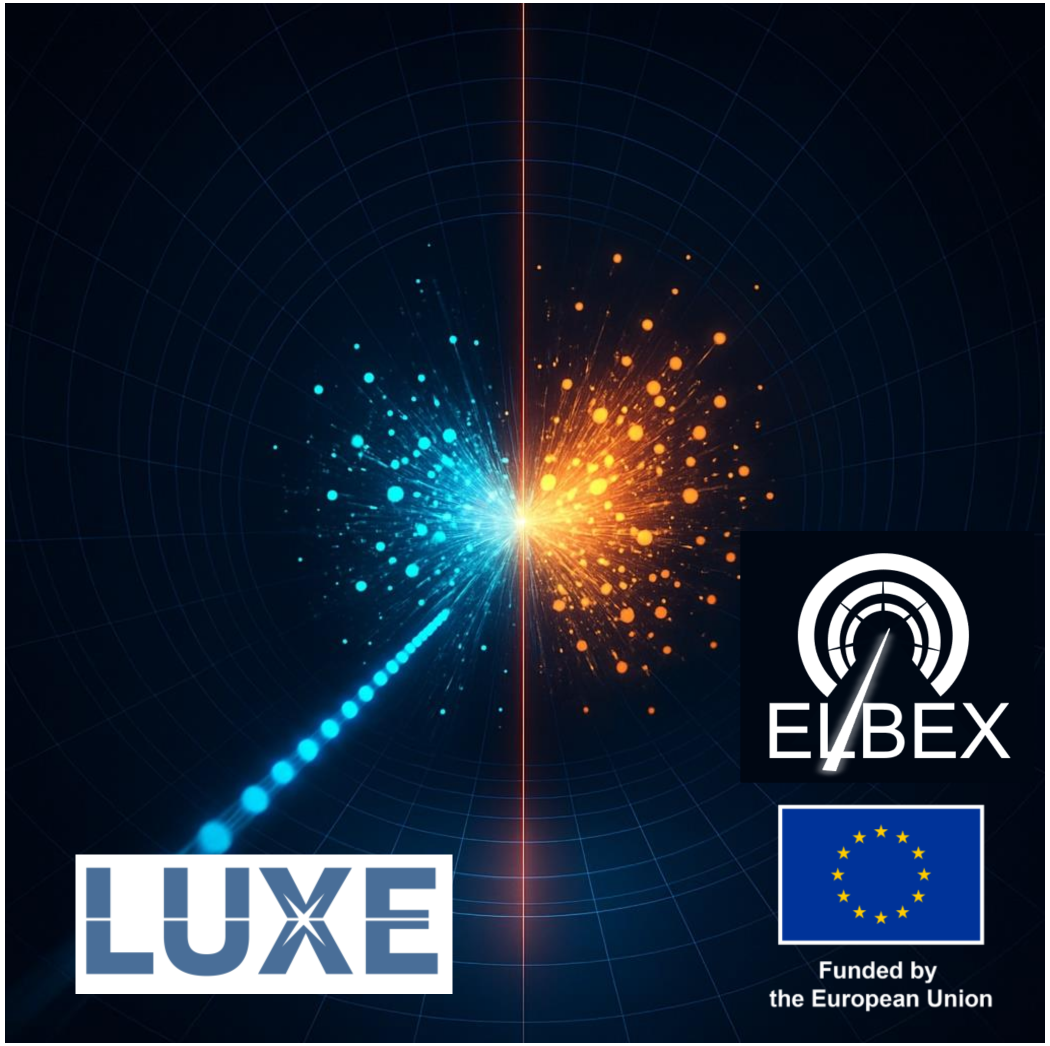
ELBEX & LUXE

Ruth Jacobs, DESY

for the LUXE and ELBEX teams

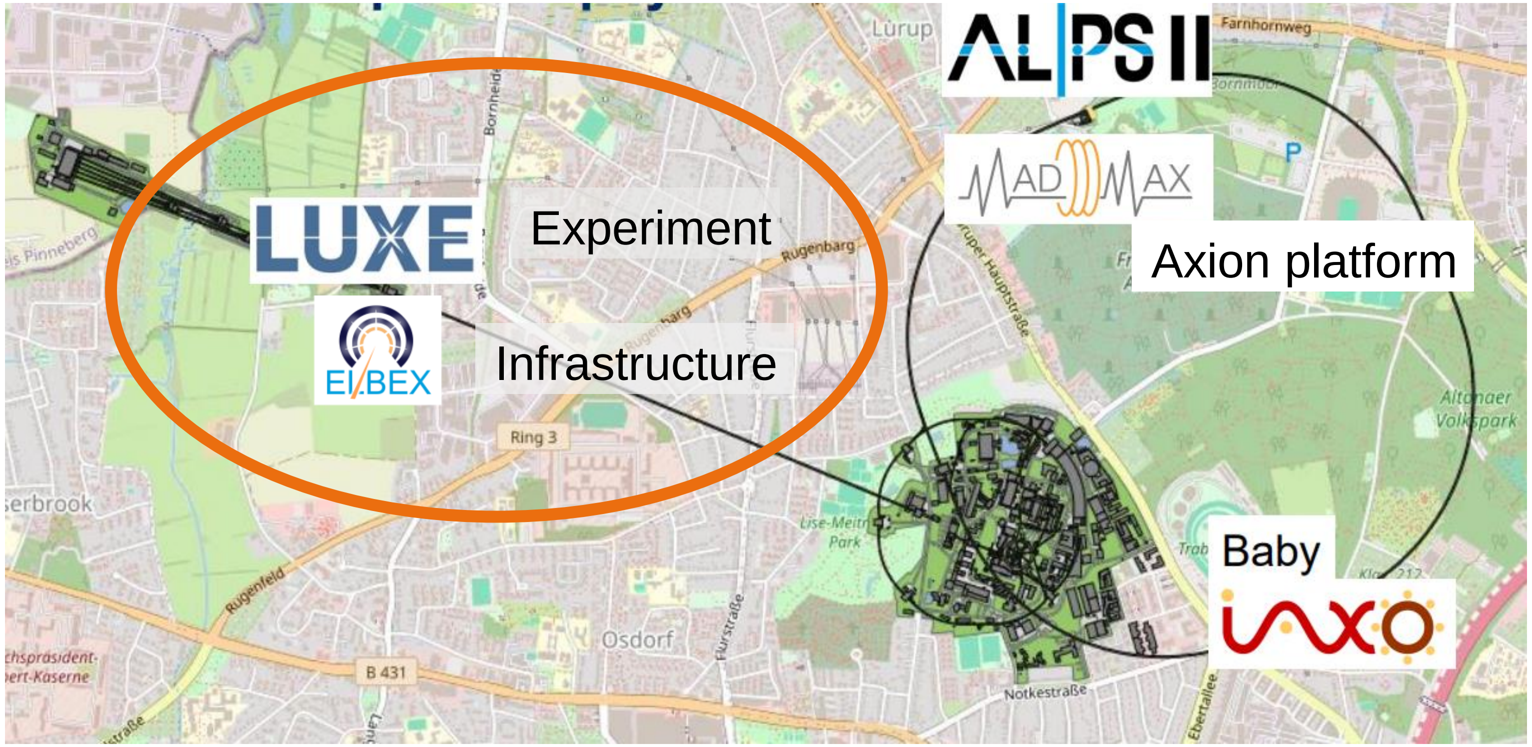
KET ErUM-Pro Strategy Workshop
22.11.2025

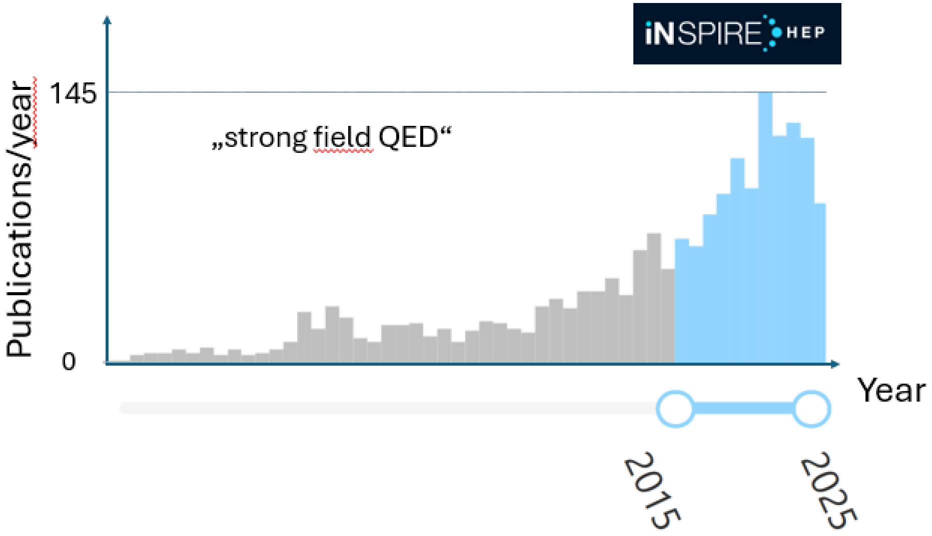


HELMHOLTZ

DESY.

DESY on-site particle physics experiments





LUXE experiment (intnl. collab.) to study strong-field QED

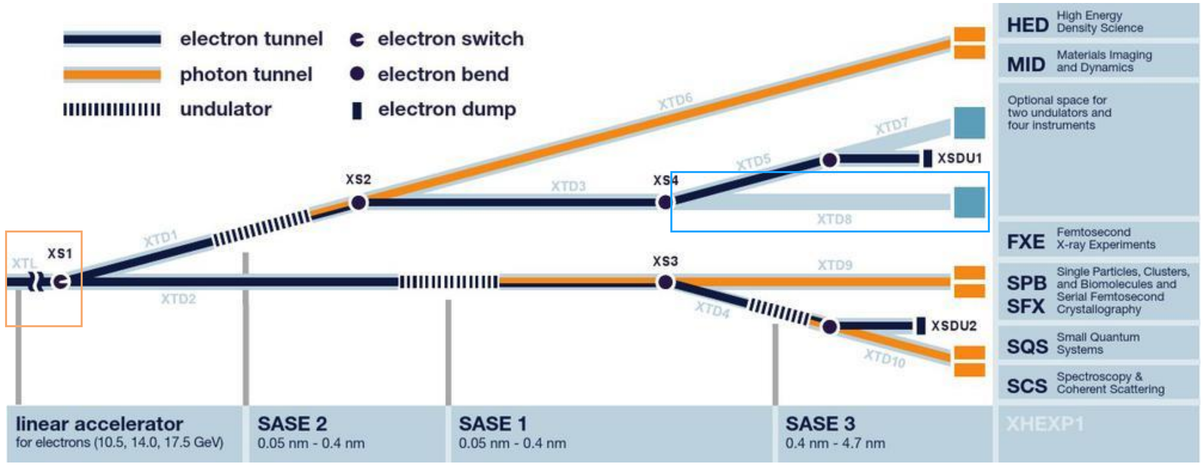
ELBEX infrastructure provides beam extraction, financed (partly) by EU Infrastructure grant

ELBEX overview

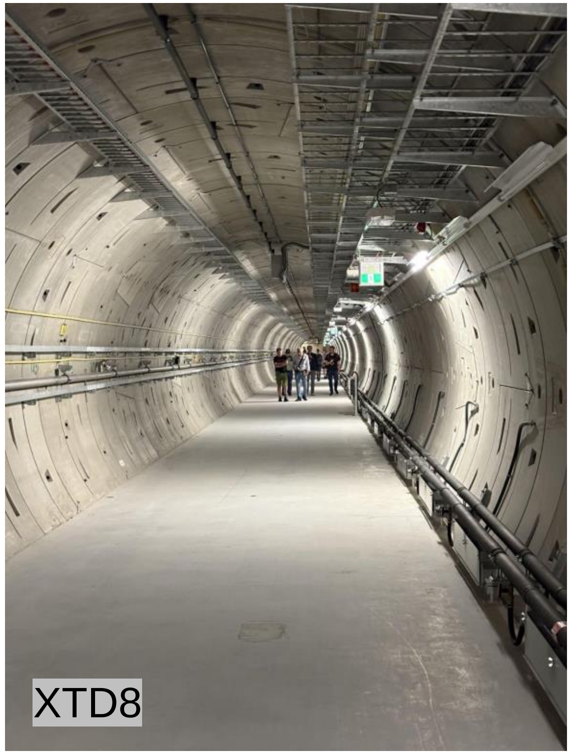
- ELBEX goal: prepare beamline to extract 16.5 GeV EuXFEL electron beam for users
- Horizon Europe project (4.3M€, 2025 -2029): DESY, EuXFEL, IFIC Valencia, INFN Padova, University of Manchester

New site for ELBEX:

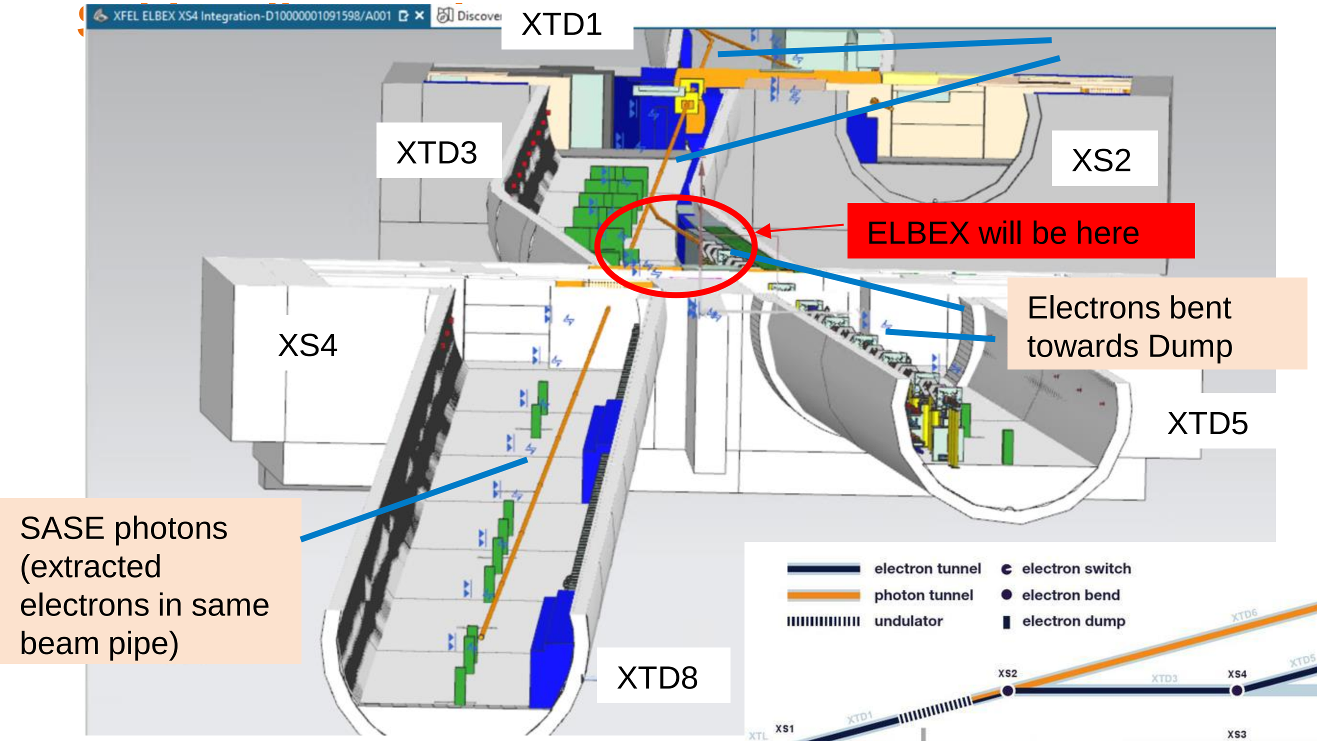
- Opportunity: ELBEX in XTD8 tunnel, co-use with planned EuXFEL fusion facility
  - tunnel separately interlocked
    → no extended shutdown for installation, frequent access
  - more longitudinal space than old site XS1
    → multi-user facility
  - plans for fusion project still developing
    → closely coordinating with EuXFEL

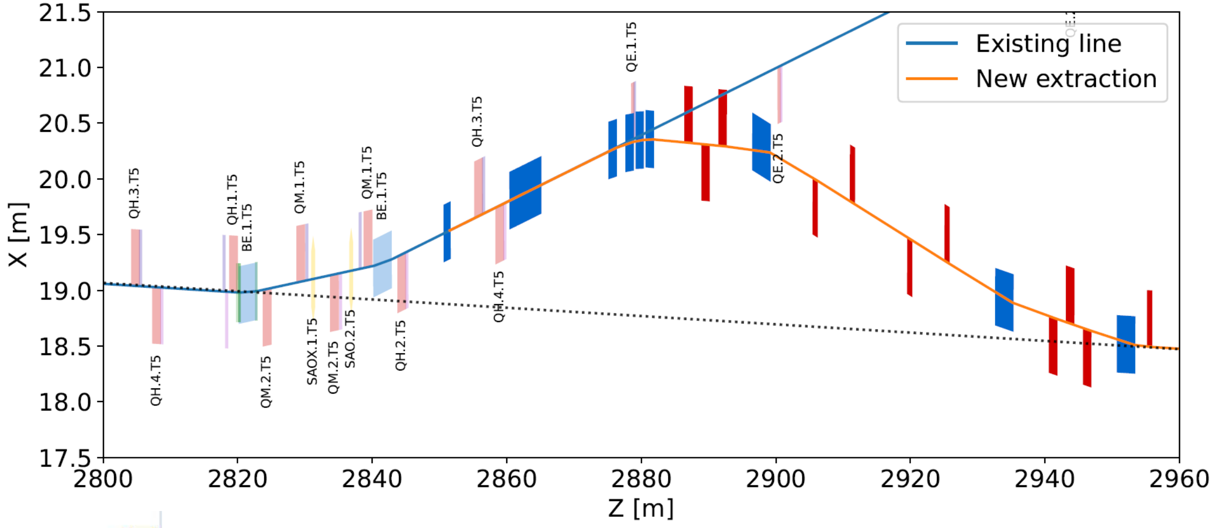


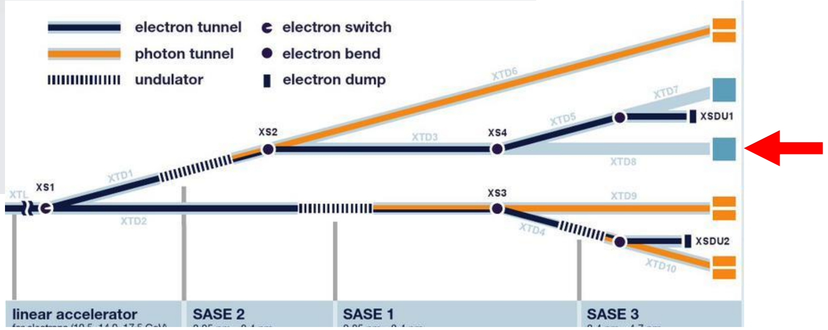

XTD3 near ELBEX branch-off


XTD8

ELBEX extraction beamline design

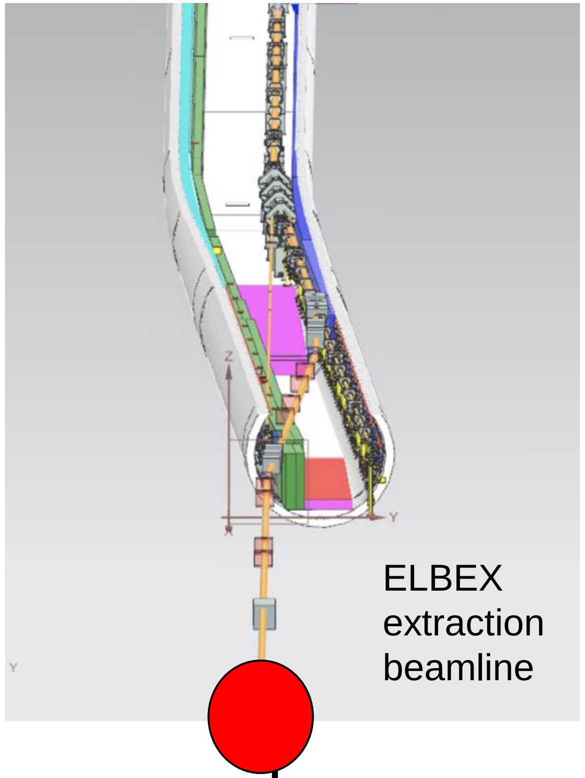


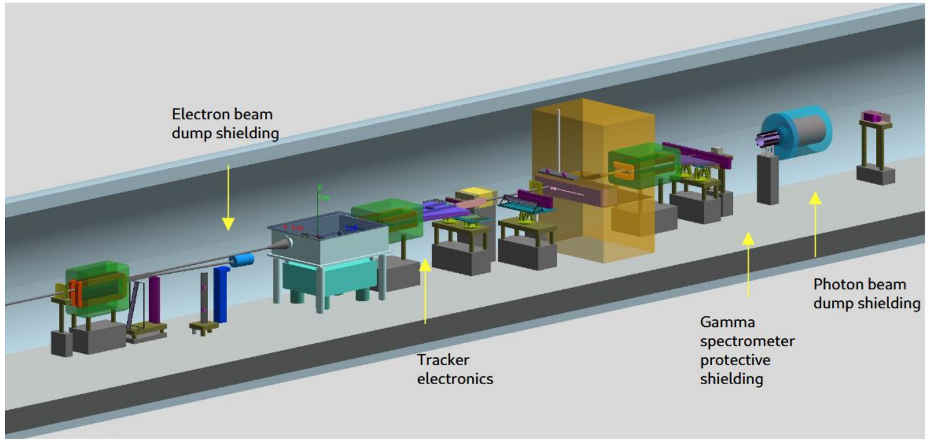




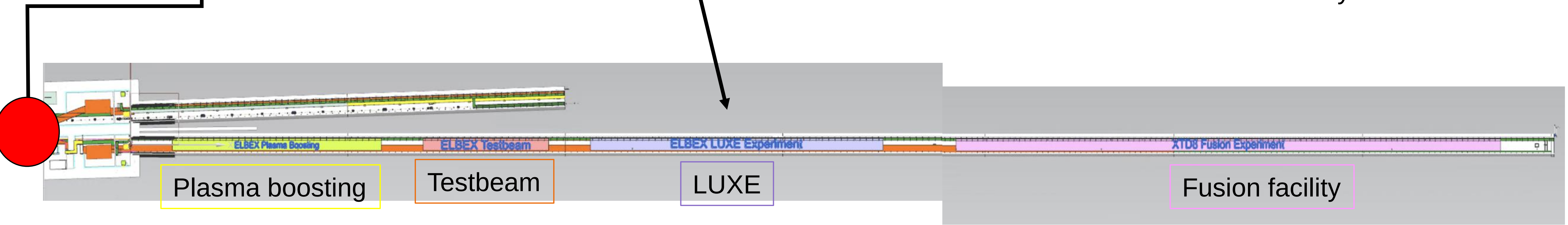
- Challenge: ELBEX electrons share beam pipe with SASE2 x-rays from mirror at XTD1 to fusion area
  → ELBEX extraction beamline: dogleg double bend from XTD3 into XTD8
- Matched lattice design achieved, optimization ongoing
  → goal: 10µm spot size at IP

ELBEX beamline and users status





LUXE



ELBEX beamline:

- Design effort for beamline in new XTD8 location → aim for CDR end of year
- Developing XTD8 safety and space usage concept → joint task force with EuXFEL

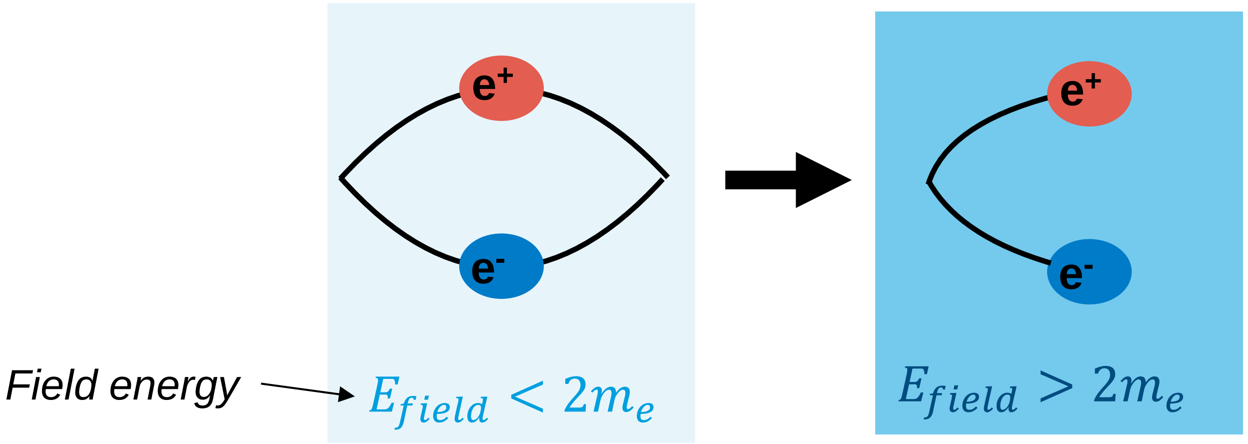
ELBEX users:

- LUXE: strong-field QED and long-lived particles search (this talk)
- Plasma: joint effort from FH and M to explore use of ELBEX for beam-driven energy doubling
- Testbeam: crystal-based extraction of GeV electrons for test beam facility

Strong-Field QED (SF-QED)

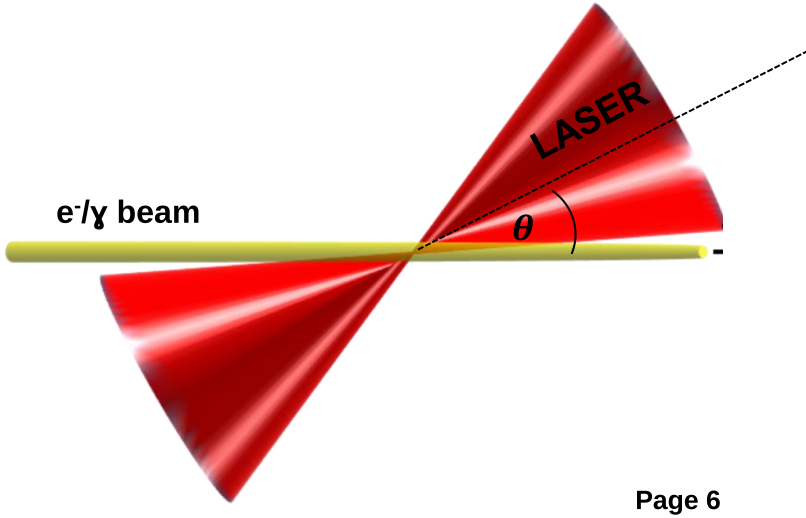
SFQED Review paper: A. Fedotov et al, 2203.00019 [arXiv:hep-ph]

- QED is one of the most well-tested theories in physics → based on perturbative calculations
- LUXE: QED in non-perturbative strong-field regime
- Schwinger critical field: $\mathcal{E}_{cr} = \frac{m_e^2 c^3}{e\hbar}$ (e.g. for electrical field: $\mathcal{E}_{cr} = 1.32 \cdot 10^{18}\, V/m$)

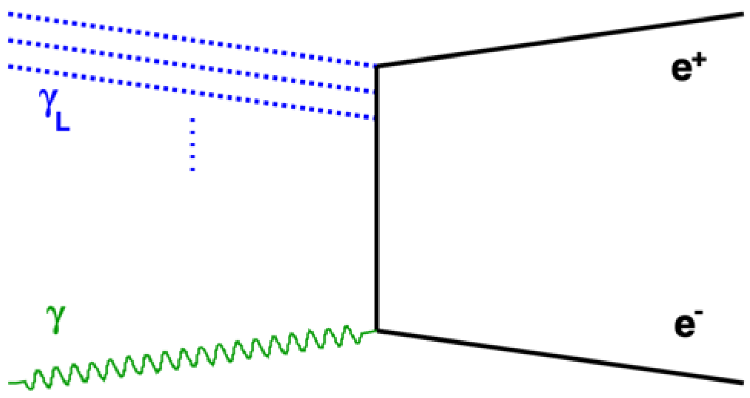


- Schwinger effect: creation of e^+e^- pair from vacuum in constant field
  → unobservable: existing constant fields $\ll \mathcal{E}_{cr}$

LUXE: relativistic probe particles (e,γ) colliding with laser
→ fields $\mathcal{O}(\mathcal{E}_{cr})$ in particle rest frame!

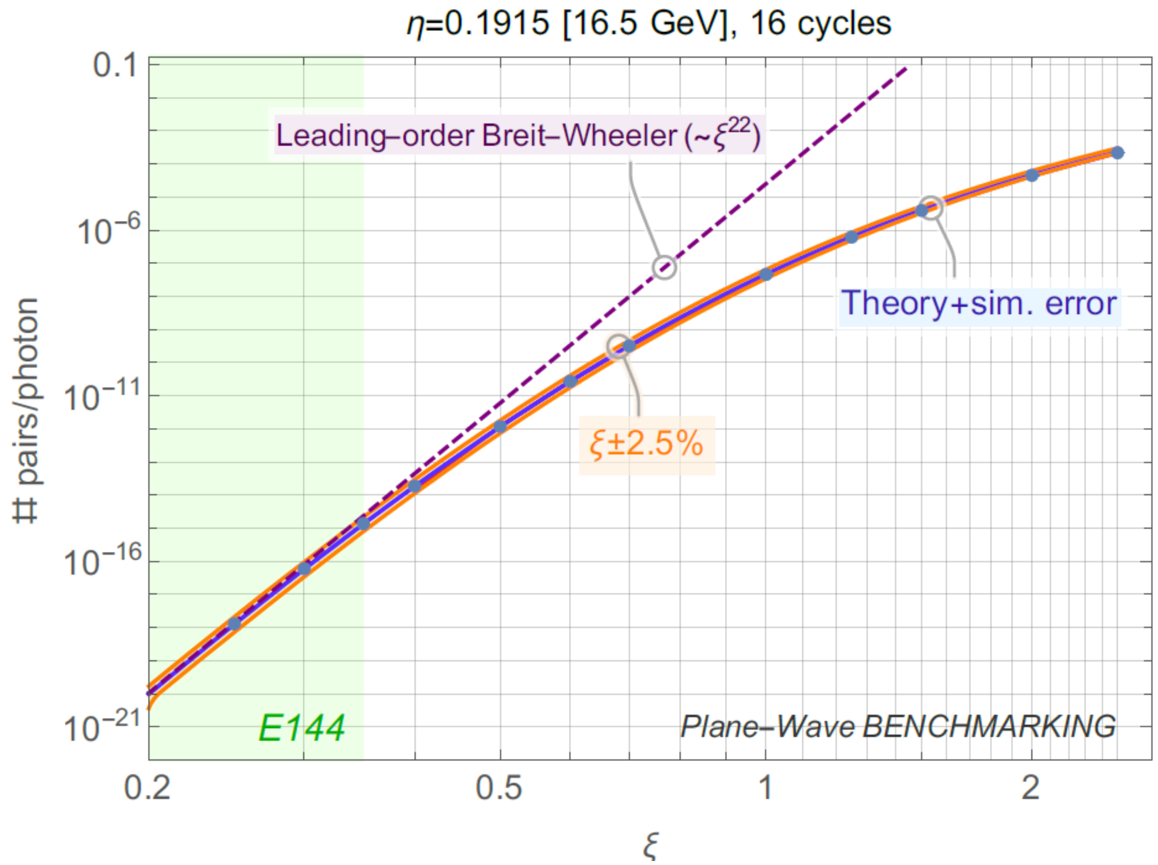


Breit-Wheeler pair production



(non-linear) Breit-Wheeler pair production

$\gamma_{C/sec} + n\gamma_L \rightarrow e^+ + e^-$



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

Perturbative regime
→ power law

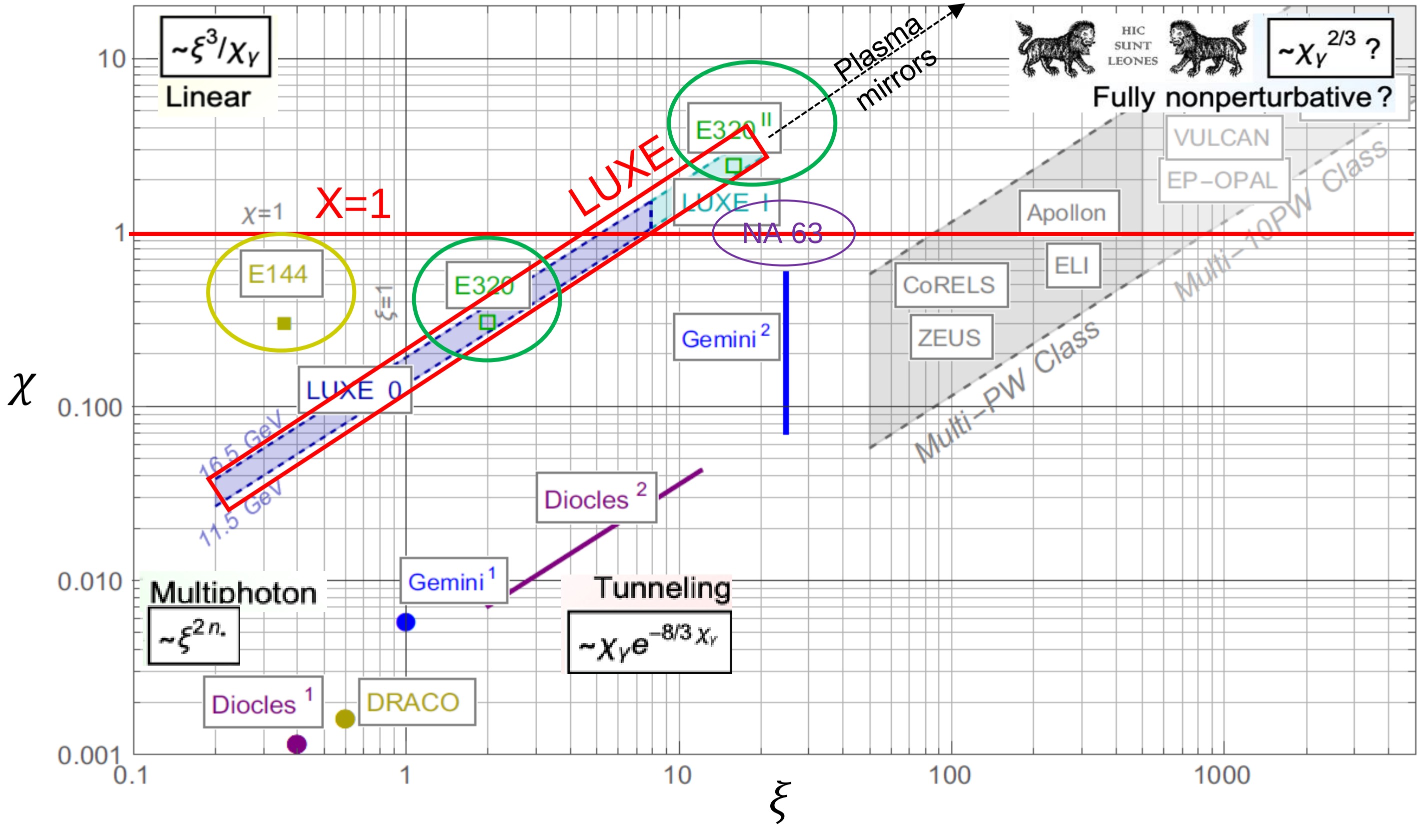
Intensity parameter
(classical)

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

Non-perturbative regime
→ departure from power law ("tunneling")

Intensity parameter
(quantum)

LUXE in SF-QED Parameter Space



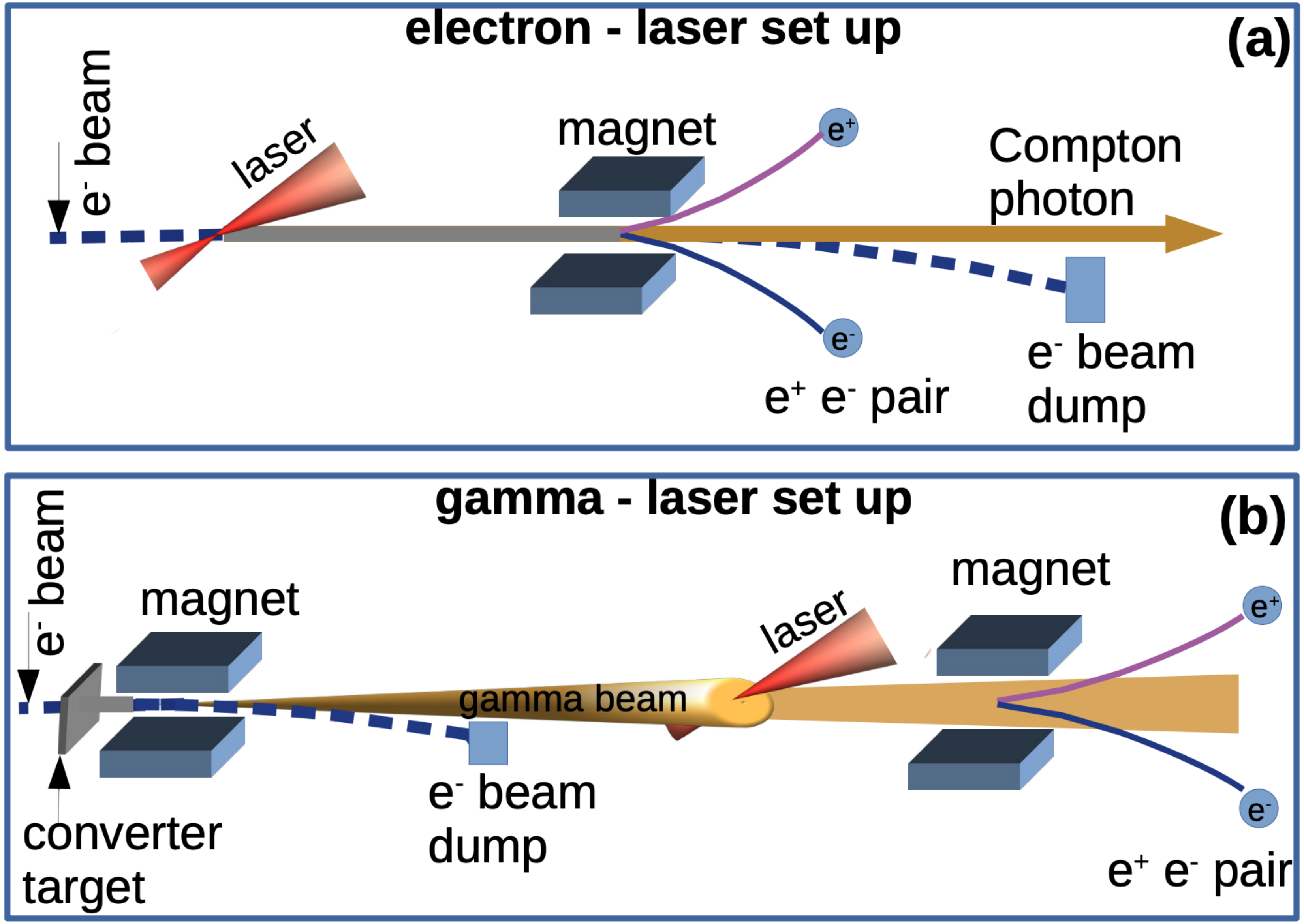
10.1103/PhysRevD.108.052013
NA63 (CERN, Solid-state target)

Phys. Rev. D 60 (1999) 092004
E144 (SLAC, e-laser)

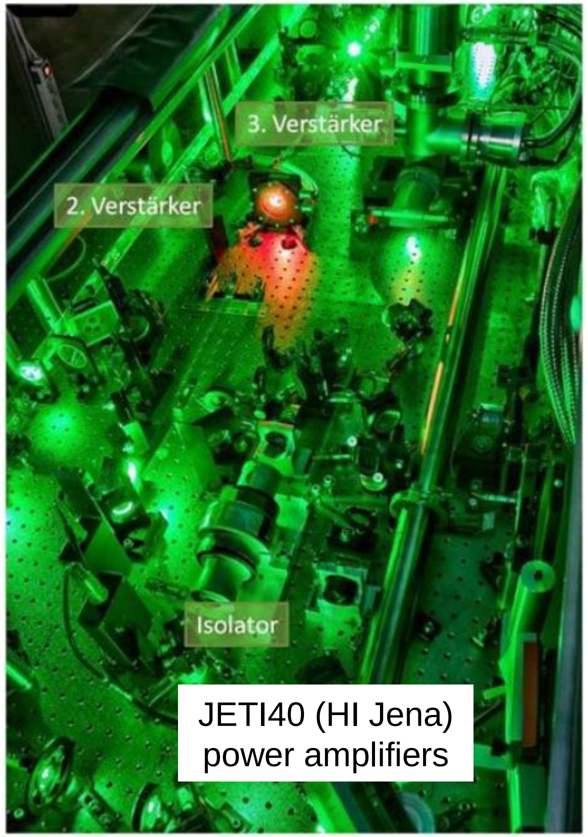
HILAS-2022-HF4B.6
E320 (SLAC, e-laser)

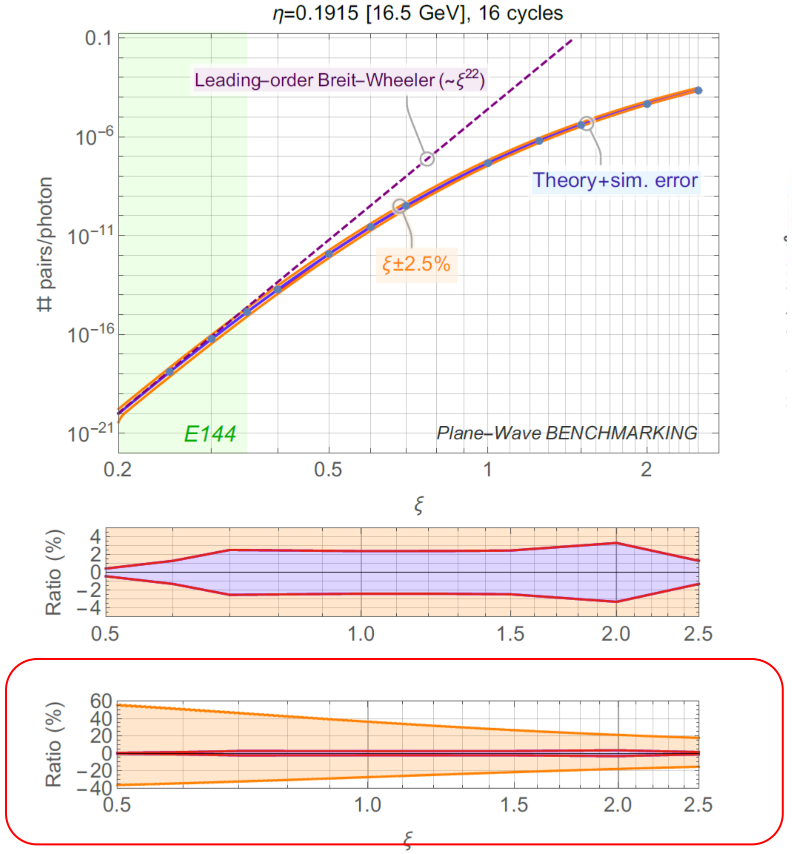
- LUXE reach in SF-QED parameter space (ξ, χ) driven by beam energy, laser intensity
  → transition between perturbative and non-perturbative QED
- LUXE unique ability: high-statistics datasets with variable laser spot size
  → precision mapping of SF-QED parameter space
  → confront SF-QED theory predictions with precision data

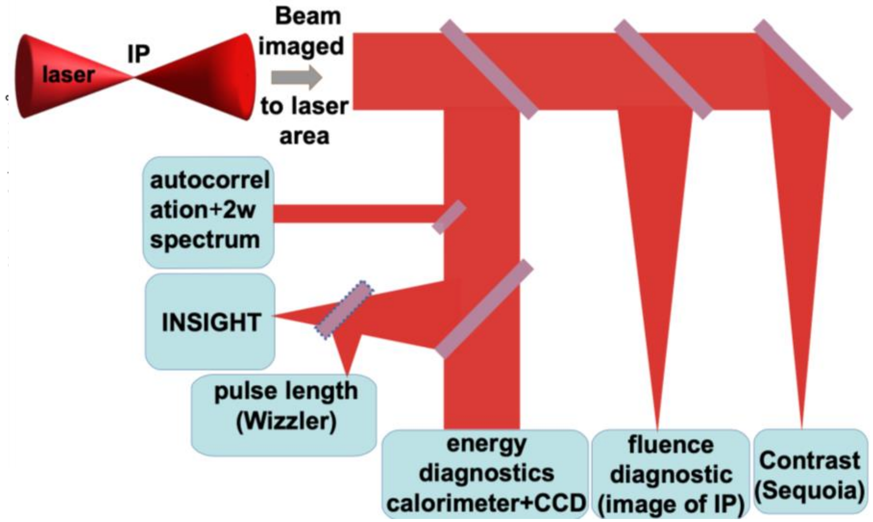
LUXE experimental setup(s)



The LUXE laser & diagnostics

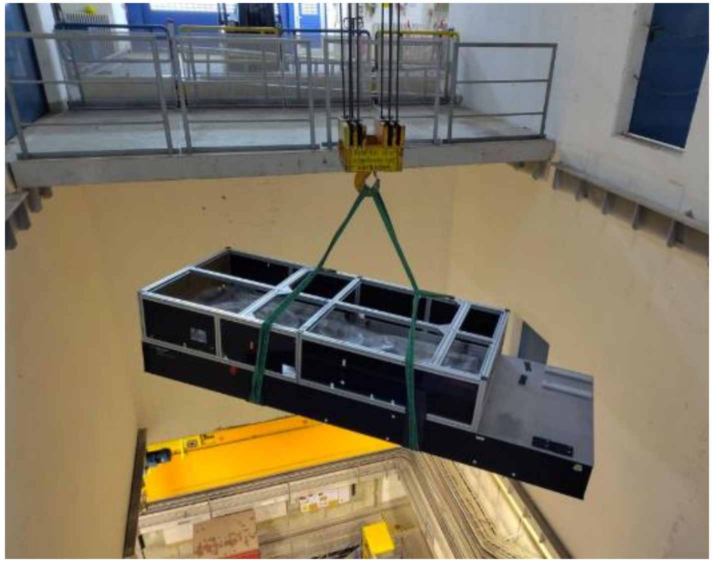






- LUXE laser: TiSa (40TW, upgradeable to 350TW)
- electron boost: current state-of-the-art in laser intensity is sufficient
  → require exceptional shot-by-shot stability (≲1%)
- laser intensity uncertainty has a large impact on sensitivity → high-precision diagnostics

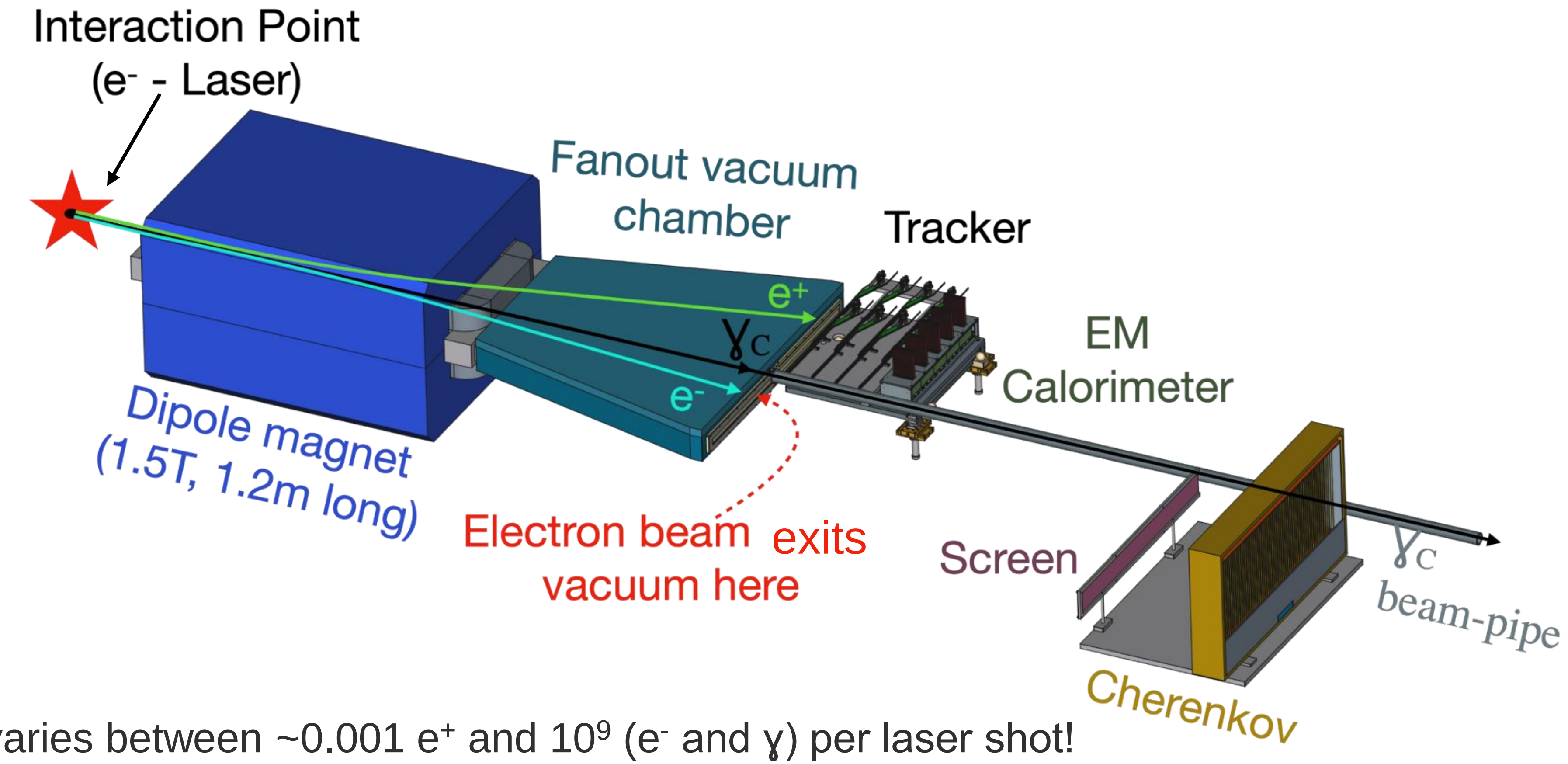
JETI40 laser at DESY



- JETI40 (now 10 TW) laser transported from FSU Jena to DESY May 2025
- Setting up clean room in HERA West.
- Aim to have laser operating early next year and maintain
- Opportunity for laser experiments, discussion ongoing
- Potential commissioning laser system for LUXE
- Laser technical and safety team in place

Thanks to the many people who made this possible

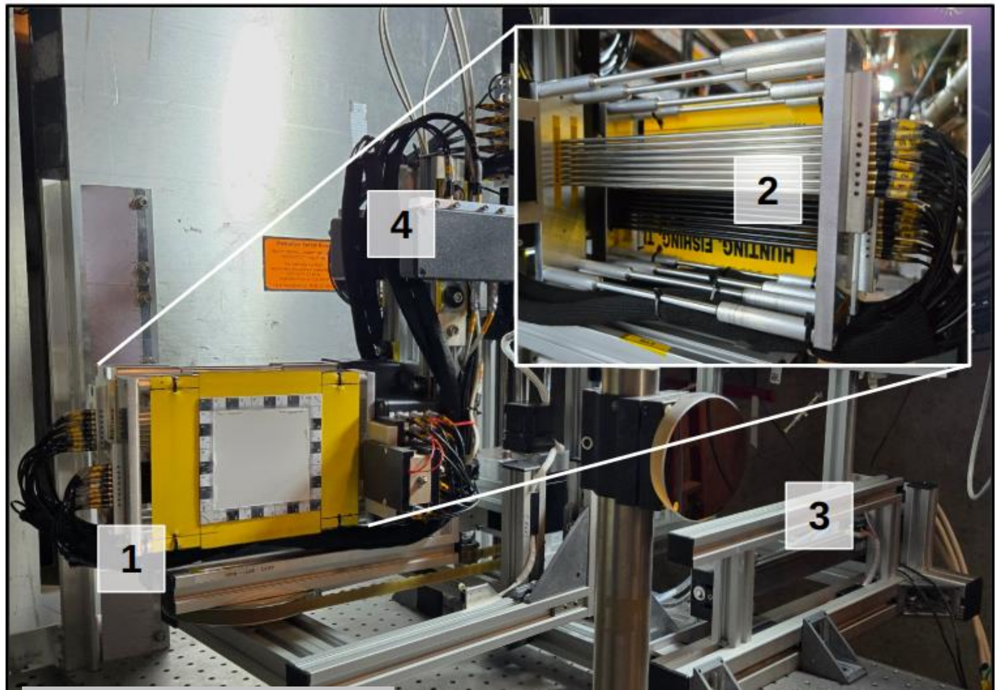
LUXE IP Detectors



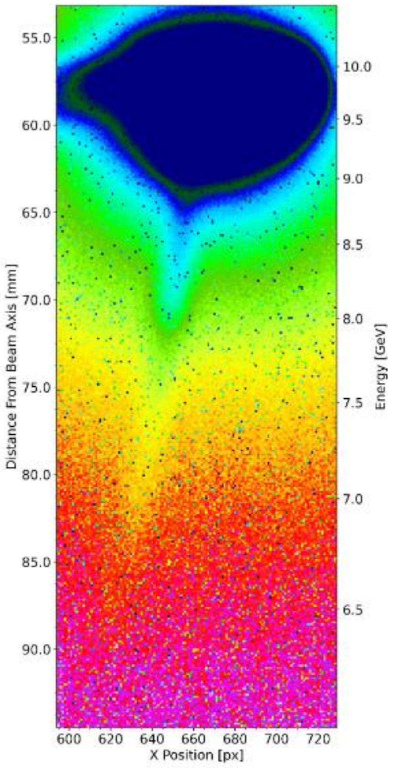
- Particle flux varies between ~0.001 e^+ and 10^9 (e^- and γ) per laser shot!
- LUXE detector technologies adapted to signal and background flux
  → baseline defined, but rich opportunities for further upgrades
- Testbed for detectors (e.g. pixel tracker, high granularity calorimetry) + software (e.g. key4hep, ACTS,…) for future colliders

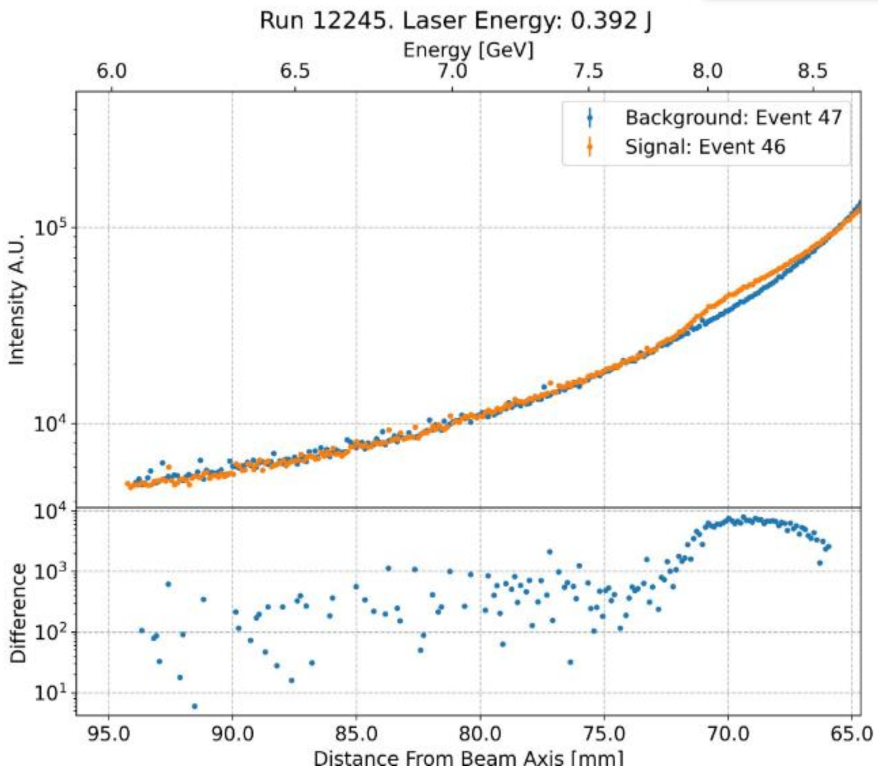
UCL, DESY

LUXE electron detectors at E-320



1 Scintillator screen
2 Cherenkov straw detector
3 Translation frame
4 LED calibration box

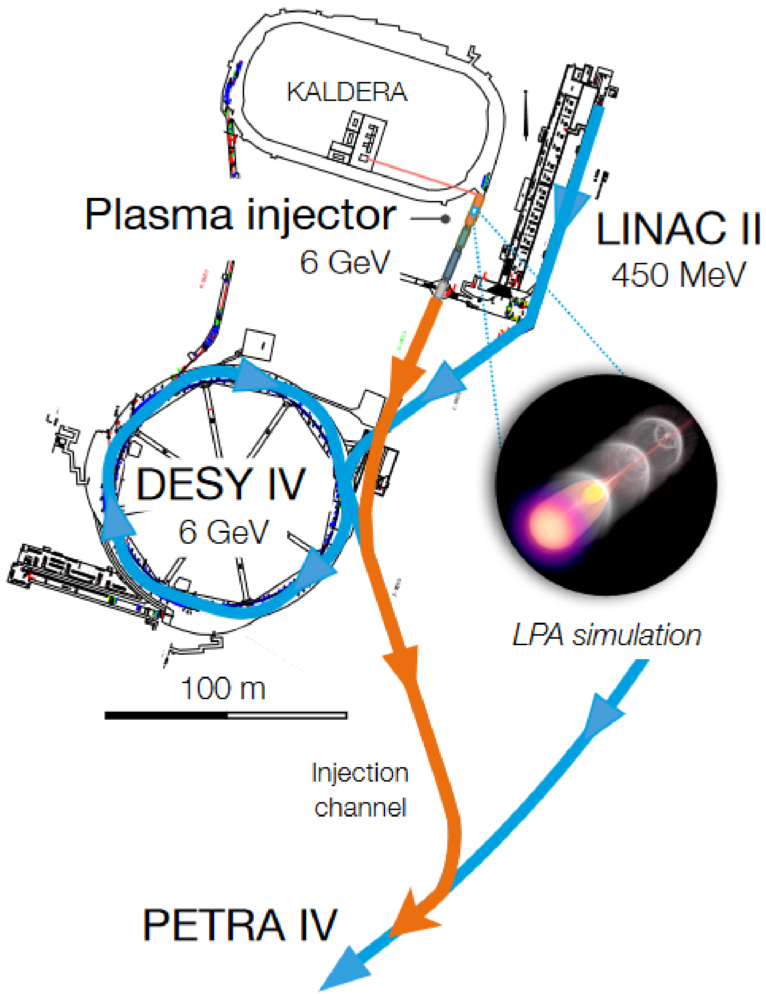


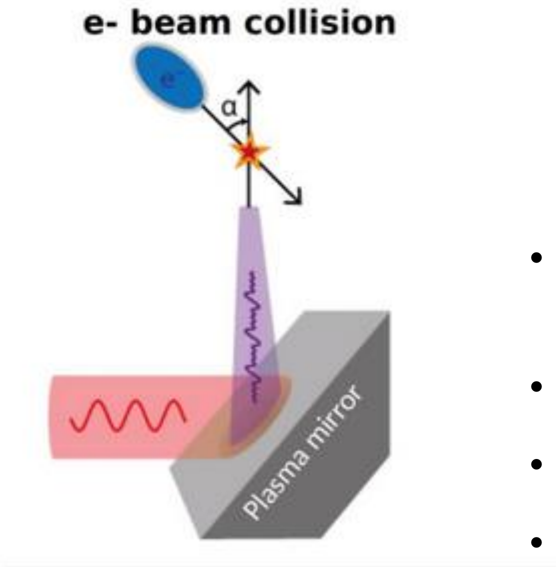


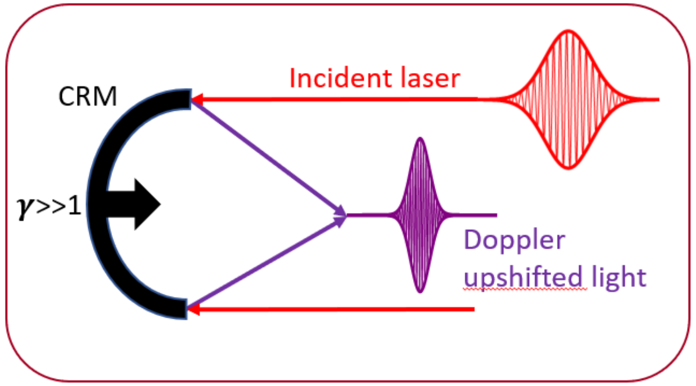
- LUXE high-rate electron detection system (Scintillator + camera and Cherenkov straw tube detector)
- DESY + UCL team performed combined test campaign at E-320 (FACET-ii, SLAC)
- Collisions between 10GeV electron beam and 10TW laser (ξ~1…5)
- Edge from non-linear Compton scattering visible in scintillator screen data

SFQED on the DESY campus

NP-QED/LUPE - Laser Und Plasma Experiment





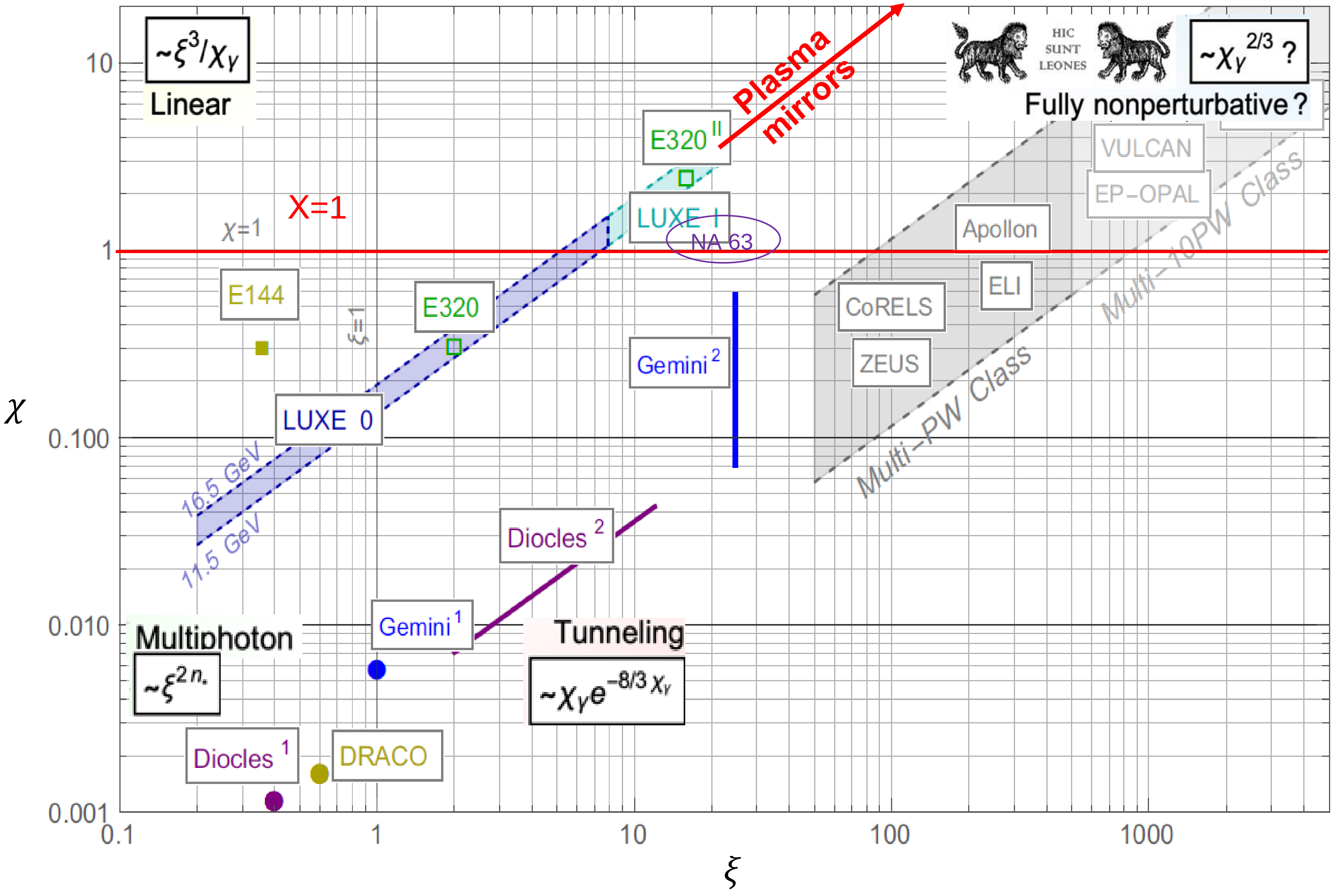


- LUPE concept: e-laser collisions with Plasma-boosted laser and LPA electron beam
- Laser: 100TW system boosted by Plasma mirrors
- e-beam: 6 GeV Plasma injector for Petra IV
- reach fully non-perturbative regime χ~50 in SFQED phase space

DESY PIs: J.List, A. Maier

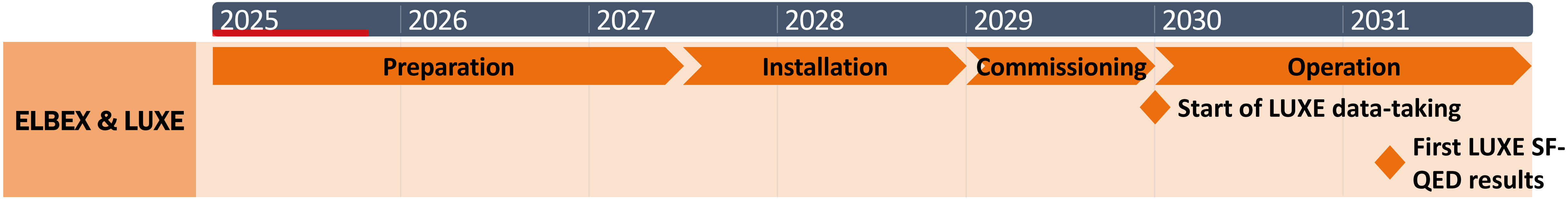
NEW Opportunity:
NP-QED ERC Synergy Grant approved

LUPE in SF-QED Parameter Space



Summary

- ELBEX: New high-energy electron beam = new on-site opportunities for particle physics at DESY
- LUXE: SF-QED precision experiment to confront theory with data in transition regime (+ long-lived particle search)
- New site XTD8 is a game changer for ELBEX and LUXE
- ELBEX and LUXE strongly rely on German expertise
- Schedule: ELBEX commissioning 2029, start of LUXE operation 2030, first SF-QED results 2031
  → could come online during next ErUM-Pro funding period
- Recent boost for SFQED at DESY with successful ERC Synergy Grant NP-QED



Opportunities for contributions (Detector upgrades, Software,…) linked to ErUM-Pro projects

Interested? Join us!

Thank you

Contact

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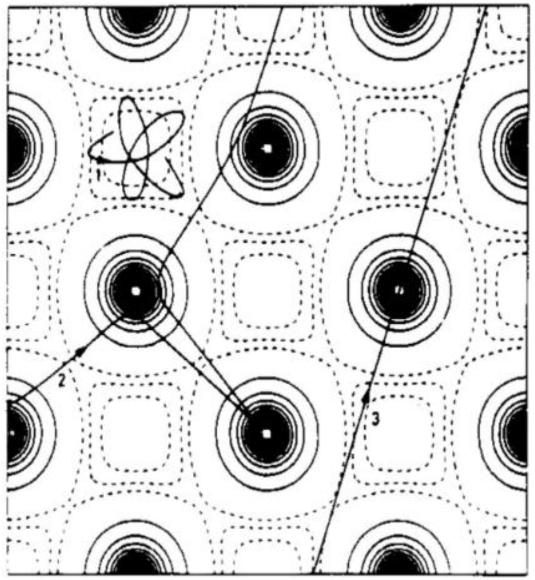
Backup

Creating strong fields in the laboratory

NA63: 10.1103/PhysRevD.108.052013

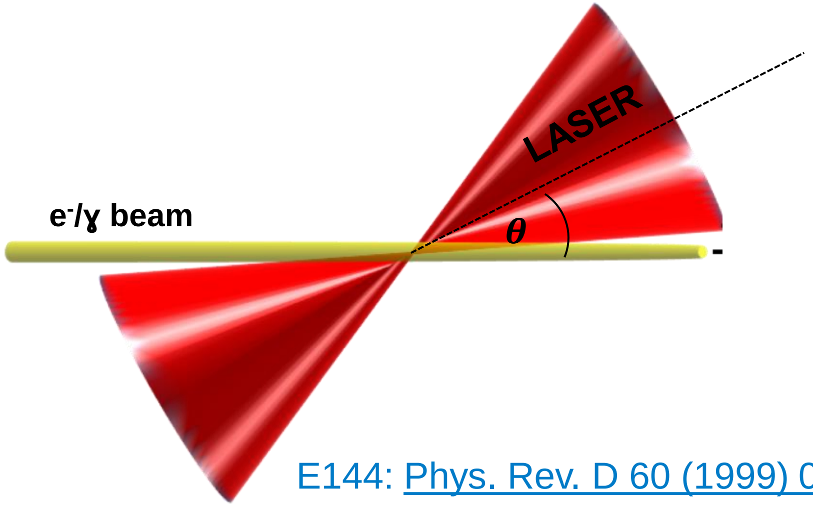


1) Solid state fixed-target experiments (e.g. NA63)

- Highly relativistic electrons impinging on crystalline target
- Crystal: EM field of ~10^{11} V/m
  → reach Schwinger limit in probe electron rest frame
- Observed multiple SF-QED processes at critical field

2) Laser – particle beam collisions (LUXE, E320, E144)

- High-intensity optical laser pulse colliding with GeV particle beam (e^-, γ)
- Lorentz-boosted EM field in particle rest frame: $\mathcal{E}^* = \gamma \mathcal{E}_L (1 + cos\theta)$
- Collisions with secondary GeV photon beam possible (LUXE)
- „Clean lab conditions“: no dependence on solid-state dynamics



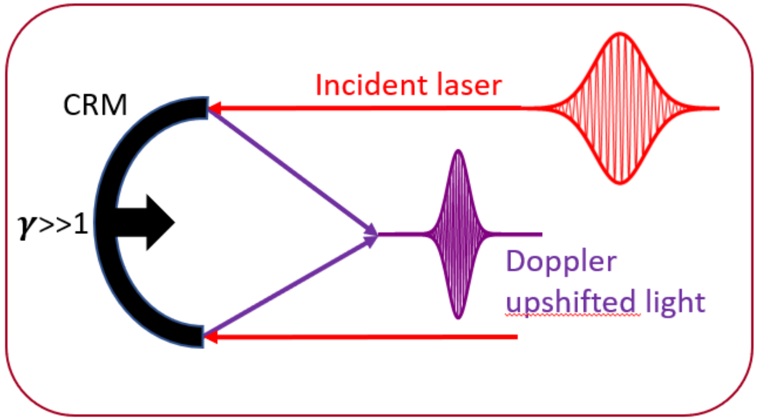
E144: Phys. Rev. D 60 (1999) 092004
E320: HILAS-2022-HF4B.6
LUXE: arXiv:2308.00515

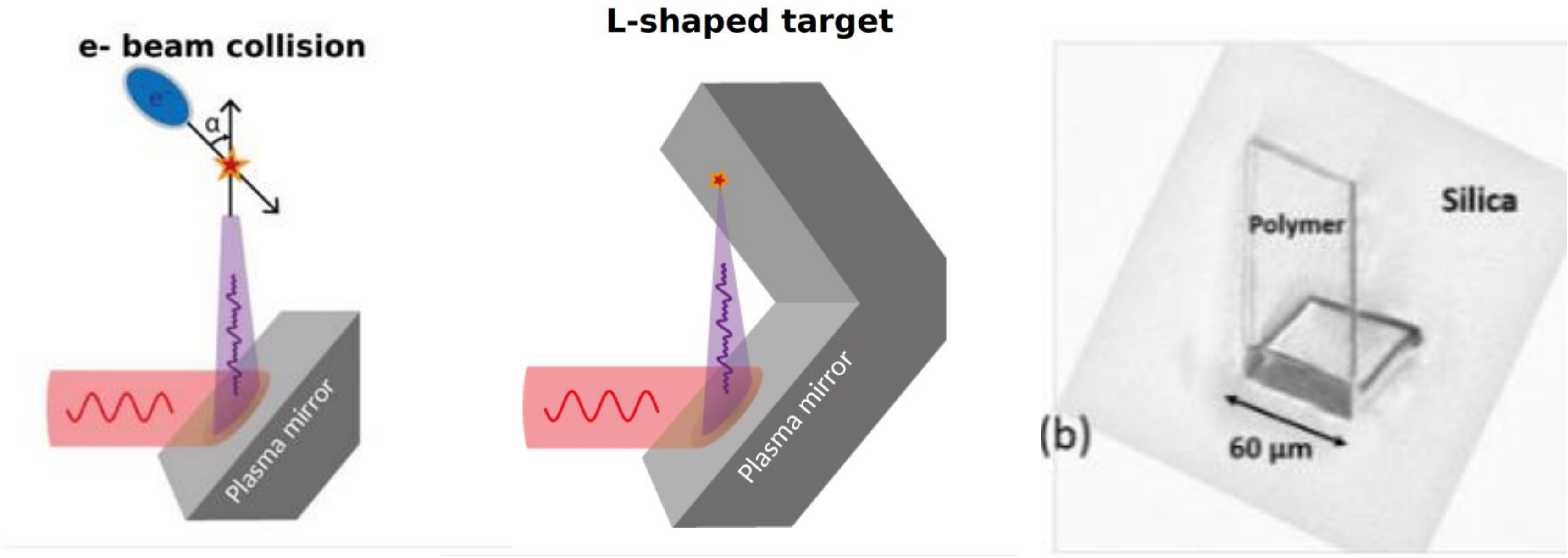
Creating strong fields in experiments

C. Thaury et al, Nat. Phys (2007)
Dromey et al, Nat. Phys (2009)

3) Relativistic curved mirrors

- Doppler-boosting Laser intensity using curved relativistic mirrors
- „Plasma mirrors“ ejected by impinging laser light on solid state taget
- solid-state fixed target experiment, or collision with particle beam
  → reach extreme regions of SF-QED phase space





Vincenti et al, Nat. Comm. (2014)
Fedeli et al, PRL (2021)

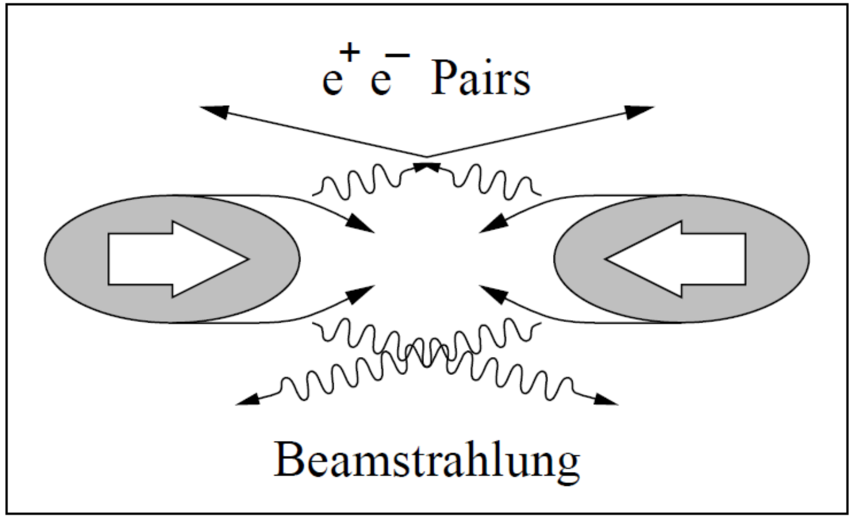
Source: Thesis A. Vogel (2008)

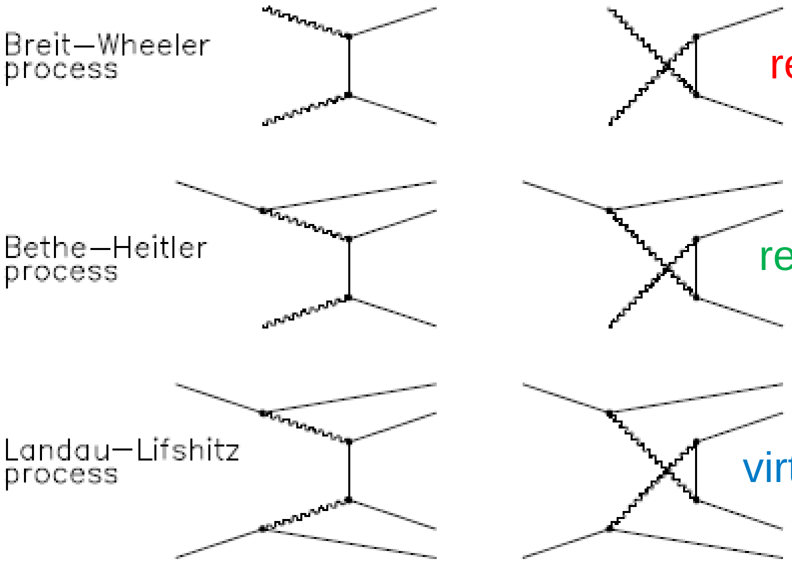
Creating strong fields in the laboratory

4) Beam-beam interactions (linear colliders)

- Schwinger critical field reached in collision of dense e+/e- bunches
  → aided by particle boost
- Pinch effect: - particles in one bunch deflected by strong field of the other
  - deflection → Beamstrahlung photons
  - scattering of photons → pair production

→ Luminosity enhancement, beam energy spread, detector backgrounds



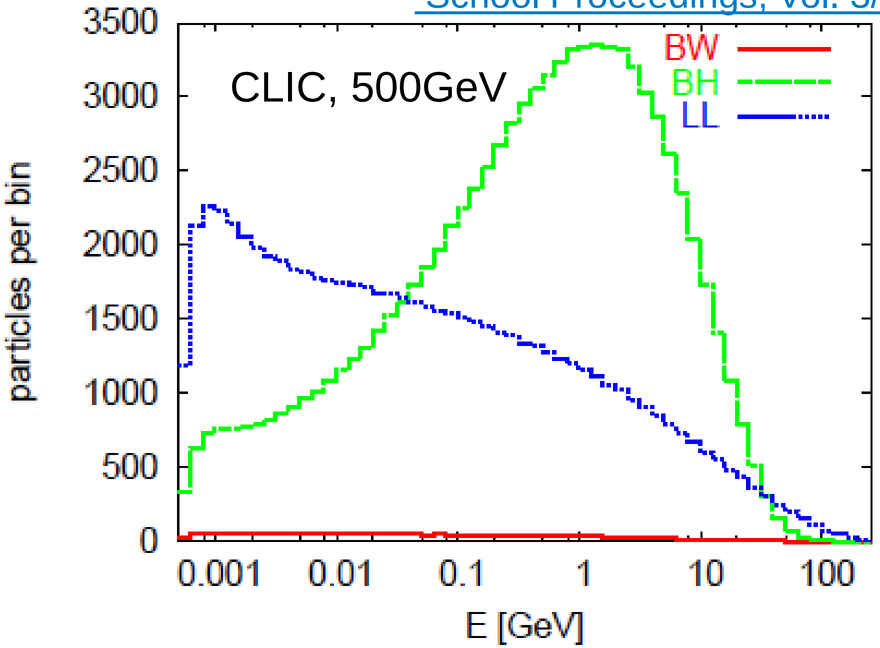


real + real (few %)

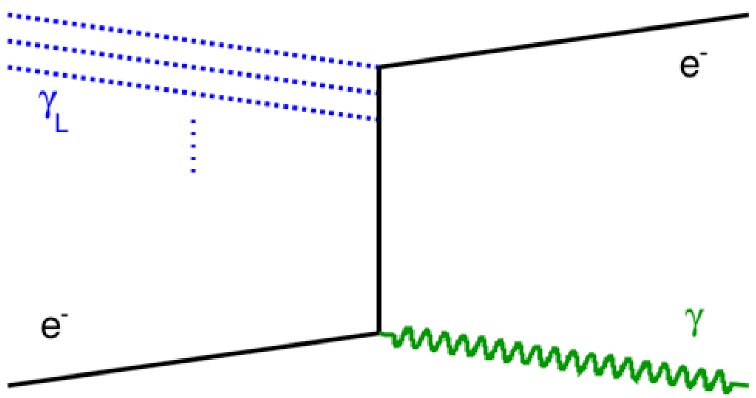
real + virtual (~1/3)

virtual + virtual (~2/3)

D. Schulte, CERN Yellow Reports: School Proceedings, Vol. 3/2017)

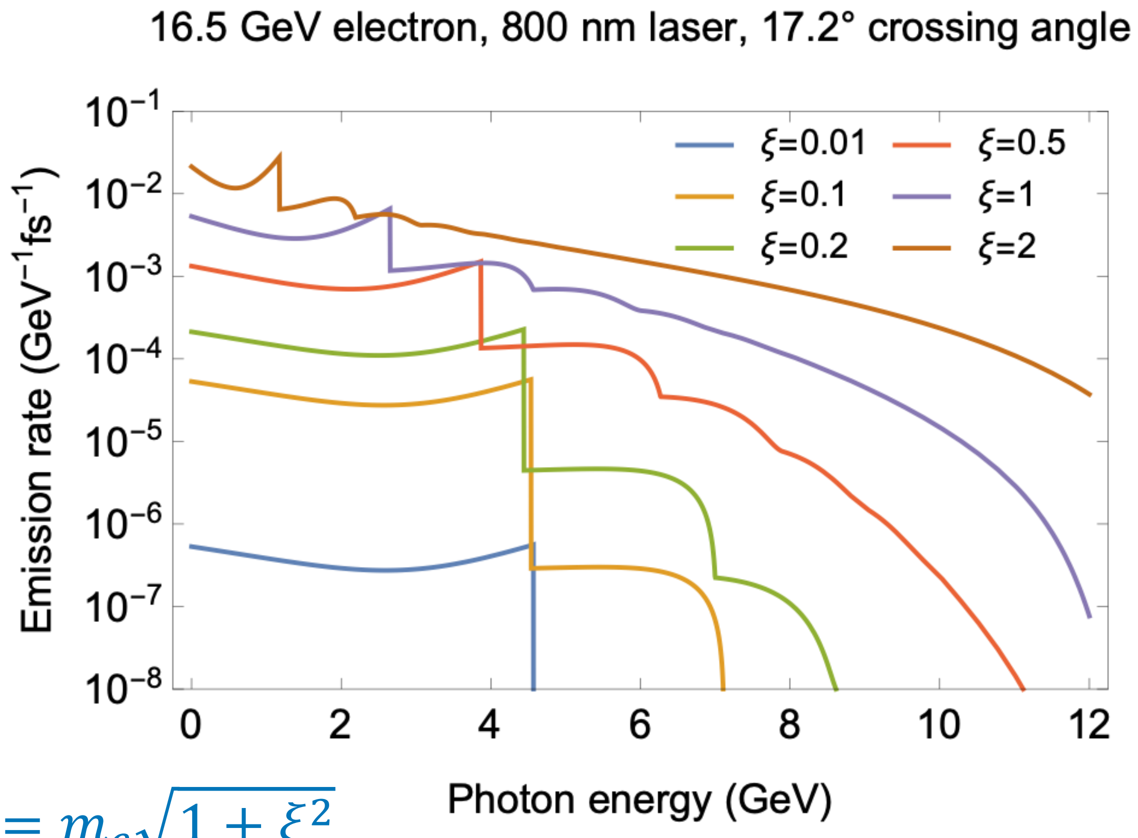


Non-linear Compton scattering



Non-linear Compton Scattering

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



- in strong fields, electron obtains larger effective mass $m_* = m_e\sqrt{1+\xi^2}$
  →Compton edge shifts with laser intensity parameter ξ
  →n-th order harmonics (interaction with n laser photons)

- Note: Non-linear Compton scattering has a classical limit
  → deviation between non-linear QED and non-linear classical Compton: quantum non-linearity parameter χ

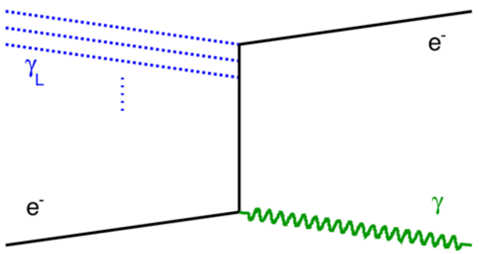
- Parameters ξ and χ determined by laser intensity and electron beam energy

Different combinations of ξ and χ result in different types of non-linear behavior!

Phys. Rev. D 106, 115034

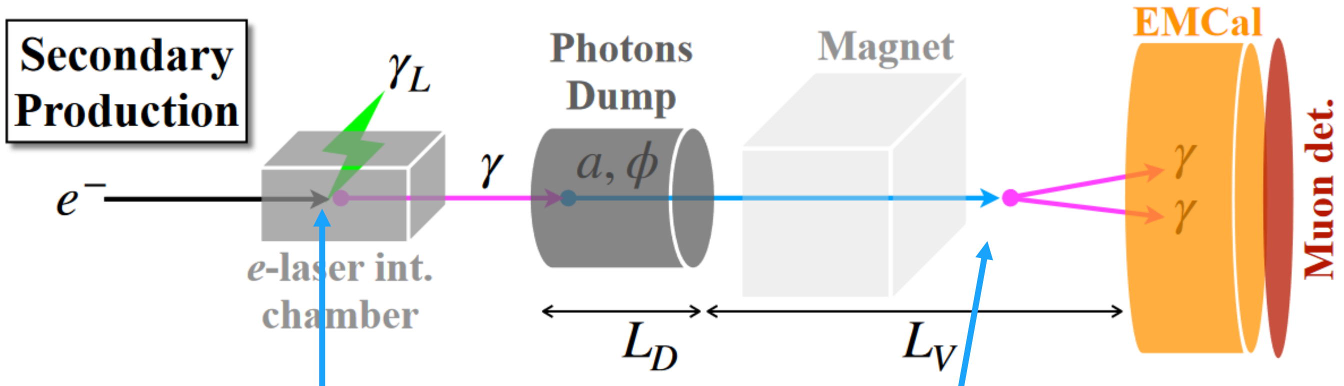
LUXE BSM Searches (LUXE-NPOD)

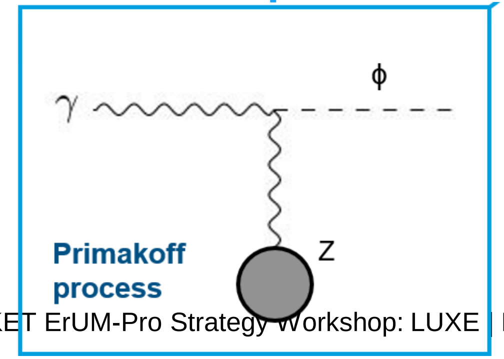
- LUXE will produce a high-intensity photon beam through Compton Scattering
  → produce e.g. axion-like (ALPs) in photon beam-dump
  → detect via new particle decay to two photons
- production of new particles also possible in primary electron/LASER interaction
- advantage of photon-on dump compared to electron-on dump: lower background
- conceptual design of photon detector with pointing capabilities ongoing
  → similar technologies applicable as e.g. in SHiP

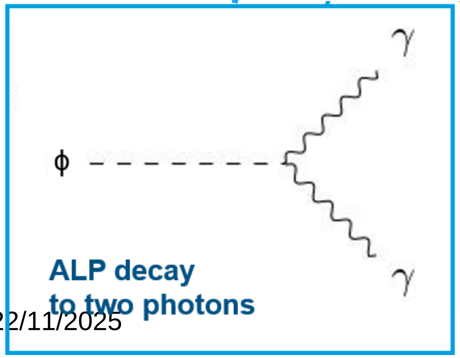


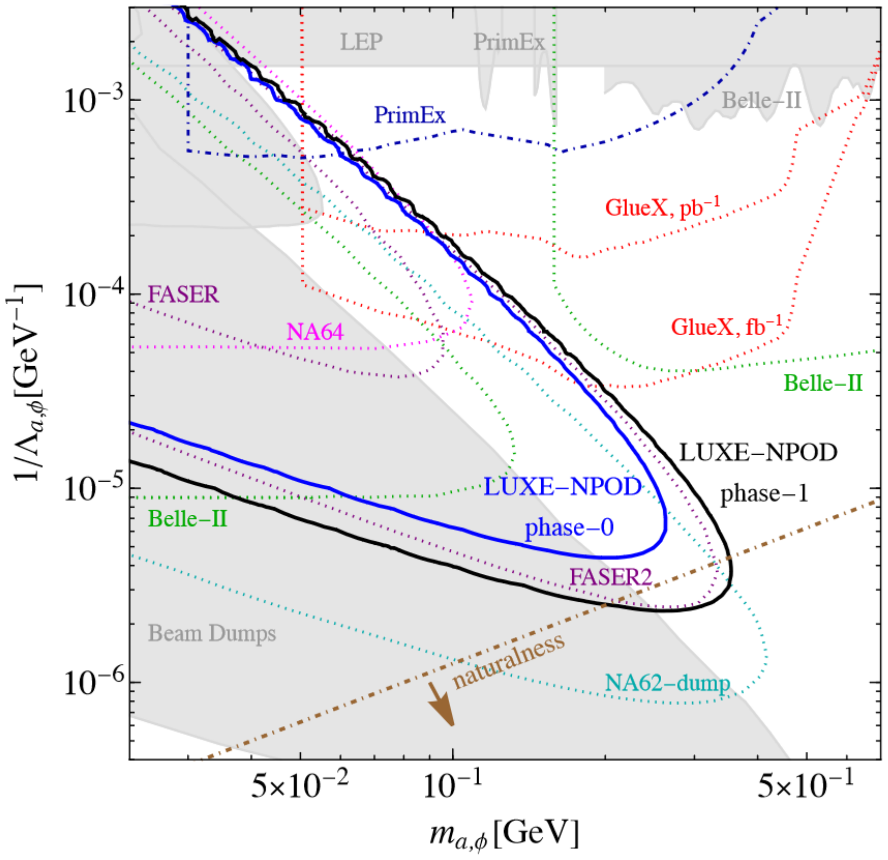
Non-linear Compton Scattering

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

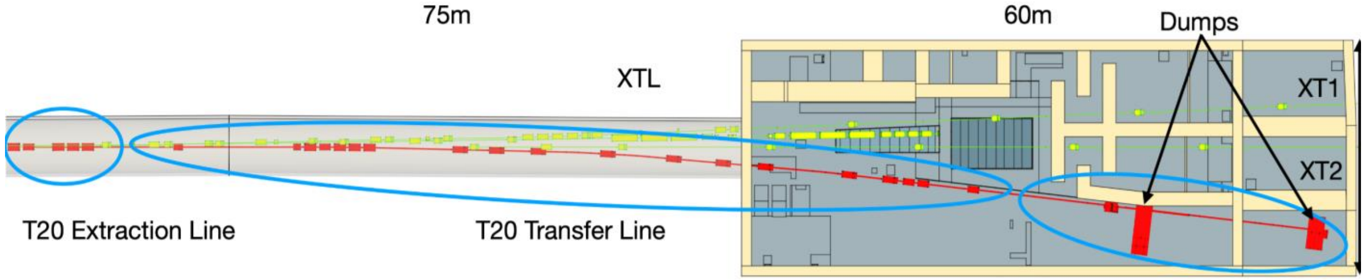


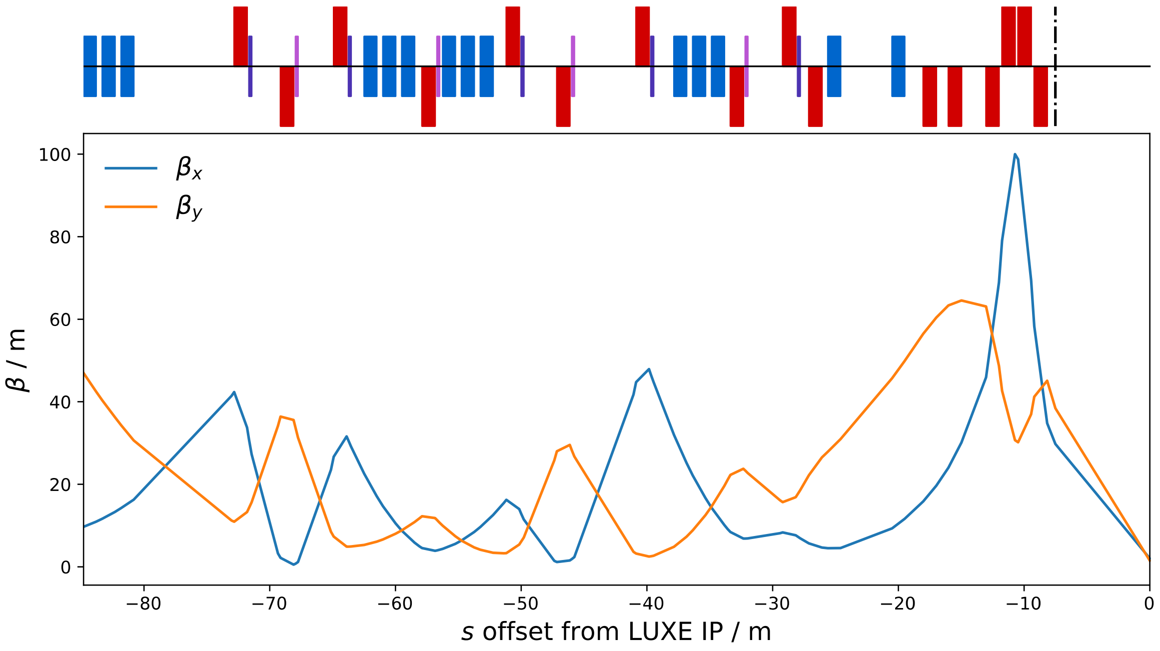


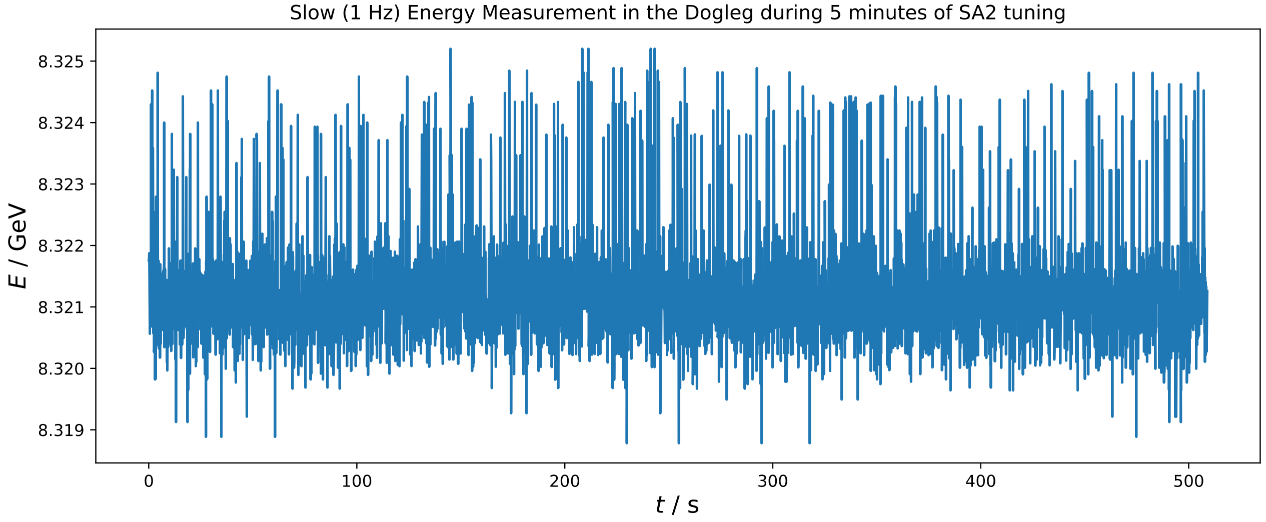




T20 electron beam extraction



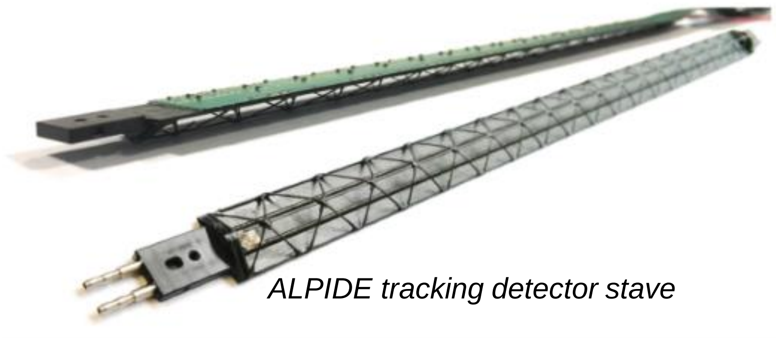


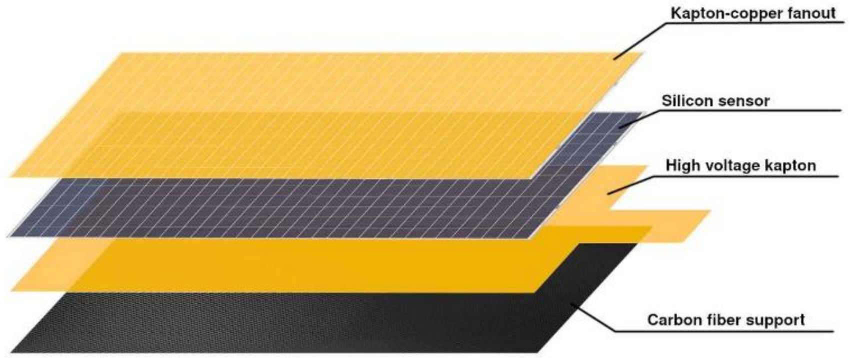


- Goal: kick out 1 bunch at angle -6.742° and transport to LUXE experimental area
- Lattice: Fast kicker magnet, Septa (asymmetric deflection magnets), Dipoles (deflection), Quadrupoles (focusing)
- Performance: - beam spot size: $\sigma_x = 9.3\mu\text{m}$, $\sigma_y = 8.1\mu\text{m}$
  - pulse size 130fs
  - jitter parameters (measured): - shot-to-shot position variation: $1\mu\text{m}$
    - time-of-arrival jitter: 20fs
    - energy variation: 0.01%

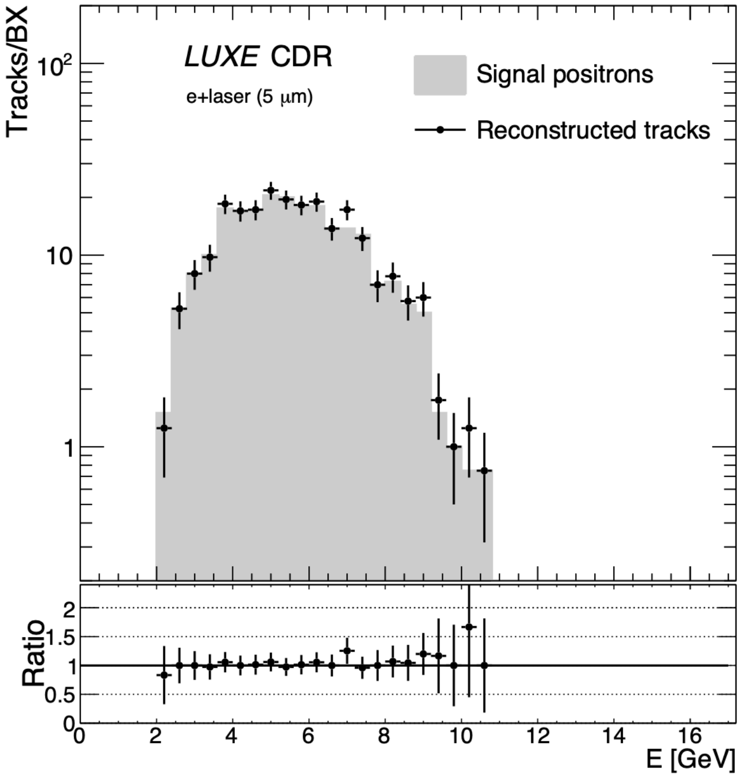
Beam properties after extraction line fulfil requirements for LUXE physics

Positron Detection System





High-granularity ECAL layer



Silicon Pixel Tracker:

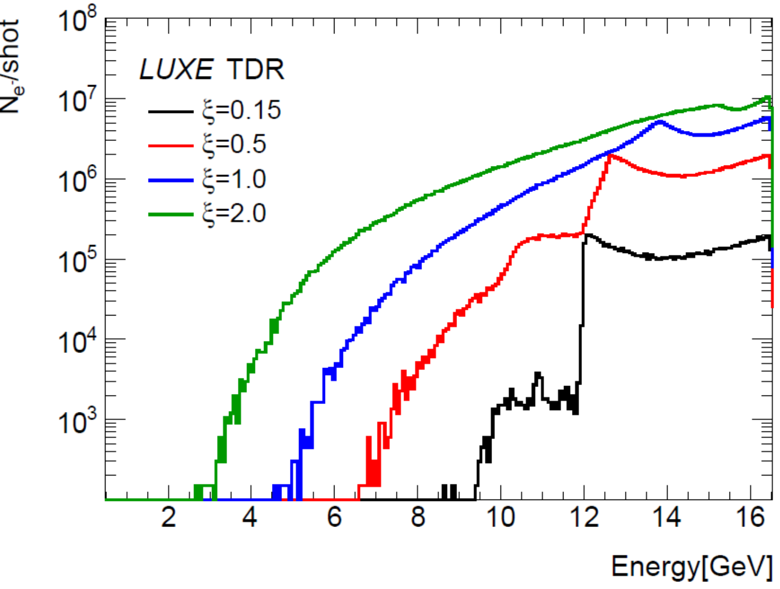
- four layers of ALPIDE silicon pixel sensors → developed for ALICE pixel tracker upgrade
- pitch size (27 x 29 μm), 5 μm resolution
- tracking: $\varepsilon > 98\%, \frac{\delta p}{p} \approx 0.3\%$
- very small background (<0.1 event / bunch crossing)

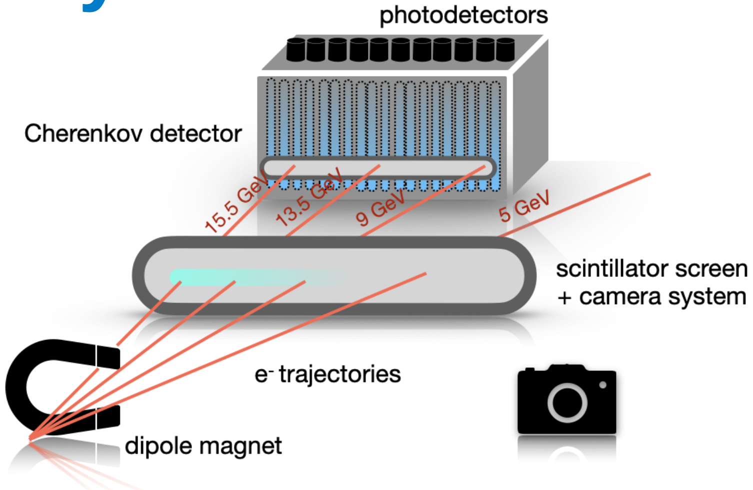
Si – W High-granularity Calorimeter:

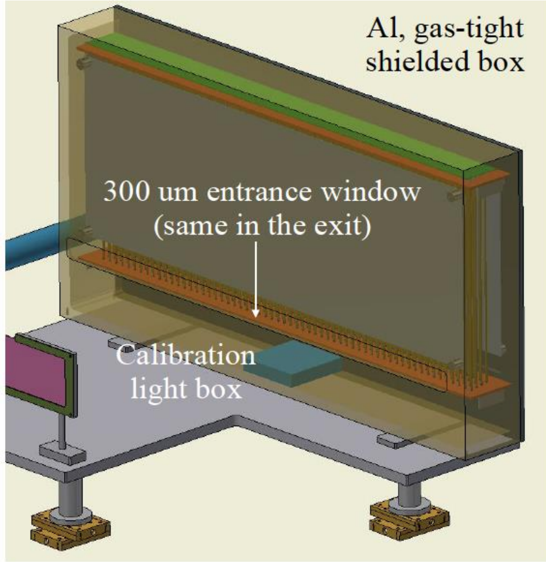
- 20-layer sampling calorimeter – high granularity: independent energy measurement through shower and position
- shower medium: 3.5mm Tungsten plates ($1X_0$), active medium: Silicon sensors ($5x5cm^2$, 320μm thick)
- read out by FLAME ASIC (developed for FCAL)

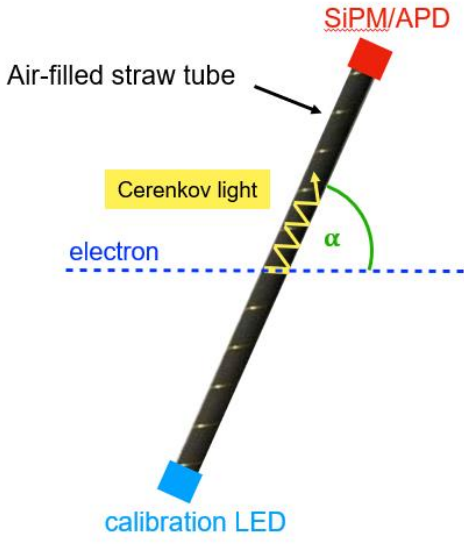
Positron detectors: High signal efficiency, high resolution!

Electron Detection System



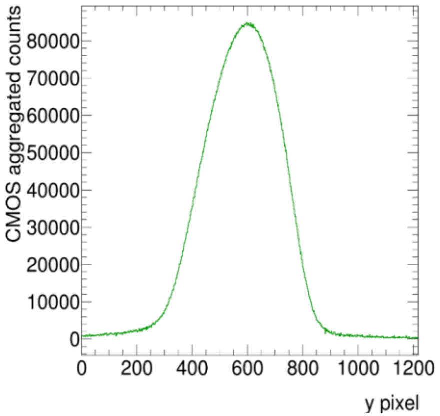


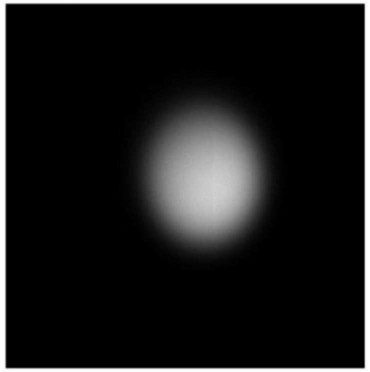




Scintillator screen (LANEX):

- camera takes pictures of scintillation light
- resolution of full system ~500μm





Beam spot imaged on Scint. Screen

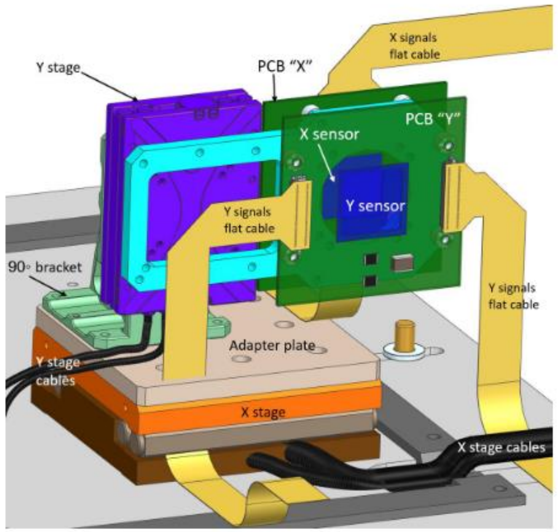
Straw prototype

Cerenkov detector:

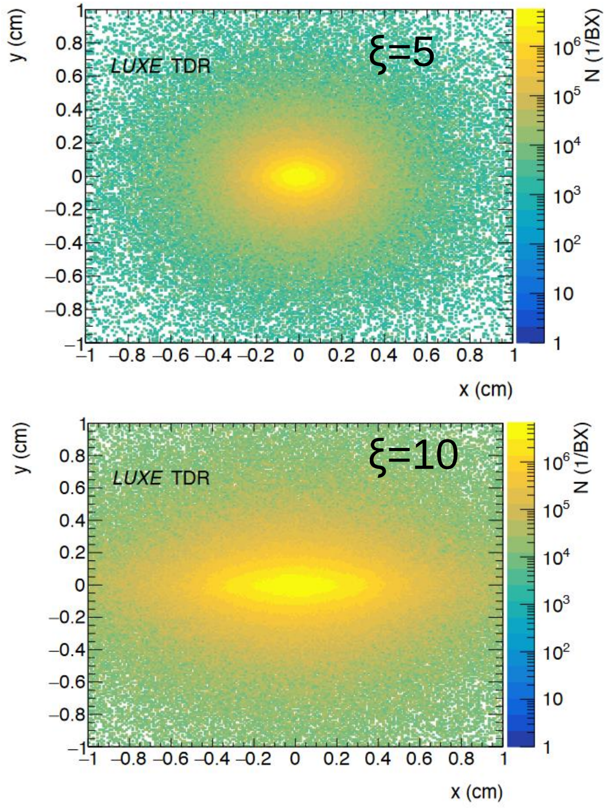
- finely segmented $(\emptyset = 4mm)$ Air-filled channel (reflective tubes as light guides) → charged particles create Cherenkov light
- Active medium Air: low refractive index - reduce light yield, suppress backgrounds (Cherenkov threshold 20 MeV)

Electron detectors: High rate tolerance, large dynamic range!

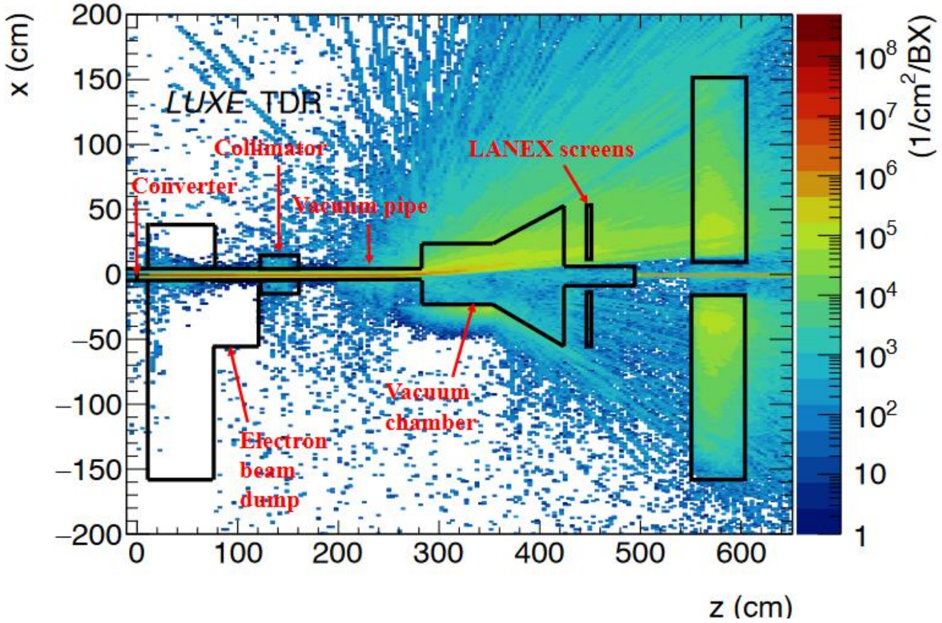
Photon Detection System

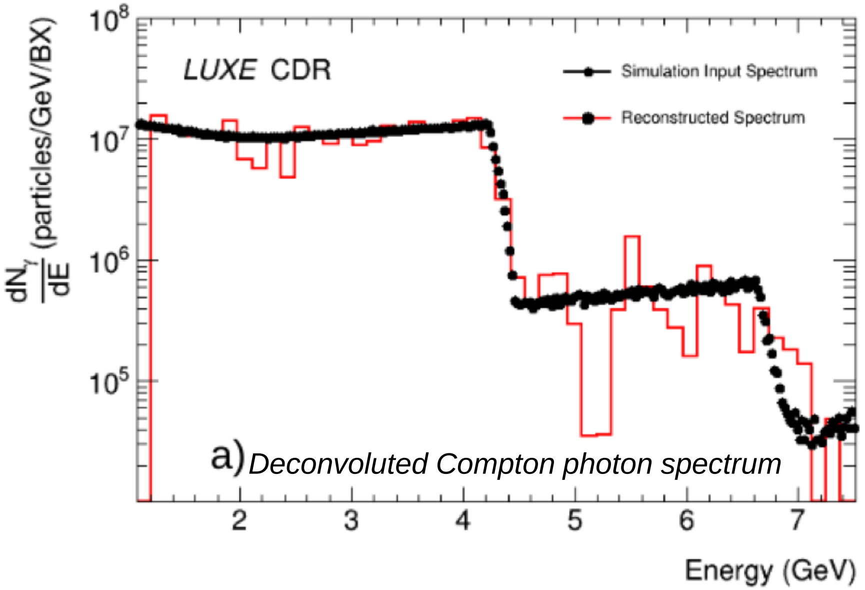


Gamma Beam Profiler



Electrons simulated in Gamma Spectrometer





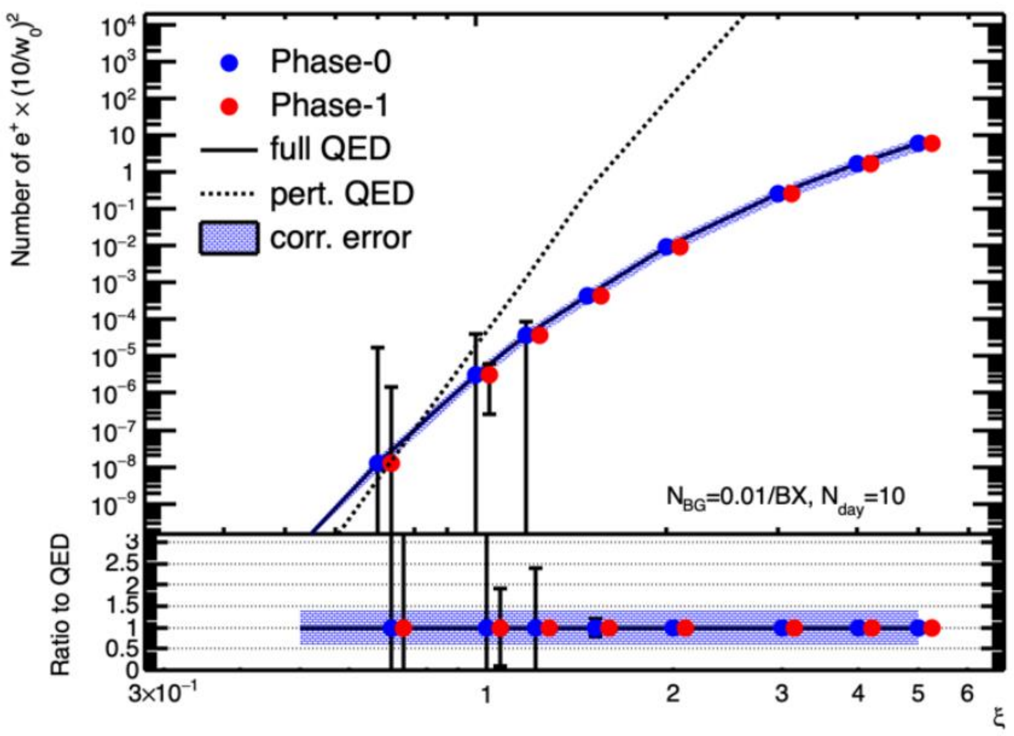
a) *Deconvoluted Compton photon spectrum*

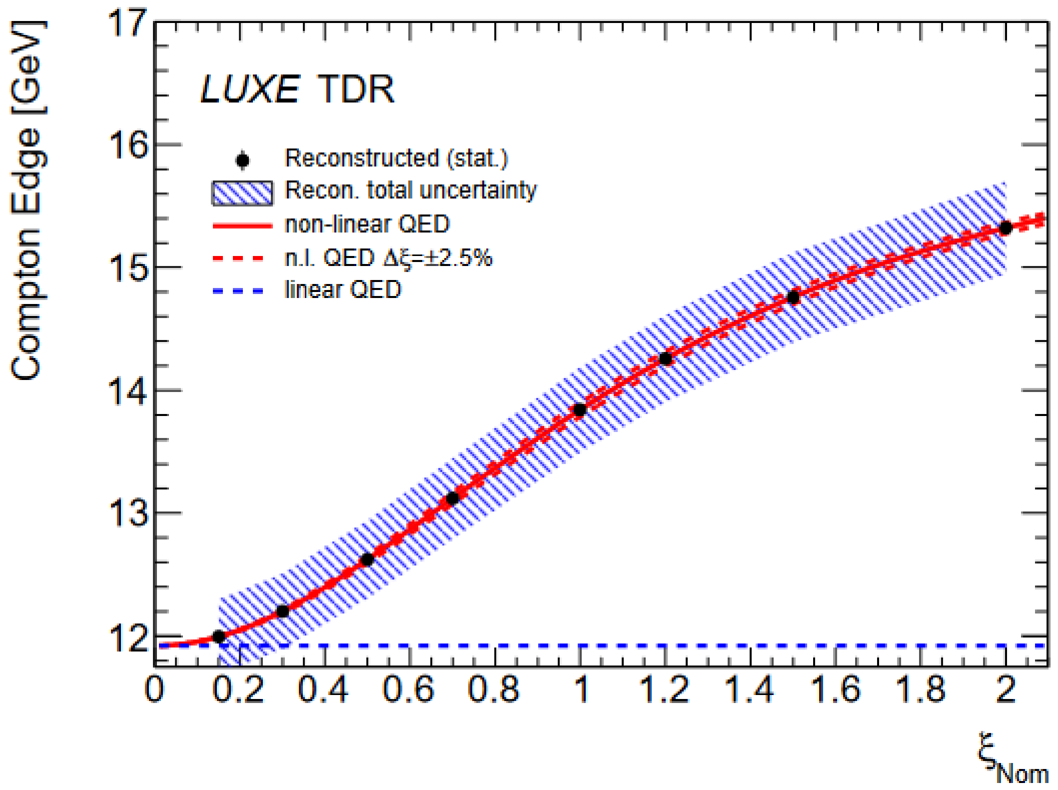
Gamma detector technologies:

- Gamma profiler (sapphire strips)
  → ɣ beam location and shape
  → precision measurement of Laser intensity
- Gamma spectrometer with scintillator screens behind converter
  → flux, energy spectrum ($\frac{\delta E}{E} < 2\%$)
- Gamma dump backscattering calorimeter → photon flux

Photon detectors: Precision measurement of ξ, complementary to Laser diagnostics

Expected Results





- Number of Breit-Wheeler pairs produced in photon-Laser collisions
- assuming 10dy of data-taking and 0.01 background events/ bunch crossing
- 40% correlated uncertainty to illustrate effect of uncertainty on ξ

- Compton edge position as function of ξ in electron-laser collisions
- assuming 1h data-taking, no background
- 2% correlated uncertainy to illustrate impact of energy resolution

SFQED parameters

Note:

$\mathcal{E}_L$: Laser field
$\mathcal{E}_{cr}$: Schwinger critical field

θ: Laser - probe crossing angle

ω_L: Laser frequency

$E_{e/\gamma}$: probe electron (photon) energy

Intensity parameter:

$$\xi = \sqrt{4\pi\alpha}\left(\frac{\mathcal{E}_L}{\omega_L m_e}\right) = \frac{m_e \mathcal{E}_L}{\omega_L \mathcal{E}_{cr}}$$

- measure of coupling between probe and Background (laser) field
(also: square root of laser intensity)
- $\xi \geq 1$: non-perturbative regime

Quantum parameters:

$$\chi_e = (1+\cos\theta)\frac{E_e}{m_e}\frac{\mathcal{E}_L}{\mathcal{E}_{cr}}$$

$$\chi_\gamma = (1+\cos\theta)\frac{E_\gamma}{m_e}\frac{\mathcal{E}_L}{\mathcal{E}_{cr}}$$

- ratio of background laser field and Schwinger critical field
- $\chi \geq 1$: non-linear quantum effects become probable
(e.g. pair production)

Energy Parameter

$$\eta = \frac{\chi}{\xi} = (1+\cos\theta)\frac{\omega_L E_{e/\gamma}}{{m_e}^2}$$

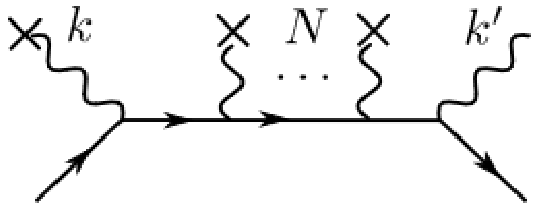
- (dimensionless) energy of collision between probe particle and background

Different combinations of ξ and χ result in different types of non-linear behavior!

Compton scattering in strong fields

Link to QU lecture by Ben King
Review paper: A. Fedotov et al, 2203.00019 [arXiv:hep-ph]

- Consider Compton scattering in plane-wave background field: $A(x) = A_0 \sin(k \cdot x)$



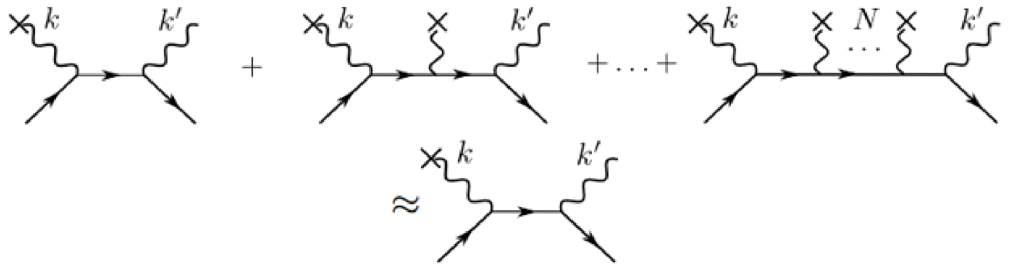
$+$ exchange diagram

fine structure constant

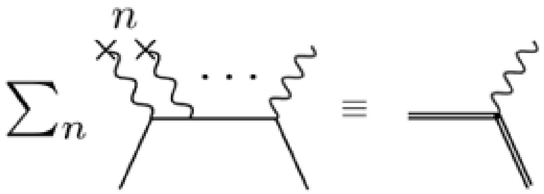
Probability $P \sim \alpha \left(\frac{eA_0}{m}\right)^{2N} = \alpha \xi^{2N}$

$$\xi = \frac{eA_0}{m}$$

'Classical nonlinearity / intensity parameter', ξ.



"weak" field $\xi < 1$



'Nonlinear' Compton scattering

strong field: $\xi \geq 1$

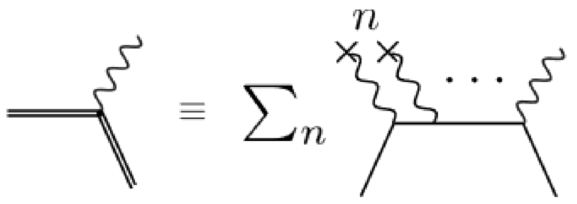
Strong field ($\xi \geq 1$): Need to take into account all order diagrams!

The Furry picture

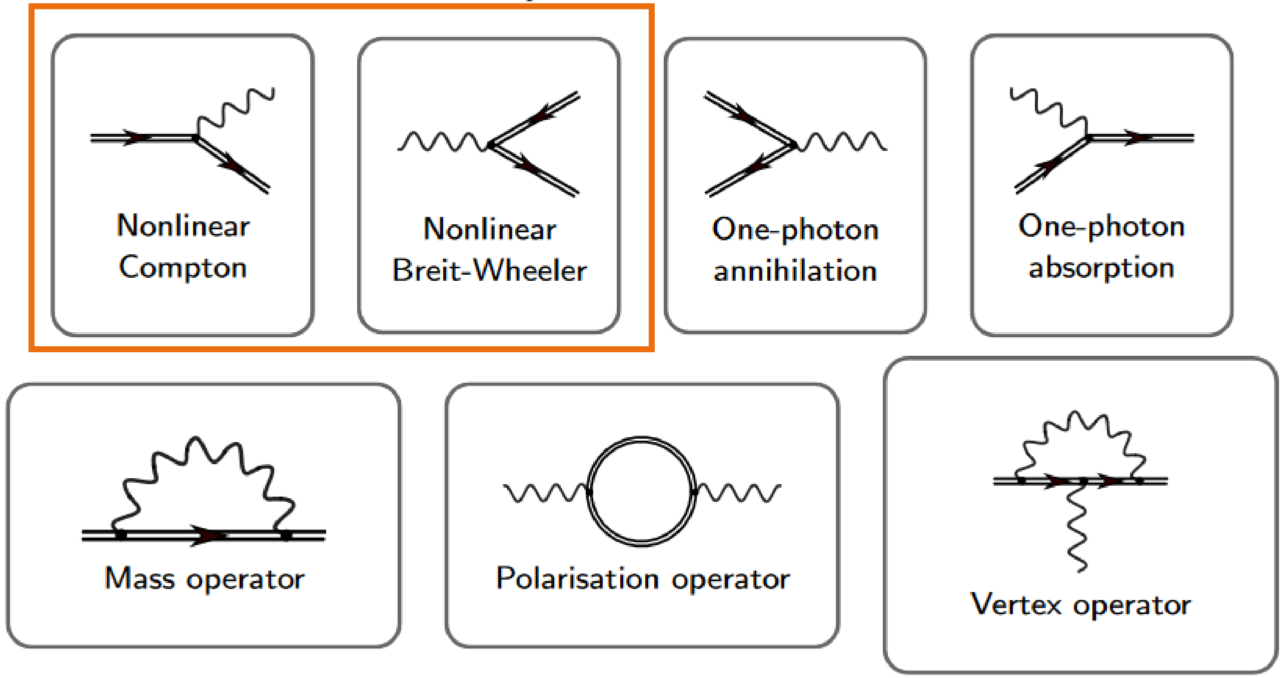
- How to do calculations? Solve equations of motion (Dirac equation) in field background
  → analytical solutions exist in plane wave background („Volkov wave functions“)

- derive Feynman rules for „dressed“ states („Furry expansion“)
  → treat background exactly, particle scattering perturbatively ($\alpha \ll 1$)

$$\mathcal{L} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}\left(i\not{D} - m\right)\psi}_{\text{'unperturbed'}} \; \underbrace{-e\bar{\psi}\not{A}\psi}_{\text{interaction}},$$



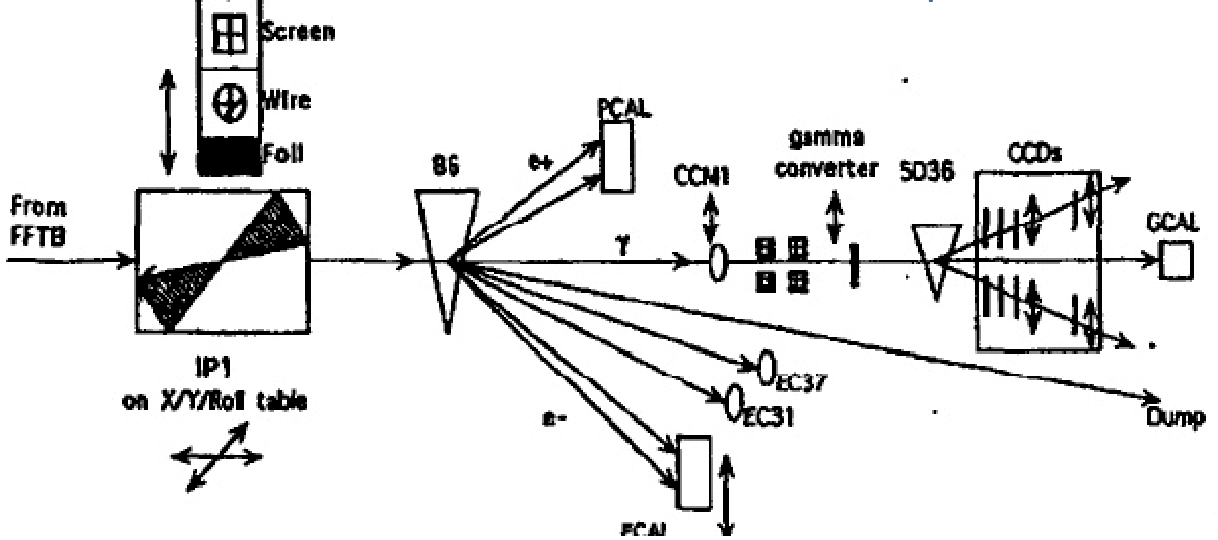
„dressed“ state

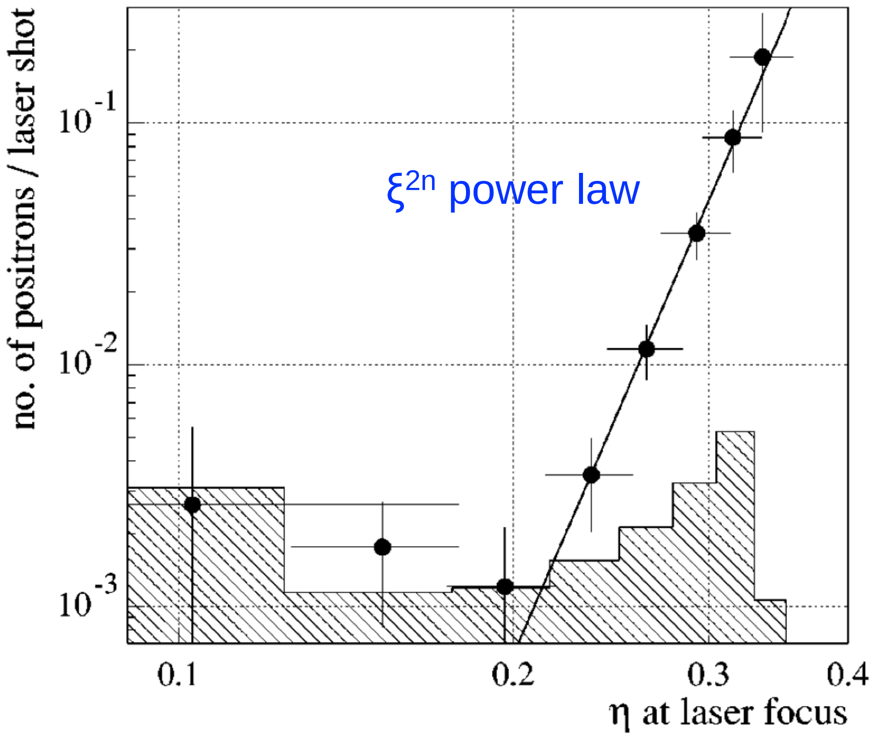


E144 experiment at SLAC

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

Cartoon of SLAC E144 experiment



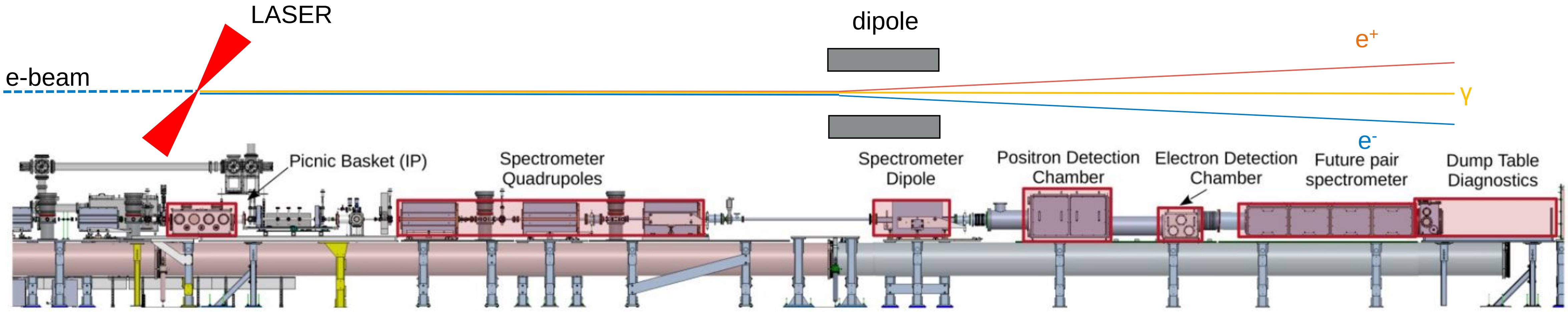


- E144: SLAC experiment in 1990's using 46.6 GeV electron beam (e+LASER only!)
- reached χ ≤ 0.25, ξ<0.4
- observed process $e^- + n\gamma_L \rightarrow e^- \; e^+ e^-$
- observed start of the ξ^{2n} power law, but not departure

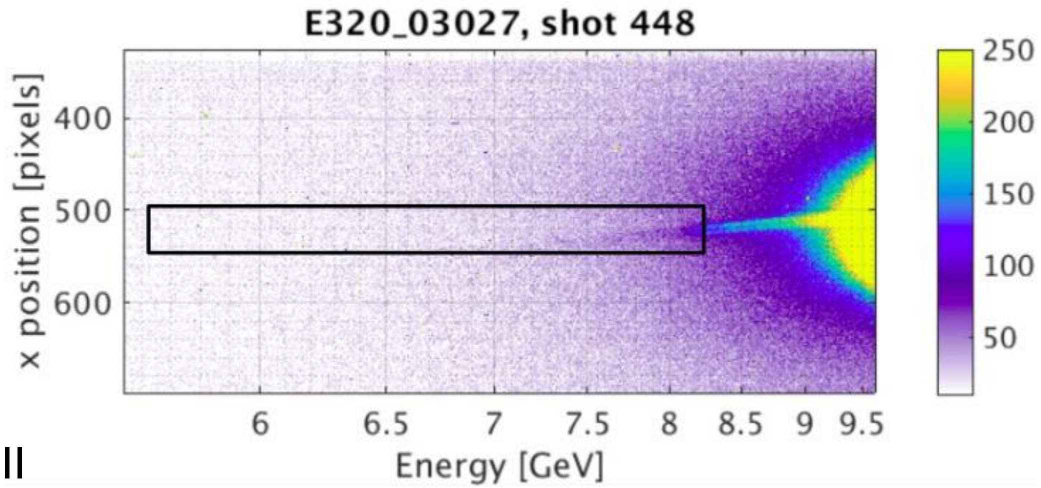
LUXE : Three orders of magnitude more powerful laser than E144, will enter non-perturbative regime

E-320 experiment at SLAC

Link to E320 overview by S. Meuren



- E320: ongoing SF-QED experiment at SLAC using 13 GeV electron beam (FACET-II) and 16 TW optical Laser
- first electron-LASER collisions in 2022
- By design: similar parameter reach as LUXE (after Laser and Detector upgrades)
- Main differences to LUXE:
  - electron-Laser collision mode only
  - E-320 data-taking time limited due to other users of FACET-II



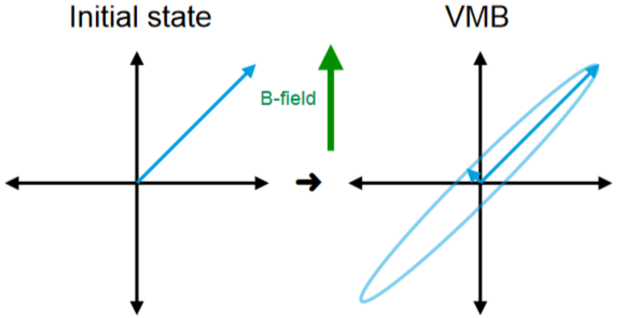
[ALPSII VMB: Talk by A. Spector](#)

[BIREF@ HIBEF Letter of Intent](#) (2024)

SFQED across the campus

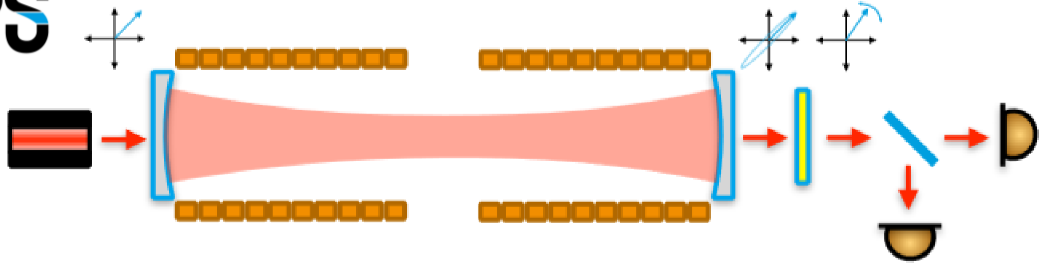
Vacuum Magnetic Birefringence: ALPS II and HIBEF

- Prediction of QED: Vacuum exhibits birefringence (polarization-dependent refractive index n) in presence of a B-field
- $\Delta n = 3A_e B^2 \quad (A_e = 1.32 \times 10^{-24} \mathrm{T}^{-2})$



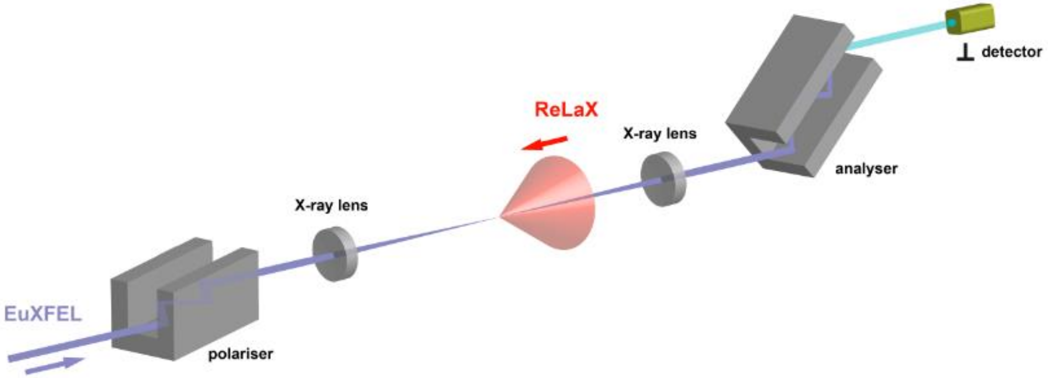
- ALPS II VMB: measure polarization changes induced by (modulating) B-field using laser interferometry
- optical cavities enhance path length in B-field

ALPS



- BIREF@ HIBEF: collision of EuXFEL x-ray photons and 300 TW ReLaX optical laser
- Measure x-ray photons with polarization flip after passing through high-intensity laser pulse
- Experimental challenge: high-precision x-ray optics and polarimetry

HiBEF HELMHOLTZ INTERNATIONAL BEAMLINE FOR EXTREME FIELDS

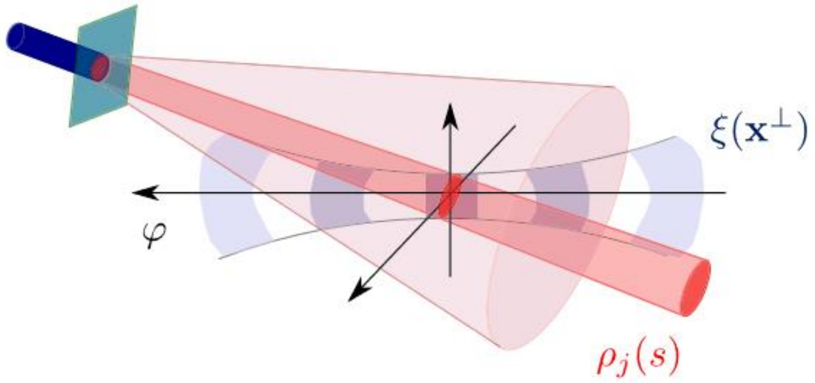


Potential portal to new physics
(alternative QED models, mixing with dark sector,…)

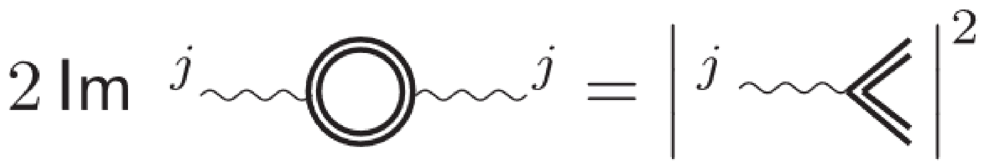
SFQED across the campus

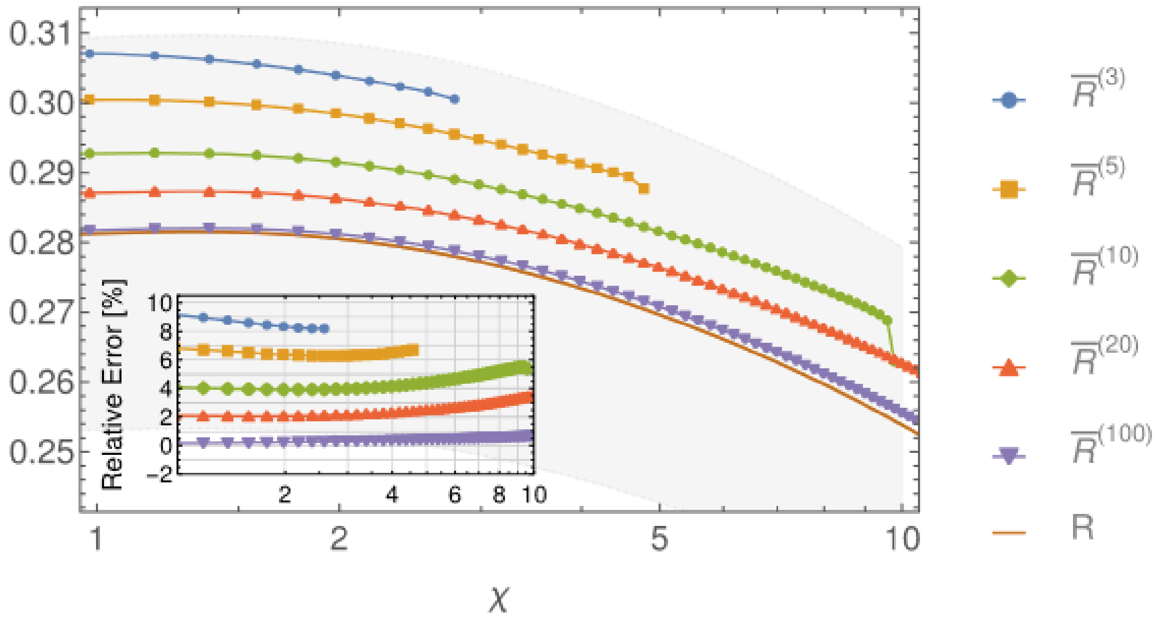
Vacuum Magnetic Birefringence: LUXE

Borysov et al. [PHYS REV D 106, 116015 (2022)]



Optical theorem:

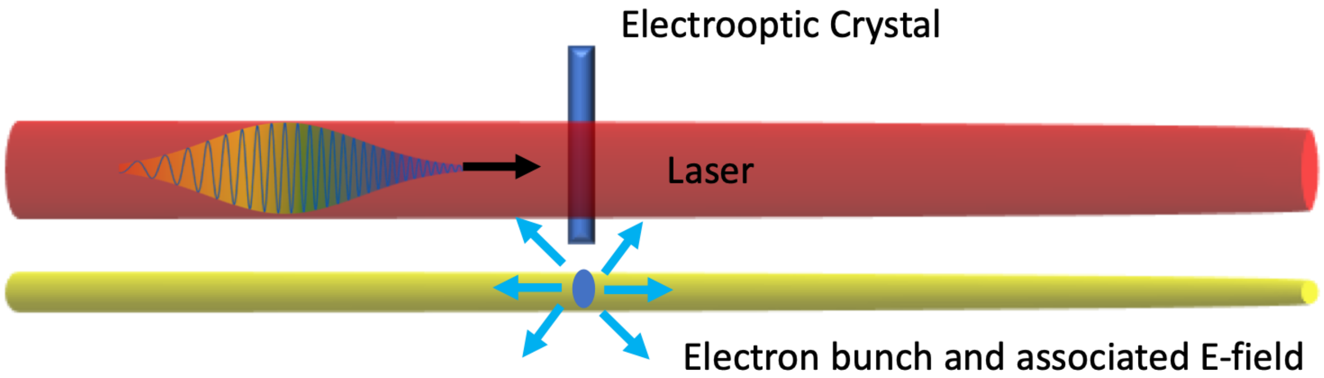




- LUXE indirect VMB measurement: one-loop dressed vacuum polarization operator related to polarized NBW pair creation
- Experiment: collide (partially) polarized photon beam (e.g. coherent bremsstrahlung in crystal) with laser
- Measure NBW pair production rate for values χ up to χ_{max}
- Hilbert transform in χ to relate pair creation yield to photon helicity flip/no-flip amplitude ratio R
- Accuracy of estimated ratio $\overline{R}$ benefits from high χ_{max}

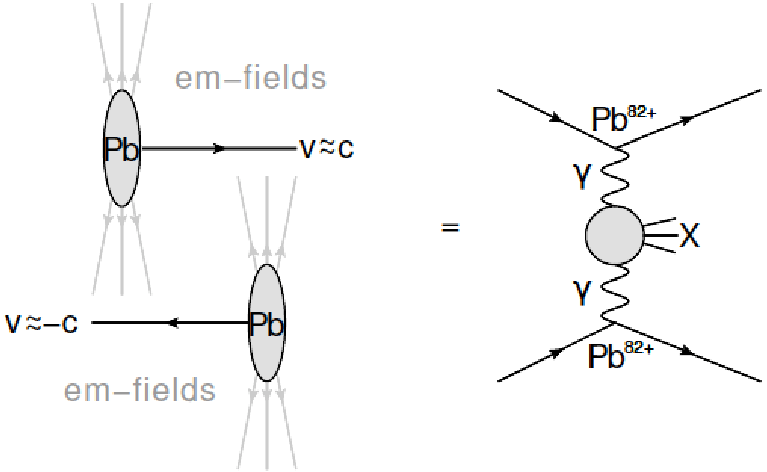
Synchronization

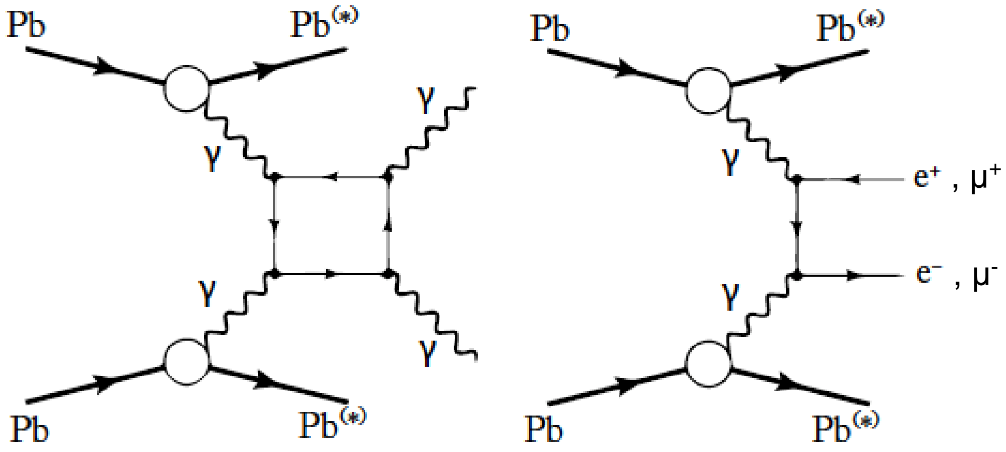
- critical: spatial and temporal overlap of electron beam and LASER
- temporal overlap requirement (30fs LASER pulse, >100fs electron bunch)
  → at least half the pulse width (50fs)
- XFEL developed world-leading syncronization system
  → sychronization of two RF signals to <13fs
- synchronise the XFEL.EU master clock oscillator to the oscillator of the Laser
  → already used across XFEL to sychronize LASERS and accelerator
  → fine-tune repetition rate via piezo-elements controling LASER cavity size
- stability against temperature variations: isolation and active feedback loops
- spatial overlap: beam pointing monitoring systems for both electron and LASER beam



How does LUXE relate to LHC light-by-light scattering?

- LHC: photon-photon interaction in ultra-peripheral heavy-ion collisions (UPC)
  → e.g. $\gamma\gamma \rightarrow \gamma\gamma$, $\gamma\gamma \rightarrow \mu\mu$
- UPC: fields above the Schwinger limit can be reached in the lab
- main difference to LUXE: in UPC, EM field is extremely short-lived, cannot travel over macroscopic distances
- this regime is still covered by linear perturbative QED



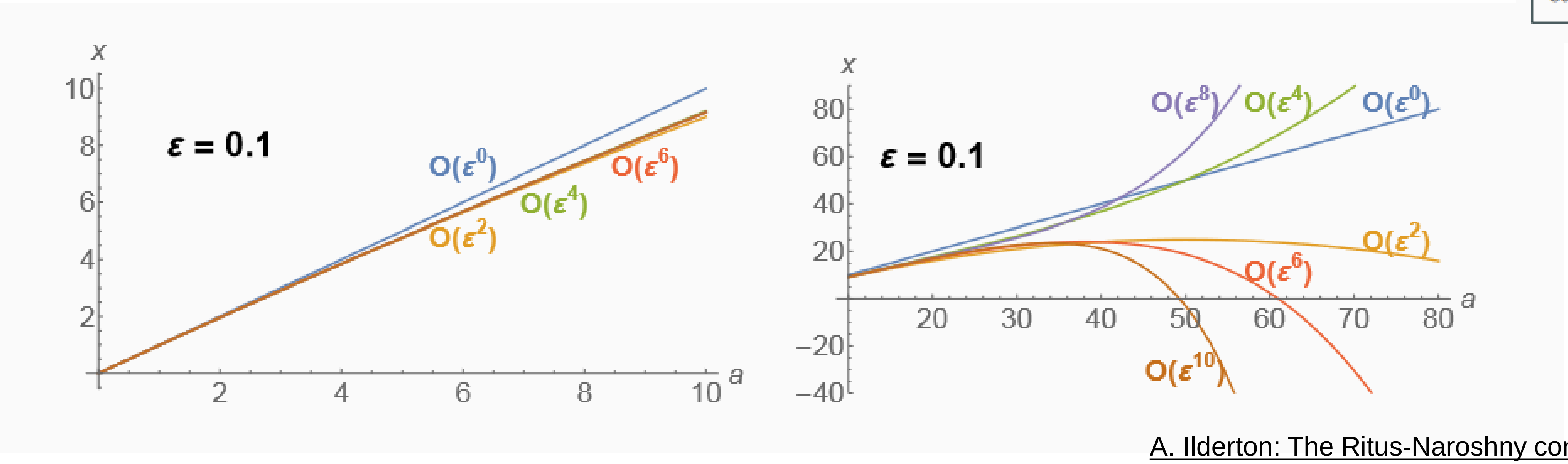


Figures from: arXiv:2010.07855v3
(Also a nice review to read, if you want to know more!)

Ritus-Naroshny Conjecture

- Ritus-Naroshny Conjecture: in the vicinity of sufficiently strong fields, the Furry expansion breaks down
  $\longrightarrow$ perturbative QED coupling α is modified by the field strength: $\alpha \rightarrow \alpha\chi^{2/3}$
- Conjecture interpreted to hold for any „locally constant“ background
  (field constant over formation length scale of physics process)

$$a \leftrightarrow a_0,\ \varepsilon^2 \leftrightarrow \alpha$$



A. Ilderton: The Ritus-Naroshny conjecture: A tutorial