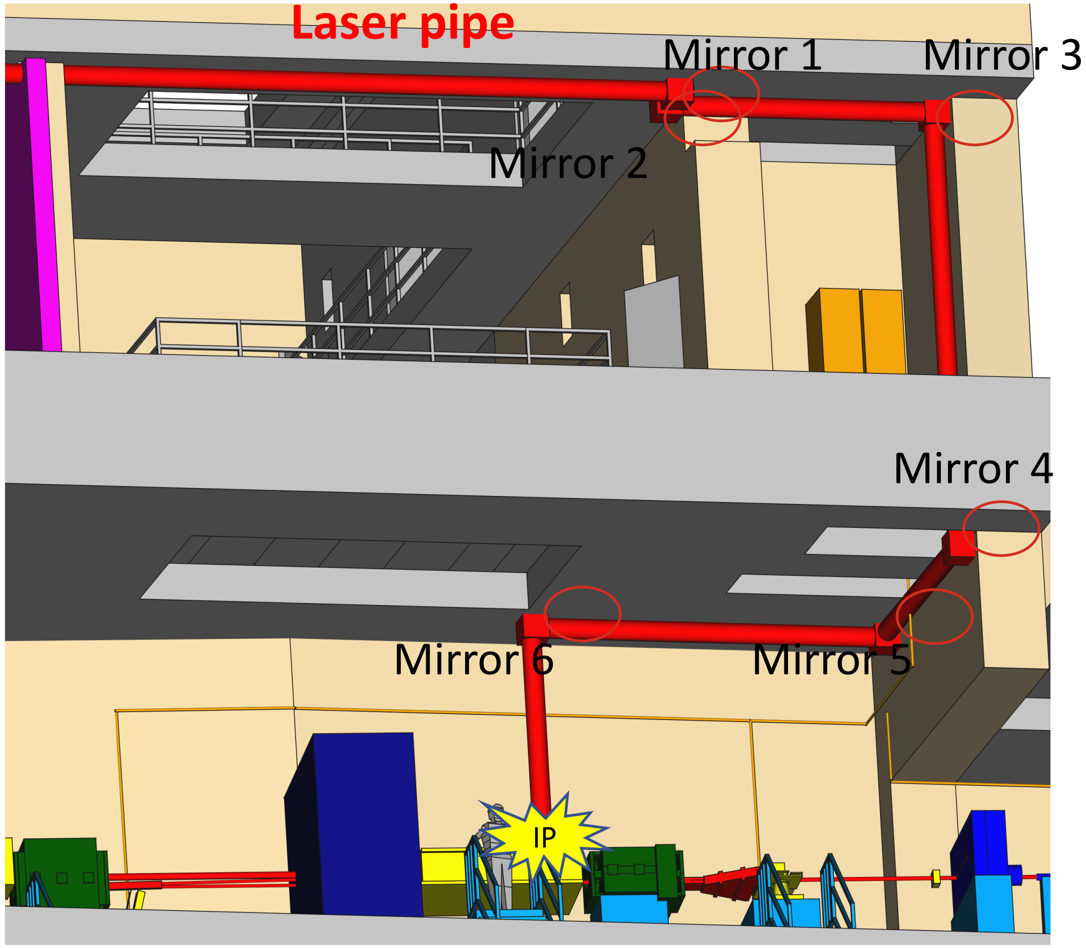
- Electron rates: 10^6-10^9 particles
  - Cherenkov detectors & scintillators
- Photon rates: 10^6-10^9 particles
  - Saphire detector and backscatter calorimeter
- Positrons and electrons at IP: 10^{-4}-10
  - Pixel tracker and calorimeter



LASER BEAMLINE

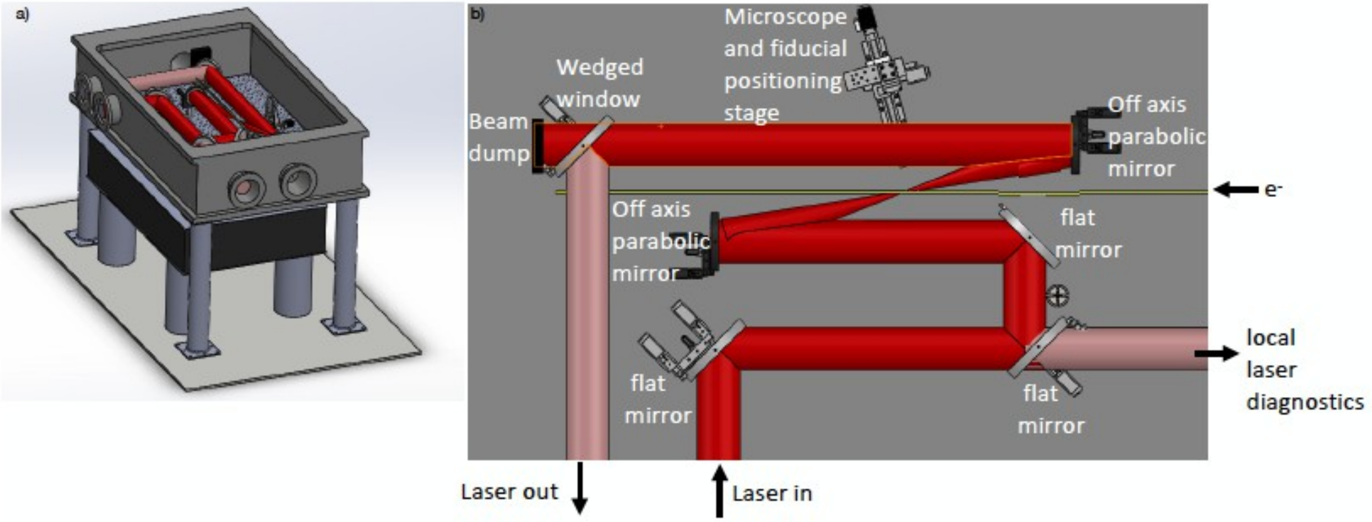
Laser guided from laser clean room to IP via 40 m long pipe and six mirrors

Laser clean room



Final focusing done just before IP via dedicated chamber

Designed by I. Pomerantz (Tel Aviv U)

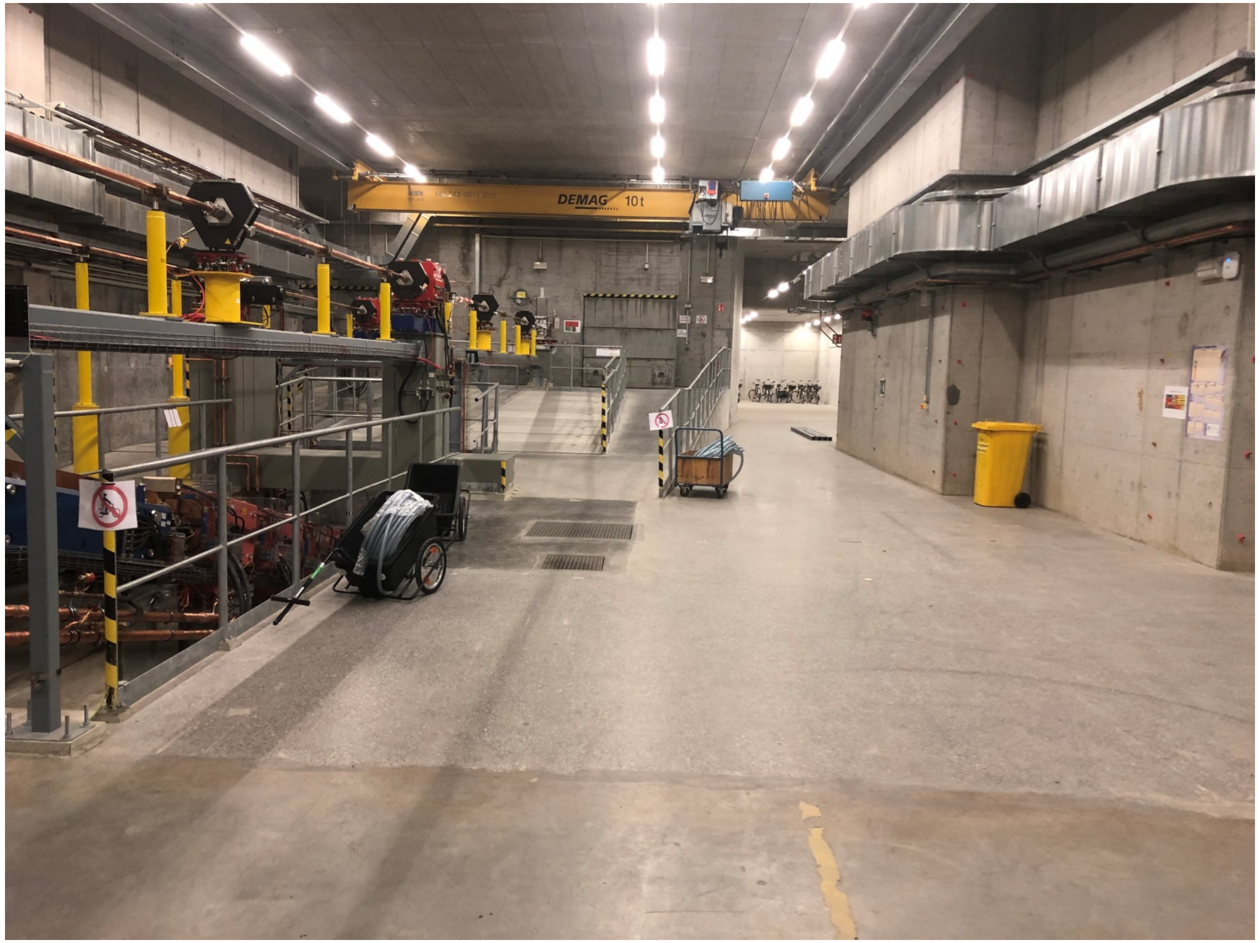


LOCATION OF LUXE

Shaft located at end of linear accelerator of European XFEL

Dimensions of annex

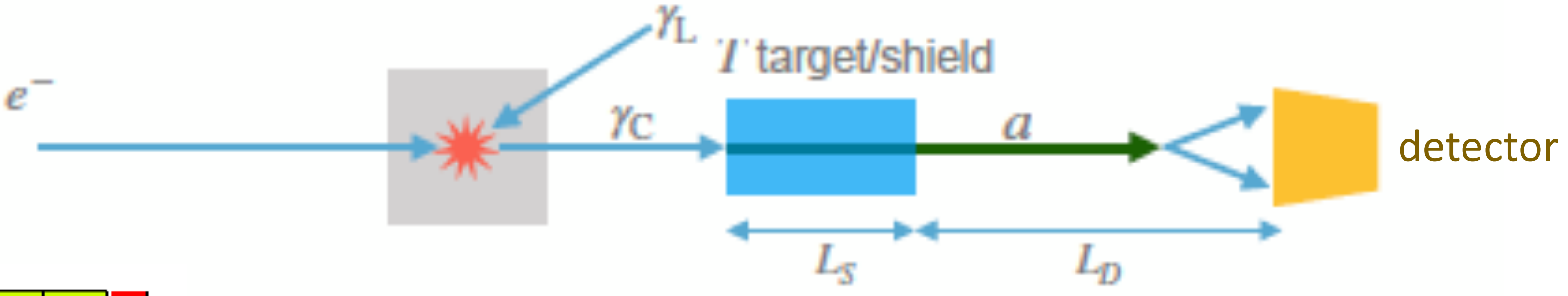
- 60m long, 5.4m wide, 5m high

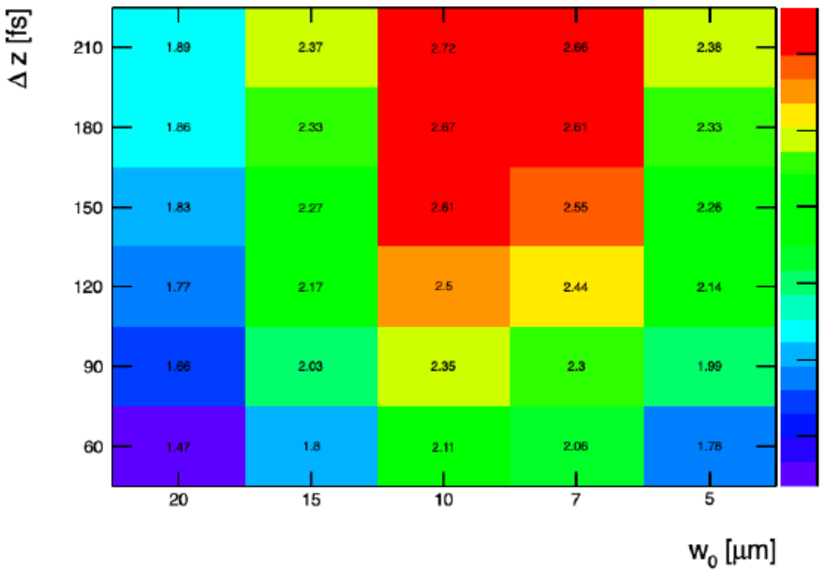


BSM PHYSICS

Use very high flux of GeV-scale photons from Compton process for BSM physics

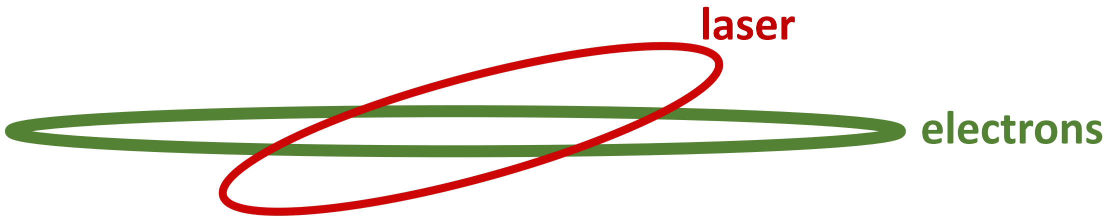
Use for beam dump type experiment => neutral particles that couple to photons (axion-like particles)



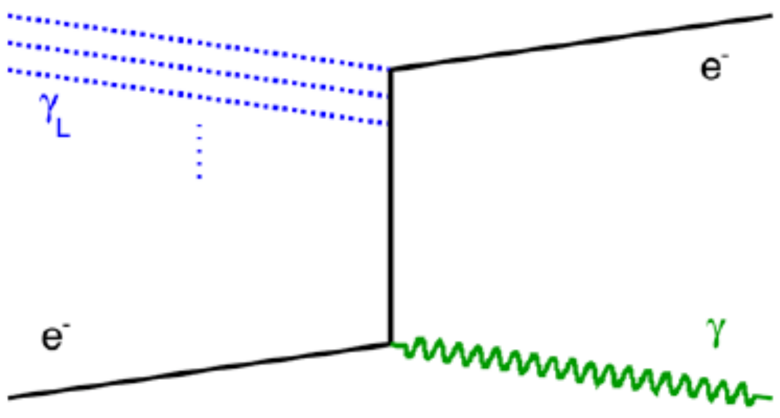


Need to maximize flux of photons with E≳1 GeV

- Scan of laser focus parameters to maximize rate
- Physics cross section convoluted with overlap area of beam and laser



NON-LINEAR COMPTON PROCESS: COUNTING PHOTONS



Non-perturbative effects:

- Number of photons radiated per electron
- Expect dependence on ξ to be reduced in full calculation compared to perturbative calculation