LUXE: a high-precision experiment to study non-perturbative QED in electron-laser and photon-laser collisions

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on behalf of the LUXE Collaboration

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QCD Quantum Chromodynamics

Quantum Field Theory describing interactions between elementary quark and gluon fields.
Perturbative QCD calculations are a key to access reach physics of the LHC.
Still, we know that the perturbative QCD fails in extreme conditions:

- high densities (eg. quark-gluon plasma, saturation effects)
- strong fields (eg. fragmentation, hadronization, hadron structure)

We use effective models (eg. string fragmentation) or move to latice calculations...

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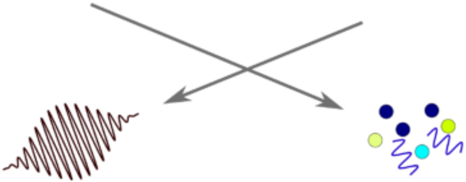
What about QED? Quantum Electrodynamics

We would expect that perturbative QED can always provide us with precise predictions for all electromagnetic interactions at fundamental level.

But it turns out that its validity range is also limited...

Classical nonlinearity



B.King @ LUXE Coll. 2023

In beam-beam collisions we always assume two particle interact, one from each beam. This can be very different in beam-laser interactions...

Laser pulse is a coherent state: multi-photon interactions possible...

LUXE

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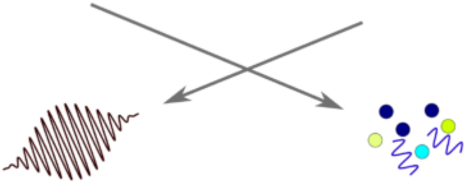

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Laser pulse is a coherent state: multi-photon interactions possible...

We can try to estimate the expected number of photons participating in the single collision:

- the characteristic scale of the interaction is the Compton wavelength: $\lambda_C = \frac{\hbar}{mc}$
- work of the laser electric field $\mathcal{E}_L$ can be estimated as $\Delta E = e\mathcal{E}_L \cdot \lambda_C$
- number of laser photons contributing to this energy transfer: $\xi = \frac{\Delta E}{\hbar \omega_L}$

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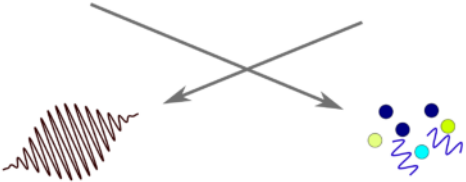

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The resulting number is called the **classical nonlinearity parameter**

$$\xi \quad = \quad \frac{e\mathcal{E}_L \cdot \lambda_C}{\hbar\omega_L} = \frac{e\mathcal{E}_L \cdot \lambda_L}{mc^2}$$

Limitations of perturbative QED

For $\xi \ll 1$ we are in perturbative regime, lowest order contribution (single photon) dominates,
Taylor series in $\alpha \sim \xi^2$ convergences fast.

For $\xi \lesssim 1$ - still perturbative regime but slow convergence,
onset of multi-photon processes, non-linear effects emerge

For $\xi \gtrsim 1$ - each photon number contribute with comparable weight
$\Rightarrow$ new approach needed to obtain solutions to "all orders"

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Volkov picture

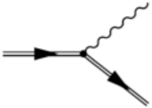
We can factorize electron interactions into "background" interactions with the laser field and actual interactions involving high energy photons ($\omega \gg \omega_L$)

Electrons and positrons "dressed" in laser radiation: Volkov states

Processes of interest double line denotes Volkov states

- Non-linear Compton scattering

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



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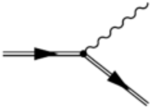

- Non-linear trident process

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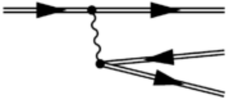

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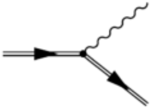

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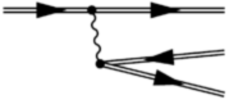
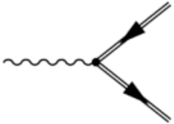


- Non-linear Breit-Wheeler process

$$\gamma + n\omega_L \to e^+ + e^-$$



LUXE

Quantum nonlinearity

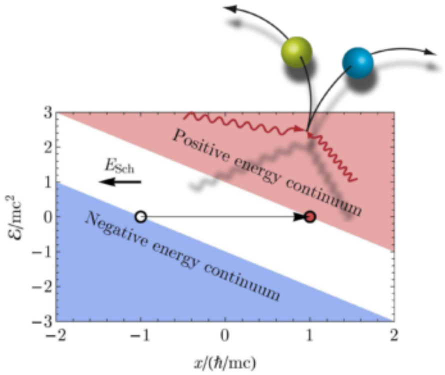
For extremely high electric field, work over the Compton wavelength can exceed electron mass.

Critical field:

$$e\,\mathcal{E}_{cr} \cdot \lambda_C \;=\; m\,c^2$$

$$\mathcal{E}_{cr} \;\approx\; 1.3 \cdot 10^{18}\ V/m$$

For fields comparable or higher than the critical field, e^+e^- pairs can be created by tunneling from vacuum.



T. Blackburn @ LUXE Coll. 2024

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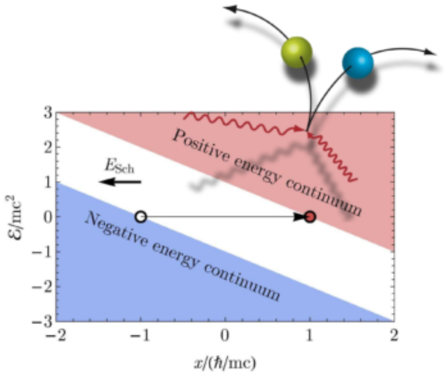
Quantum nonlinearity parameter:

$$\chi \;=\; \frac{\mathcal{E}}{\mathcal{E}_{cr}} \;=\; \frac{\hbar\omega_L}{mc^2}\,\xi$$



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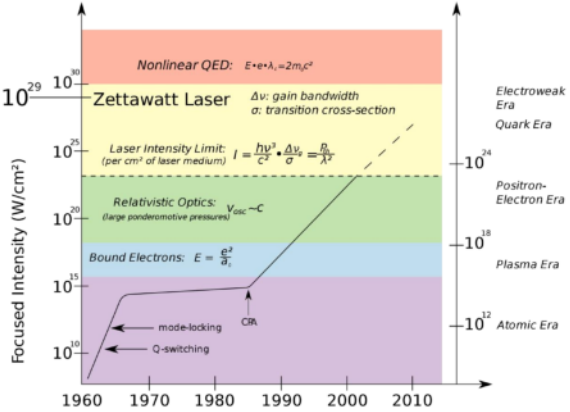
Experimental reach

Rapid progress in high-intensity lasers.

With Chirped Pulse Amplification (CPA) we can reach TW – PW power, electric fields up to

$$\mathcal{E} \sim 10^{14}\ V/m$$

Still orders of magnitude below $\mathcal{E}_{cr}$...



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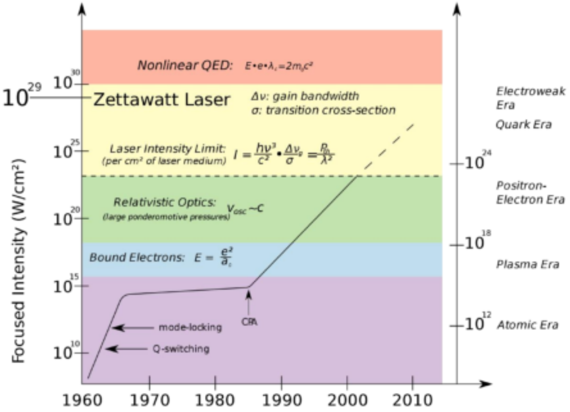
But the field can be much higher for the relativistic electron colliding head-on with the laser pulse:

$$\mathcal{E}^{\star} = \gamma \, \mathcal{E}_{LAB} \, (1 + \cos\theta)$$



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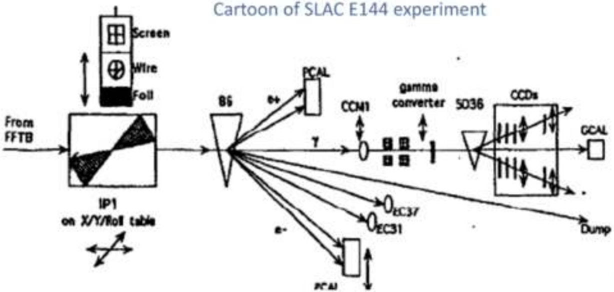
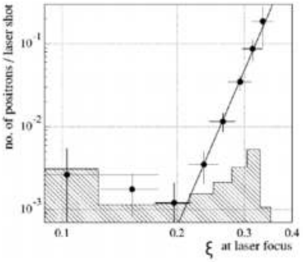
SLAC E144

First to approach the non-linear domain was SLAC E144 experiment colliding 46.6 GeV electron beam from SLC with 1 TW green laser ($\xi \lesssim 0.4$ and $\chi \lesssim 0.25$)

Non-linear Compton scattering and non-linear Breit-Wheeler pair production observed

Cartoon of SLAC E144 experiment





[Bamber et al. (SLAC 144) '99]

LUXE

Laser Und XFEL Experiment

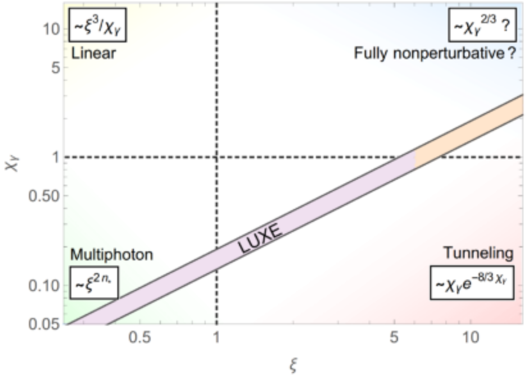
Probing SF QED in collisions of ultra-relativistic EuXFEL beam with high-power laser pulses

Designed to make precision measurements of the transition from perturbative to non-perturbative QED regime and test theoretical predictions in the previously unexplored domain

$$\xi \quad \lesssim \quad \mathcal{O}(10)$$

$$\chi \quad \lesssim \quad \mathcal{O}(1)$$

in both electron-laser and photon-laser collisions.



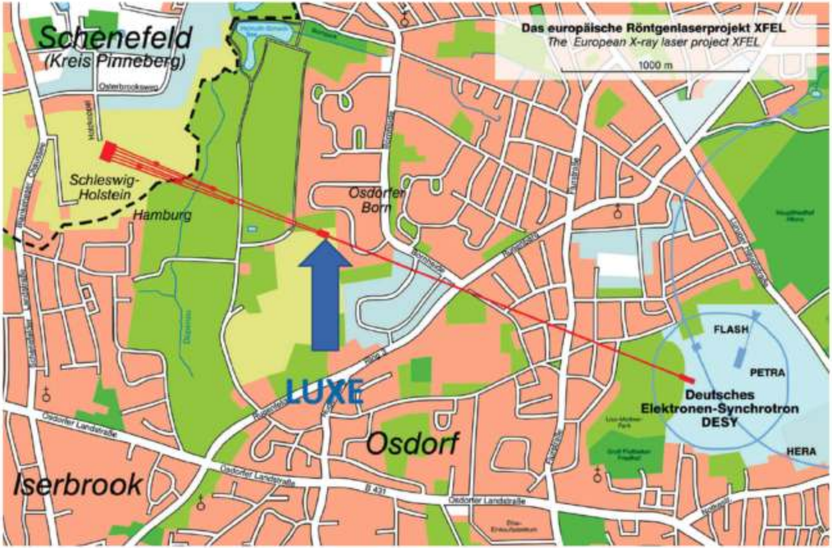
Concept

EuXFEL electron beam:

- 16.5 GeV
- 10 Hz bunch trains
- $1.5 \cdot 10^9$ e^-/bunch
  1 out of 2700 for LUXE

Laser system

- Ti:Sa laser 800 nm
- 40 TW in "phase-0"
  350 TW in "phase-1"
- 30 fs pulses at 1 Hz
- 3 μm beam spot



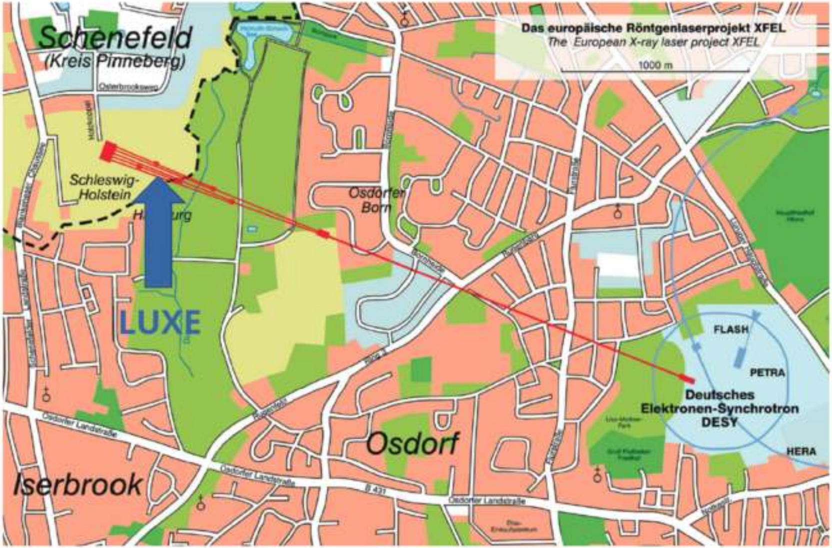
2025

New location

Extraction beamline funded through ELBEX grant (Horizon Europe)

10 TW optical laser JeTi40 arrived at DESY loan from FSU Jena

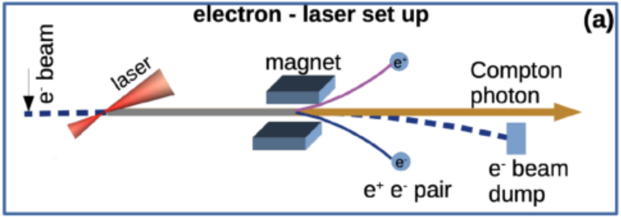
Could start in 2030...



Operation modes

- **electron-laser**

Up to 10^9 photons and electrons per pulse
$\Rightarrow$ dedicated instruments needed for precise spectra and flux measurement.
$10^{-3} - 10^5$ positrons per pulse
$\Rightarrow$ "standard" high precision tracking and compact high-density calorimeter



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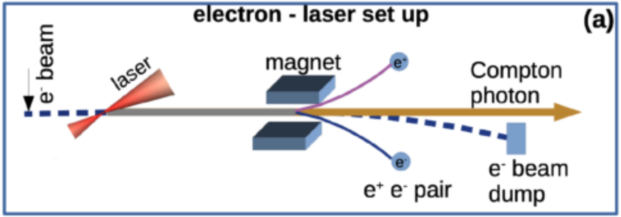
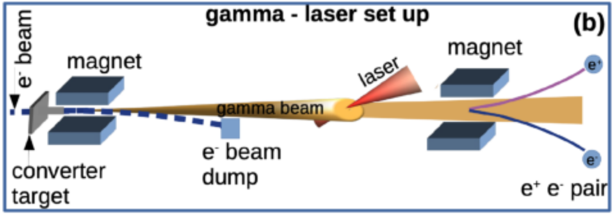


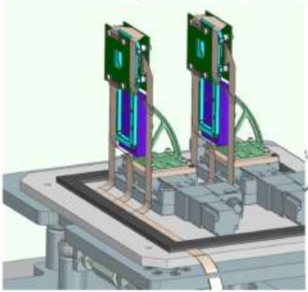
- **gamma-laser**

Up to 10^9 photons per pulse
and $10^{-5} - 10$ $e^+ e^-$ pairs
⇒ high precision tracking and calorimetry also for electron spectra measurement



Gamma profiler

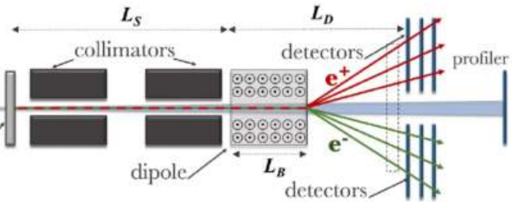
sapphire micro-strip det.
2×2 cm^2, 100 μm pitch
2×2 orthogonal strips



beam width to $< 10\mu$m

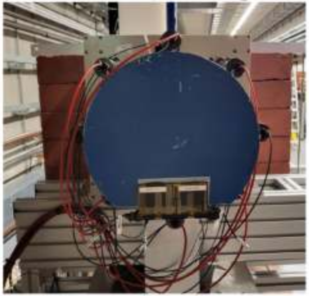
Gamma spectrometer

Photon spectra can be also reconstructed from the measured Bethe-Heitler e^+e^- pairs generated in a thin target



Gamma flux monitor

Photon beam position and intensity from photon dump leakages



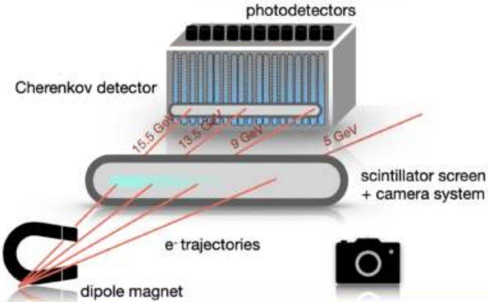
instrumented dump

Cherenkov detector

- air-filled steel straws or glass rods
- SiPM readout, 2 mm spatial resolution

Scintillating screen

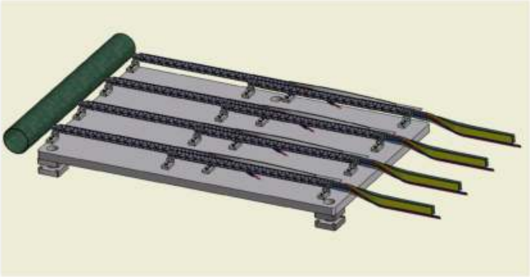
- optical readout (camera)
- 0.5 mm position resolution



Prototype tests at E-320 experiment (FACET-II)

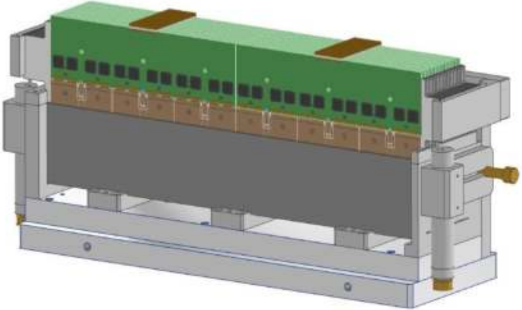
Pixel tracker

- Design based on ALPIDE chips (MAPS)
- Four layers, 18 chips per layer in two staves
- Spacial resolution $\sim 5\,\mu$m



High-density sampling calorimeter

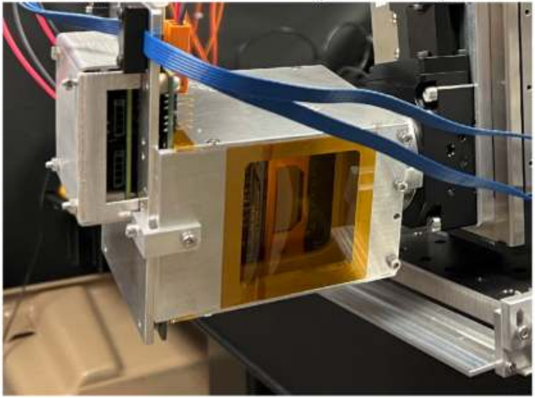
- 21 tungsten plates of 1 X_0
- thin silicon sensors, $5.5 \times 5.5\,\mathrm{mm}^2$ cells
- very compact: $54 \times 9 \times 9\,\mathrm{cm}^3$



Positron detection system

Pixel tracker

Prototype tests at E-320 (FACET-II)



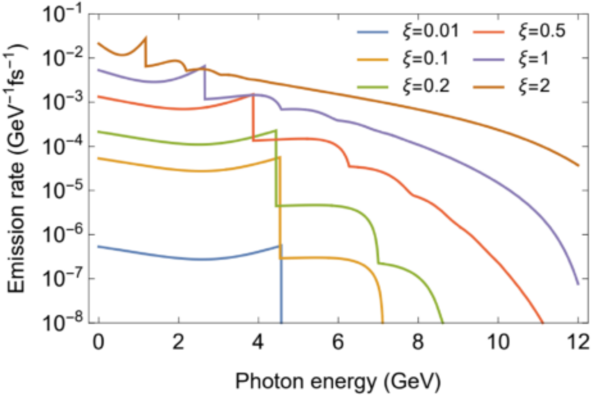
High-density sampling calorimeter

Prototype tests at DESY

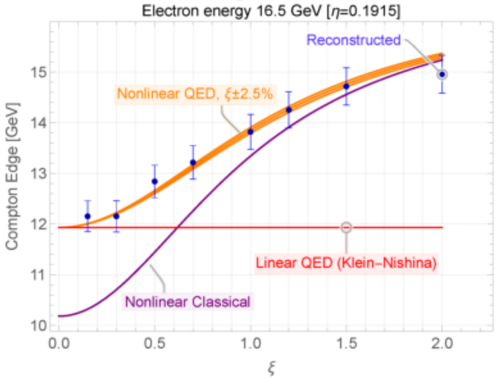
Compton edge

Expected changes in the observed Compton spectra as a function of ξ parameter:

Photon spectra shape



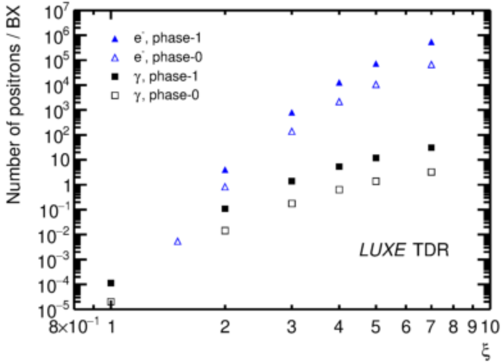
Electron spectra edge position



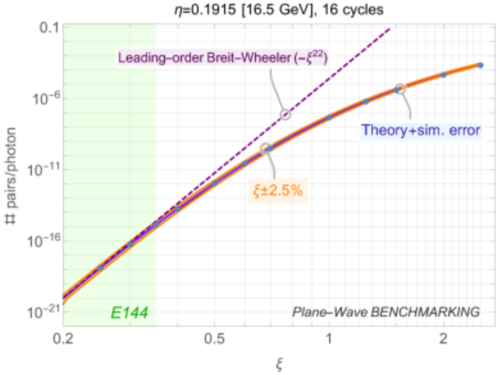
e^+e^- pair production

Expected production rate as a function of ξ parameter:

Positron flux for different running scenarios



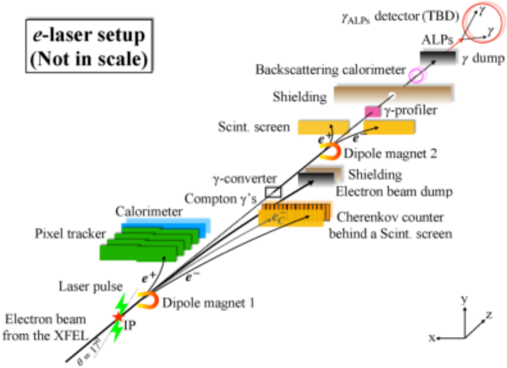
Expected theory and measurement precision



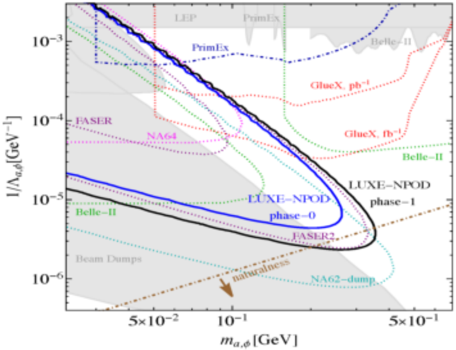
gamma-laser interactions

LUXE-NPOD

Experimental set-up can be extended to allow for light exotic long-lived particle searches.
Exotic states could be produced directly in gamma-laser collisions or in photon dump.



Expected reach of axion search



membership of Russian institutes suspended

Conclusions

LUXE experiment opens new prospects for research in Strong-Field QED entering intensity parameter domains never explored before

Experiment design with multiple complementary detectors allows for precision measurements of photon, electron and positron spectra over the wide range of expected signals.

Expected experimental accuracy matches the precision of theoretical calculations allowing for stringent tests of the theoretical prediction.

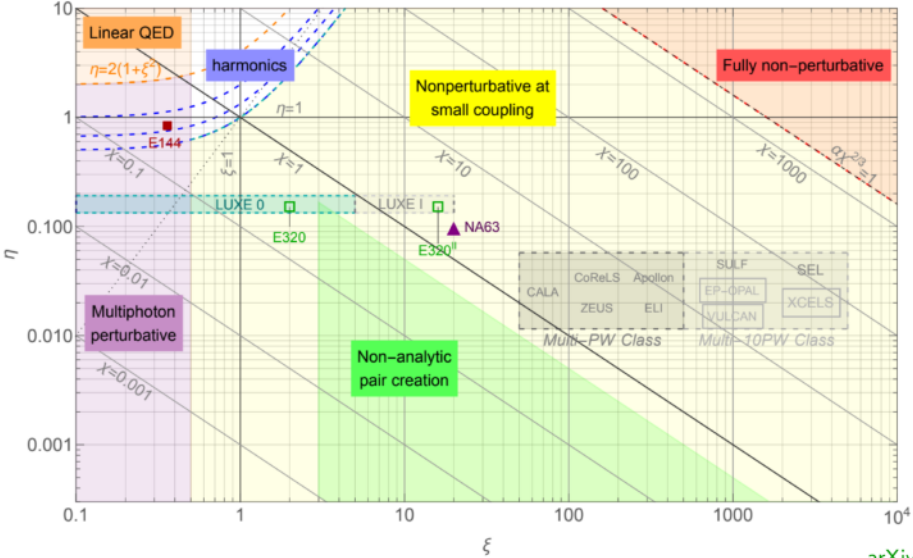
LUXE can also search for new physics exploiting the optical dump concept

see presentation in the BSM session for more detail

Extraction beam line is partially funded, and the detector installation should start in 2029


Thank you!
adidas

Backup



arXiv:2504.00873

Table 3 Laser parameters for the two phases of the LUXE experiment, and the quantum parameter χ_e is given for two different electron energies. All values are for circular polarisation with peak field parameters ξ and χ increasing by a factor of $\sqrt{2}$ for linearly polarised laser irradiation. For focal spot the lowest value targeted is given, and the peak intensity (ξ and χ_e) values given correspond to this waist value. The laser pulse is expected to be Gaussian in all three dimensions in the focal point. The laser is expected to operate at 1 Hz repetition rate, a 10 Hz repetition rate is in principle available at lower intensities

Laser parameters	Phase-0	Phase-1
Fraction of ideal Gaussian intensity in focus (%)	50	
Laser central wavelength (nm)	800	
Laser pulse duration (fs)	25-30	
Laser focal spot waist w_0 (μm)	≥ 3	
Laser repetition rate (Hz)	1-10	
Electron-laser crossing angle (rad)	0.3	
Laser energy after compression (J)	1.2	10
Laser power (TW)	40	350
Peak intensity in focus ($\times 10^{20}$ W/cm^2)	< 1.33	≤ 12
Dimensionless peak intensity, ξ	< 7.9	< 23.6

Quantum parameter	Phase-0	Phase-1
χ_e for $E_e = 14.0\,\mathrm{GeV}$	< 1.28	< 3.77
χ_e for $E_e = 16.5\,\mathrm{GeV}$	< 1.50	< 4.45
χ_e for $E_e = 17.5\,\mathrm{GeV}$	< 1.6	< 4.72

From LUXE TDR: Eur. Phys. J. Spec. Top. 233 (2024) 10, 1709-1974; arXiv:2308.00515

Backup

Timeline for the staged construction of the LUXE experiment

arXiv:2504.00873