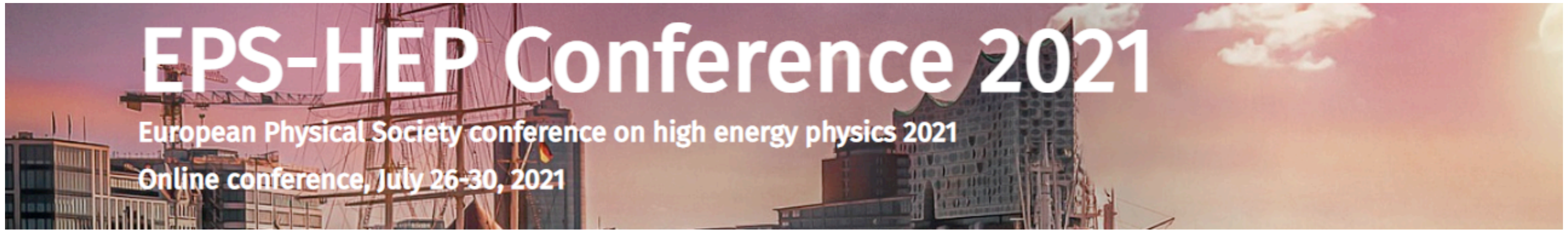
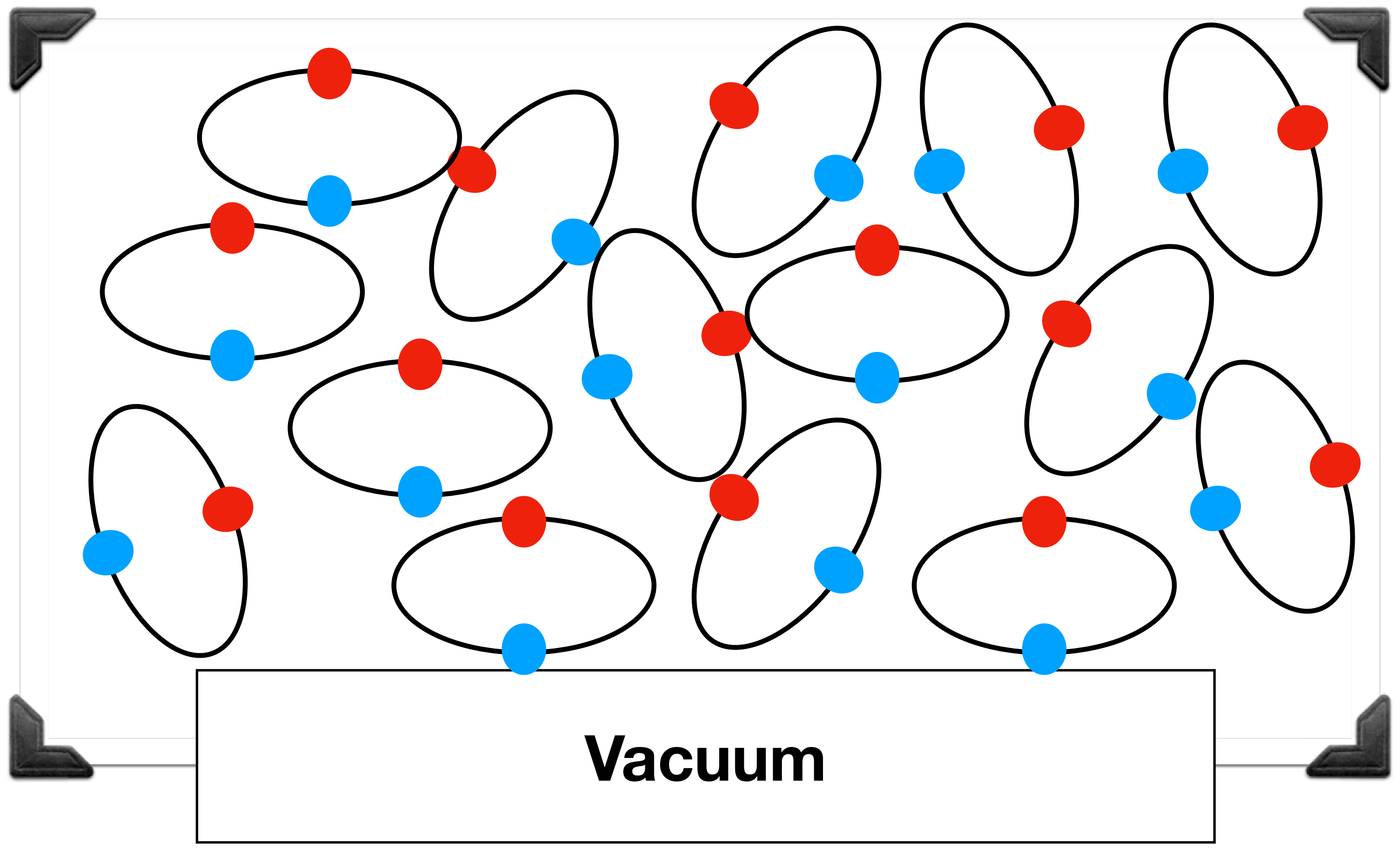
LUXE: A NEW EXPERIMENT TO STUDY NON-PERTURBATIVE QED

LOUIS HELARY (DESY) ON BEHALF OF LUXE

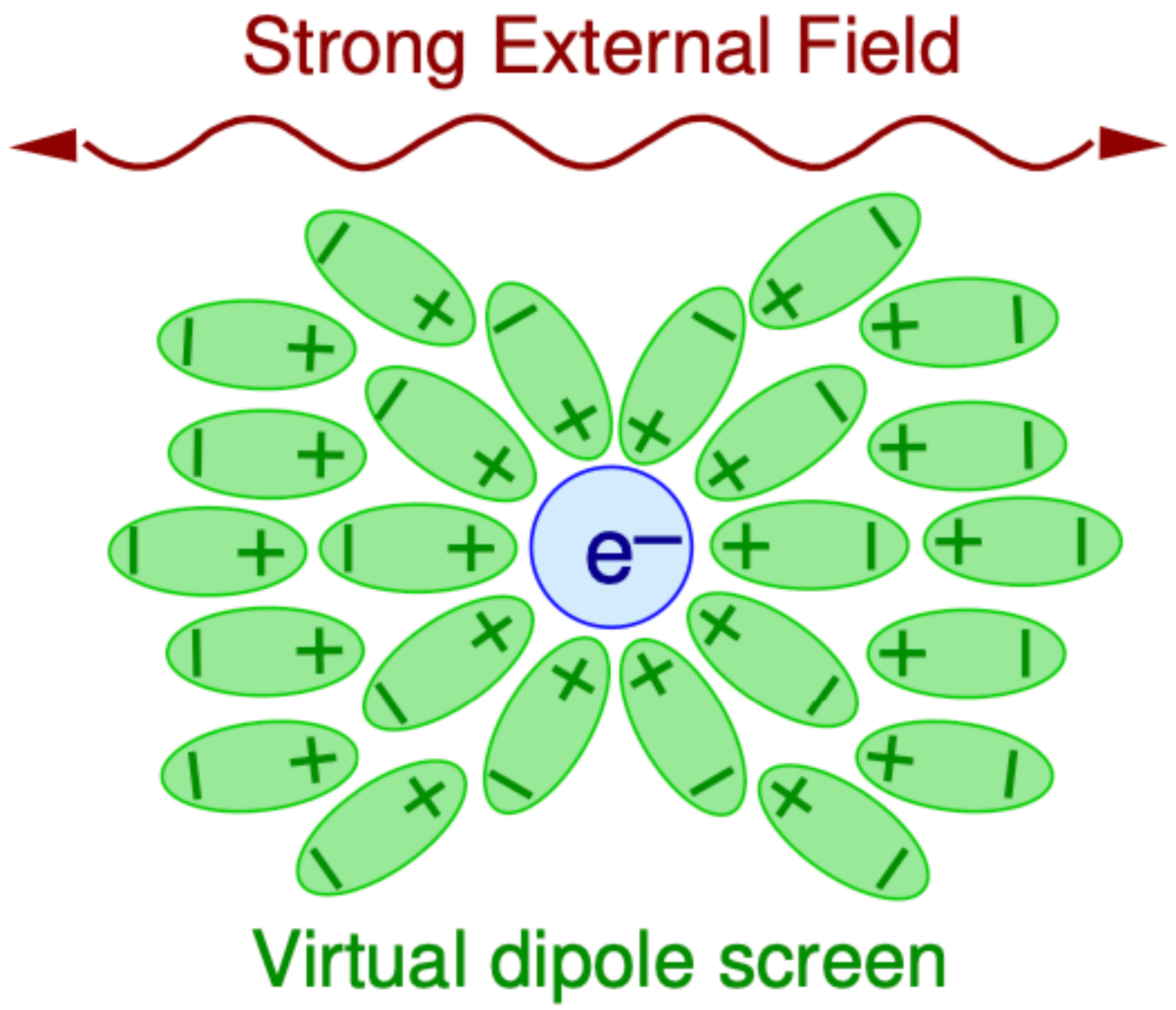
EPS HEP — JULY 26TH - 30TH 2021 — HAMBURG (ONLINE)



- QED: one of the most well-tested physics theory!
  - Calculation in QED based on perturbative theory of α_{EM}.
    - Prediction electron (g-2) precision better than 1 part in a trillion!
- Vacuum:
  - Virtual particles that can be charged and couple to fields.
  - Quantum fields: average is zero, but variance is not!
  - Physical particle travel in vacuum affected by interactions with these.



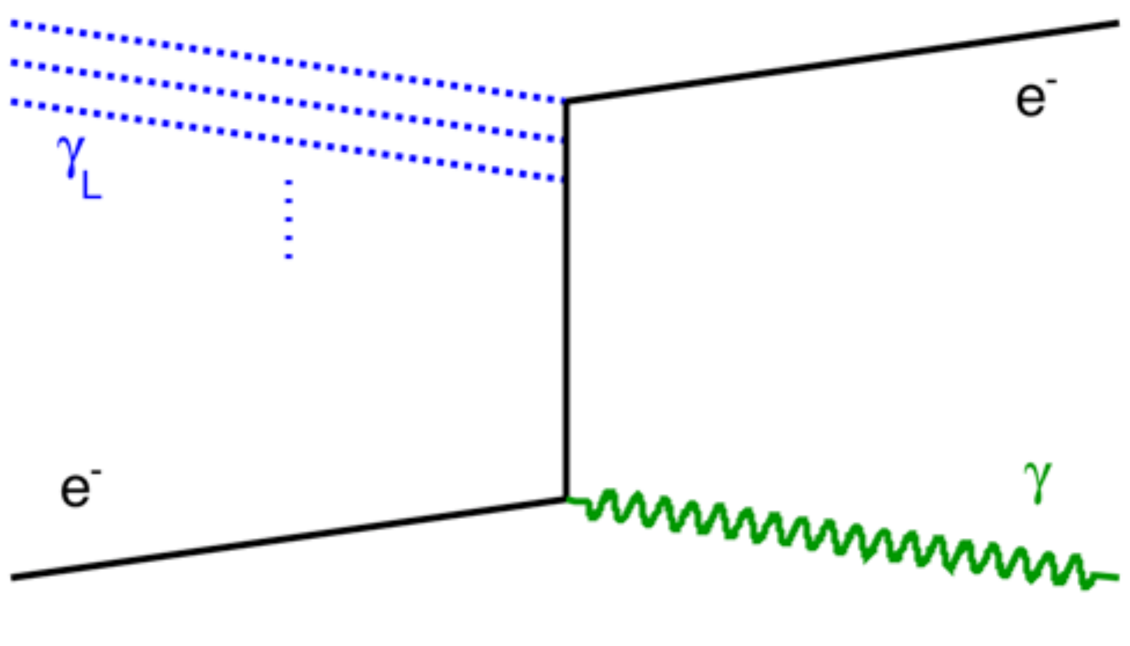
- If one apply a strong electromagnetic field on a vacuum:
  - $W_{field} < 2\ m_e$ $\qquad$ $W_{field} > 2\ m_e$, with: $W_{field} = \frac{\varepsilon e}{m_e}$ and $\varepsilon_{crit} = \frac{m_e^2 c^3}{\hbar e} \simeq 1.3 \cdot 10^{18}\ \mathrm{V/m}$



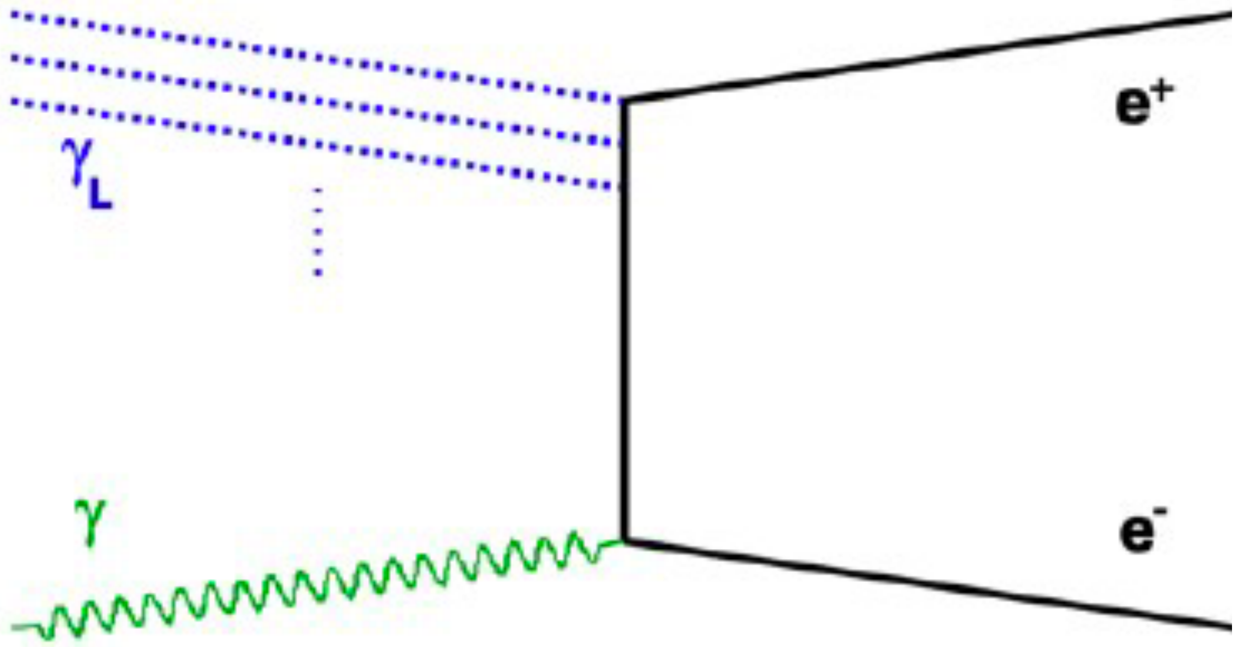
  - QED becomes non perturbative above Schwinger-limit
    → Strong field QED (SFQED)!
- Experimental consequences:
  - **Field-induced ("Breit-Wheeler") Pair Creation**
  - **Modified Compton Spectrum.**
- Non-perturbative and strong field QED have never been reached in laboratory, accessible by LUXE!
  - Experimentally reached by colliding highly boosted electrons with high-intensity laser!

INTRODUCTION: SFQED PROCESSES AND PREDICTIONS

- Processes sensitive to in LUXE:

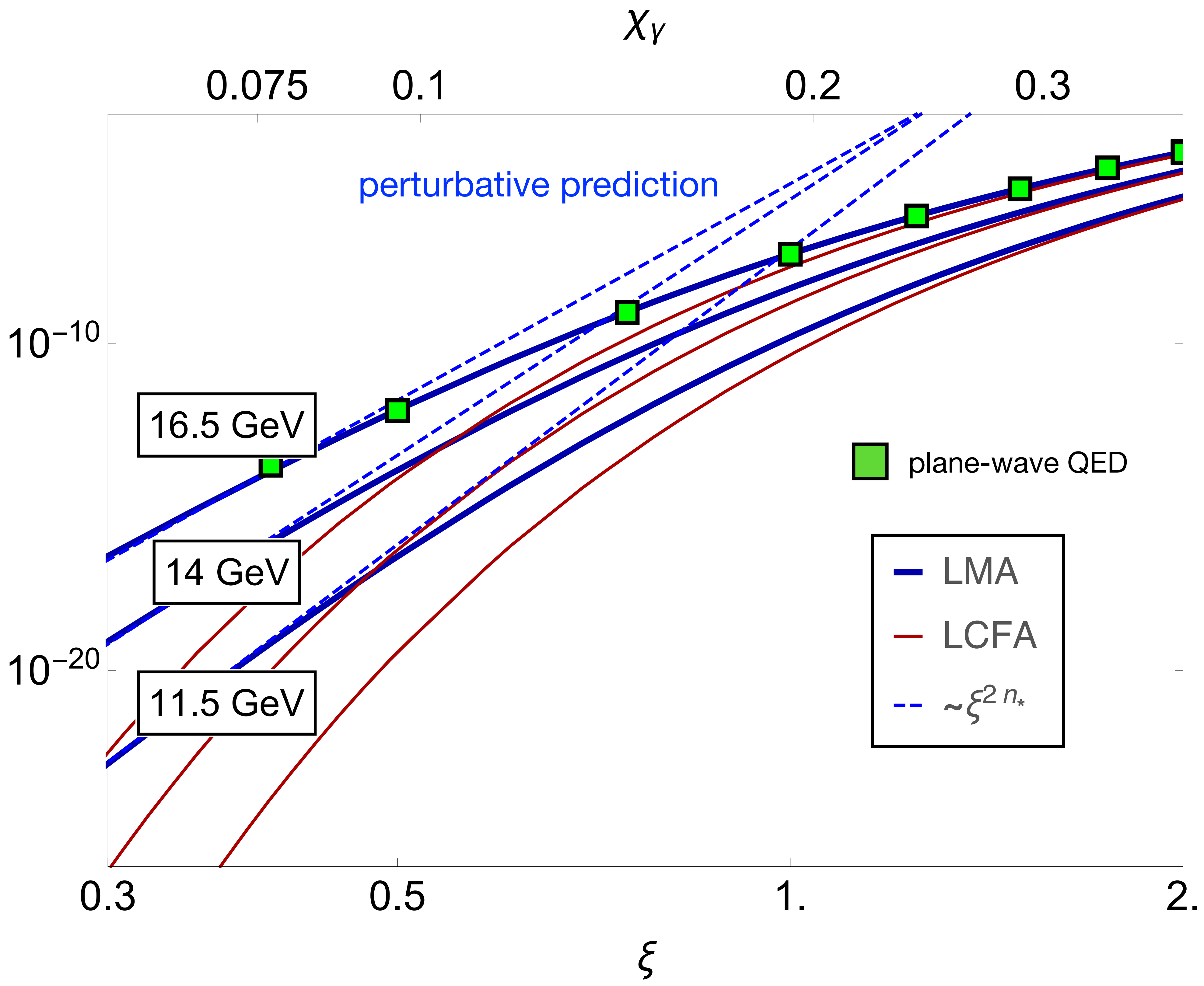


non-linear Compton scattering



Breit-Wheeler

probability
of Breit-Wheeler process



- Parameters used in SFQED:
  - ξ = Measure of e-Laser coupling and Laser intensity.
  - X^2 = fraction of Laser energy transferred to electron beam.

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

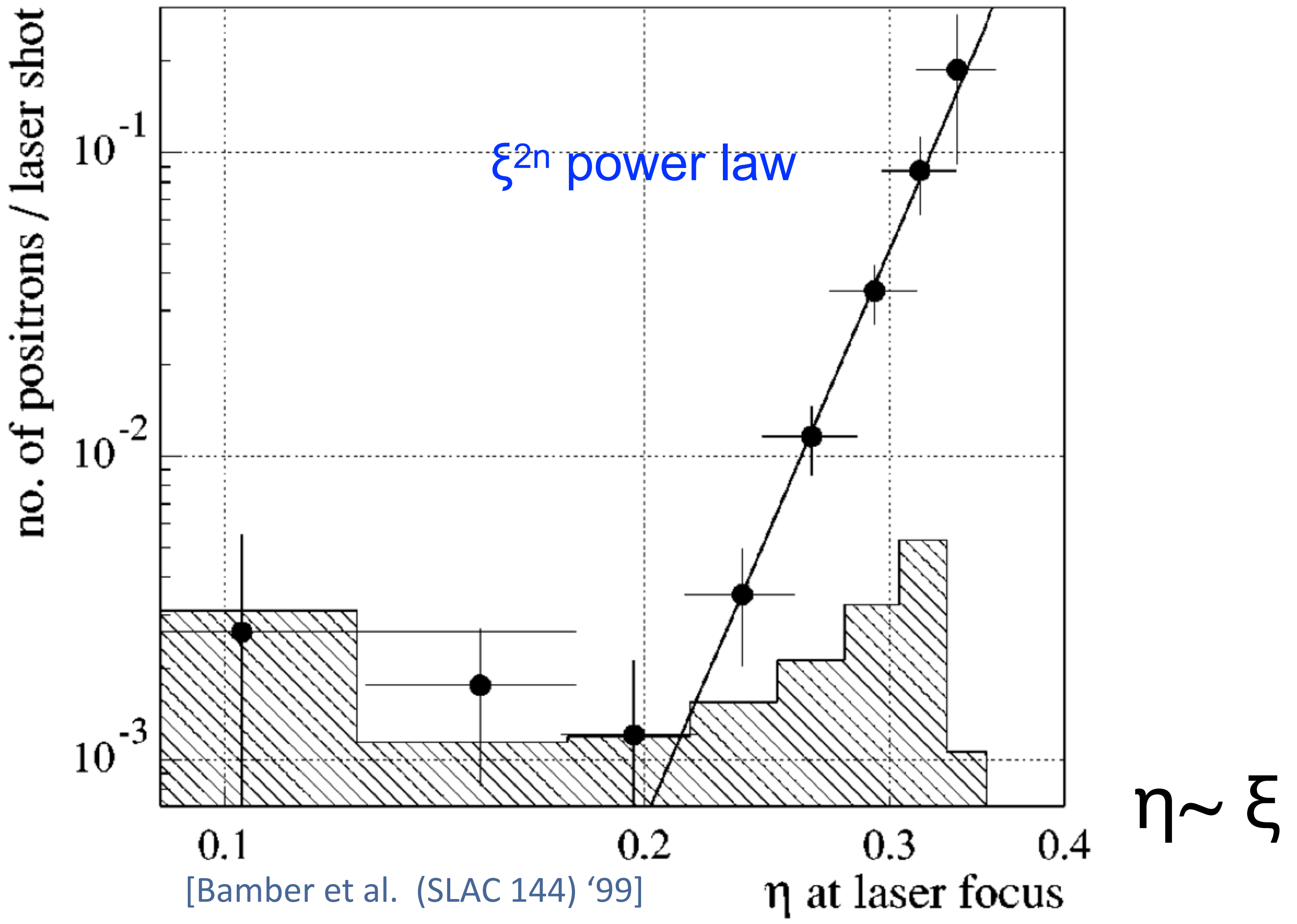
- Predictions:

$\boxed{\xi \ll 1:}$ $R_{e^+} \propto \xi^{2n} \propto I^n$ Perturbative regime, rate follows power law

$\boxed{\xi \gg 1:}$ $R_{e^+} \propto \chi_\gamma \exp\left(-\frac{8}{3\chi_\gamma}\right)$ Non-perturbative regime, departure from power law

INTRODUCTION: SFQED STATE OF THE ART

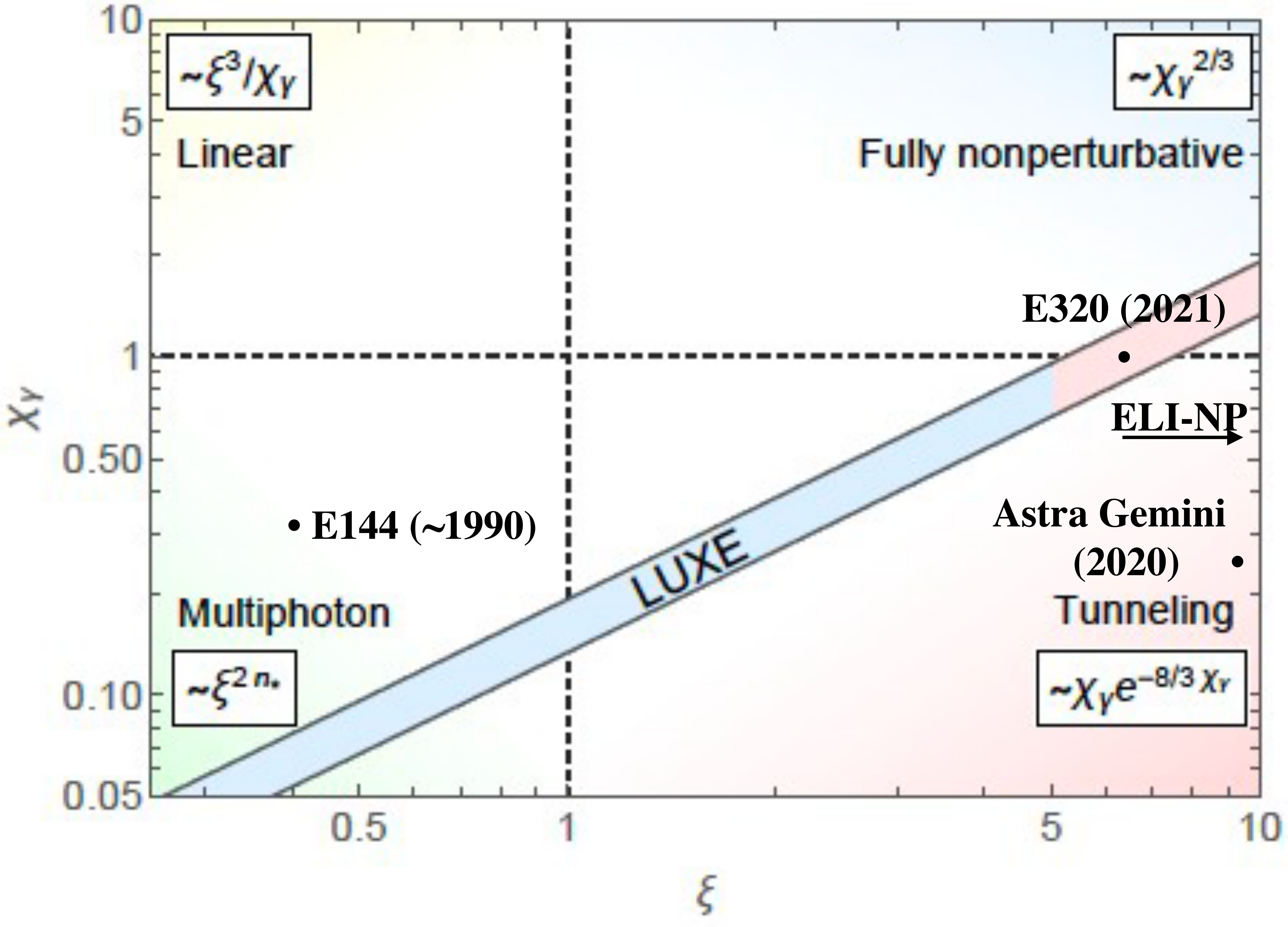
- Historically SFQED studied first in 1990's at SLAC E144 (experiment)
  - 1TW laser with $I_{Laser}=10^{18}$ W/cm^2
  - e- beam: 46.6 GeV
  - reached $\xi<0.4$, $\chi \leq 0.25$
  - observed multi-photon interaction: $e^- + n\gamma_L \rightarrow e^- e^+ e^-$ process
  - observed start of the ξ^{2n} power law, but not departure



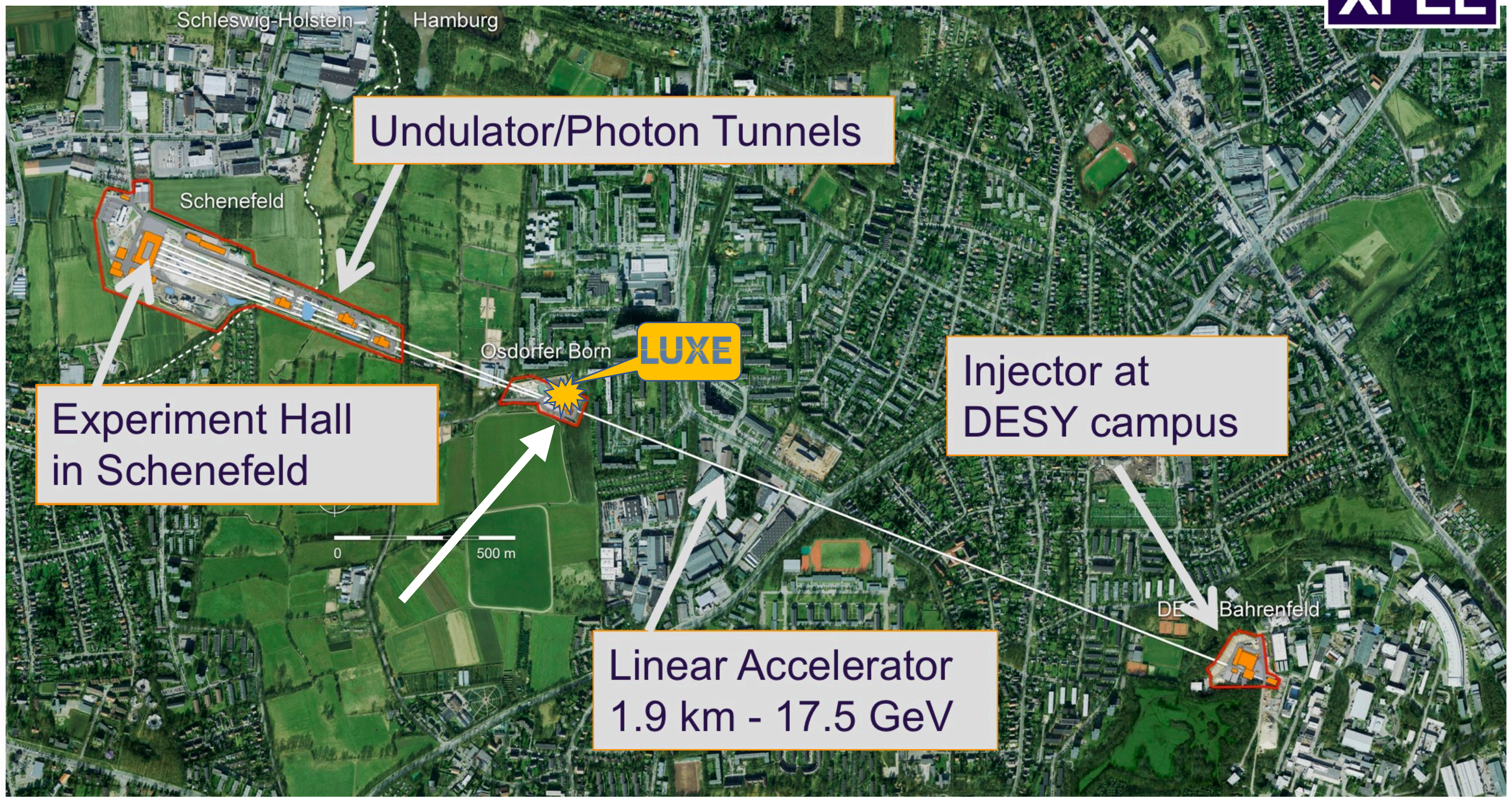
- Nowadays multiple experiments proposed worldwide:
  - SLAC-E320 (US), Astra Gemini (UK), ELI-NP (RO), LUXE (DE)

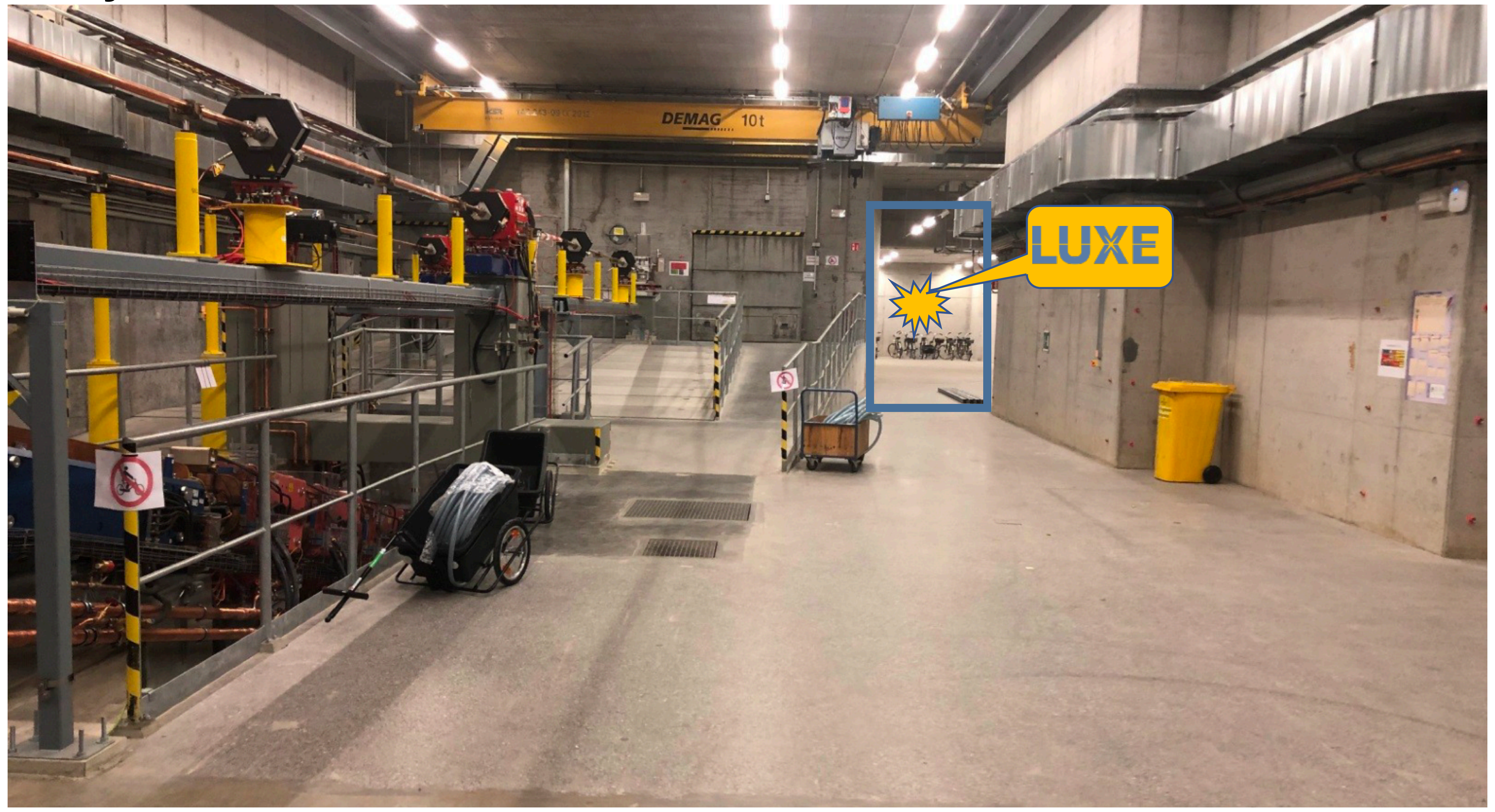
- Luxe allow to measure with precision large part of ξ vs X phase space.
  - Might be the first one to report observation of non perturbative regime.
    - Only experiment proposed to directly explore photon-laser interactions.

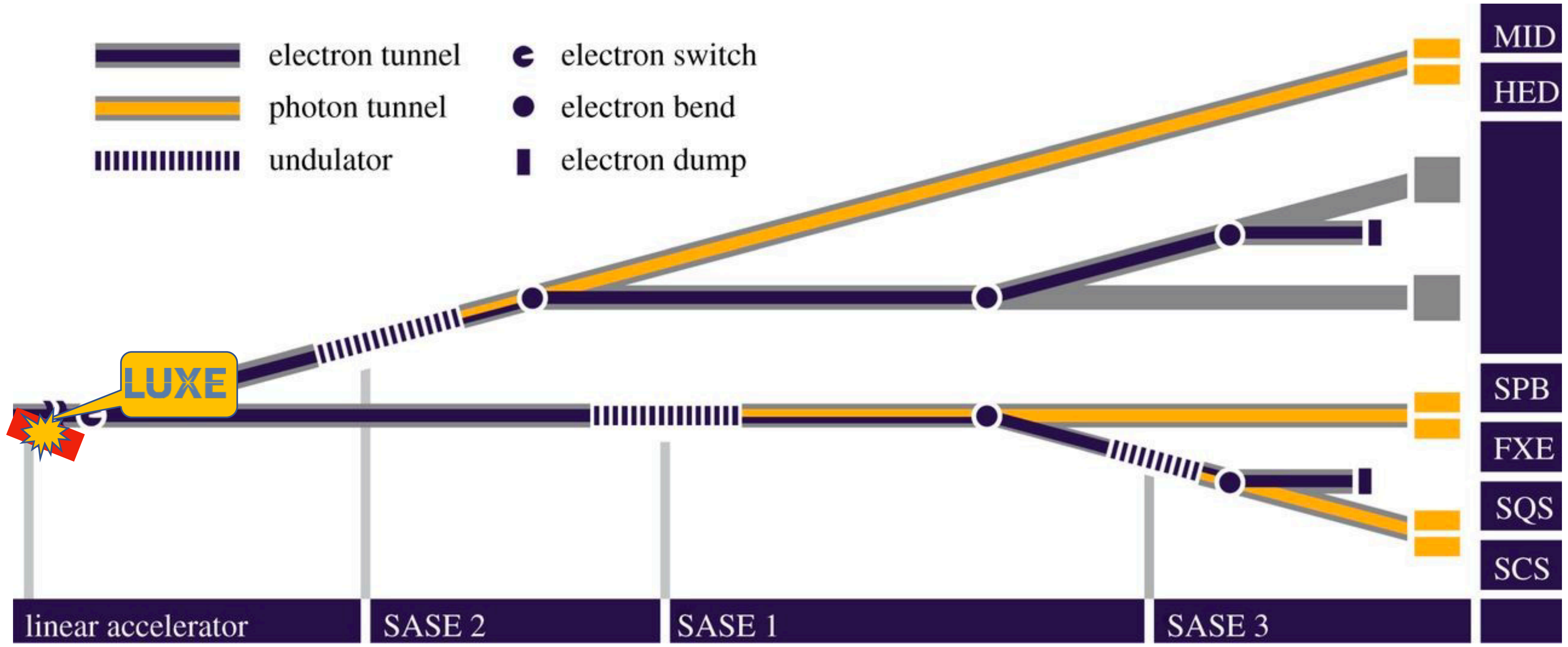
- Main Luxe scientific goals:
  - Measure electron rate as a function of laser intensity.
  - Measure Compton edges.
  - Study BSM physics.



- European XFEL:
  - Running since 2017.
  - Provide X-ray photons to 6 experiments.
    - Electron through undulator:
      - SASE (self-amplified spontaneous emission).
  - Linear electron accelerator.
    - 2700 electron bunches at 10 Hz.
      - Aim to run at 16.5 GeV with 1.5e9 e-/bunch.
- Experiment will be located XS1 shaft in Orsdorfer Born.
  - Built for XFEL extension (after 2029).
- Experiment will have no impact on photon science,
  - Only use 1 of the 2700 bunches.







LUXE IN SITU

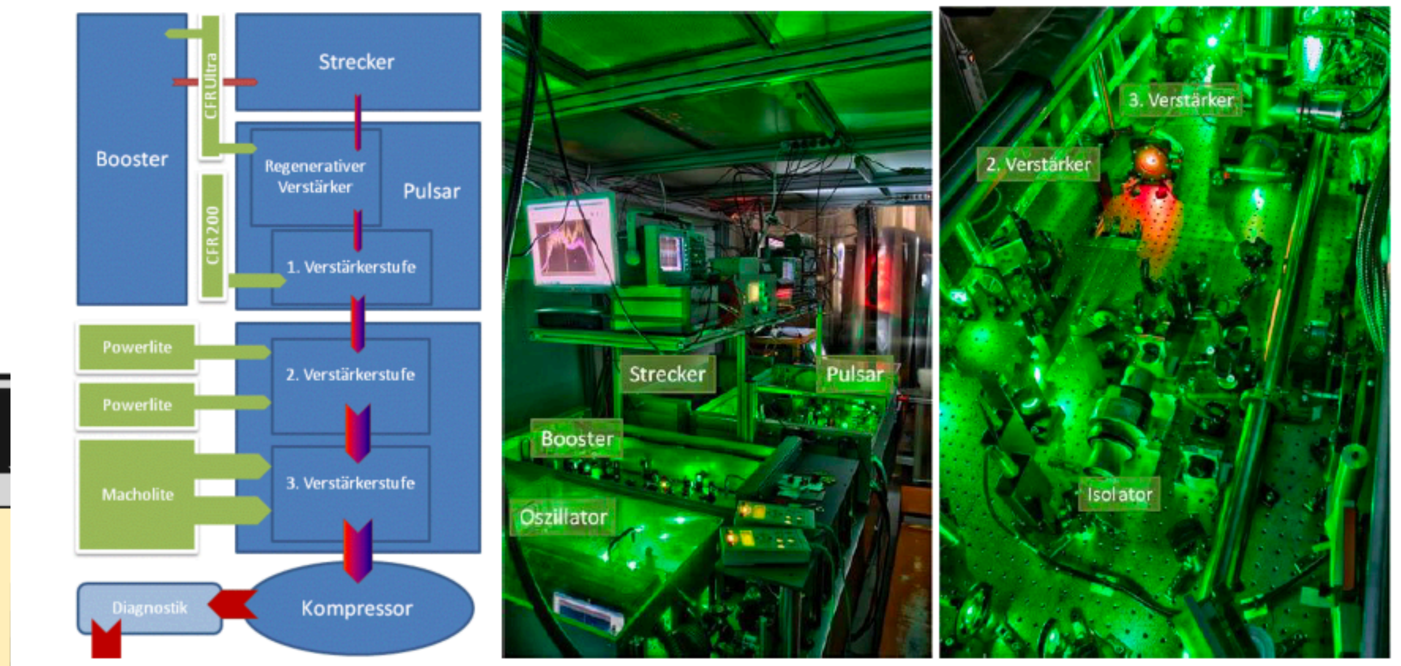
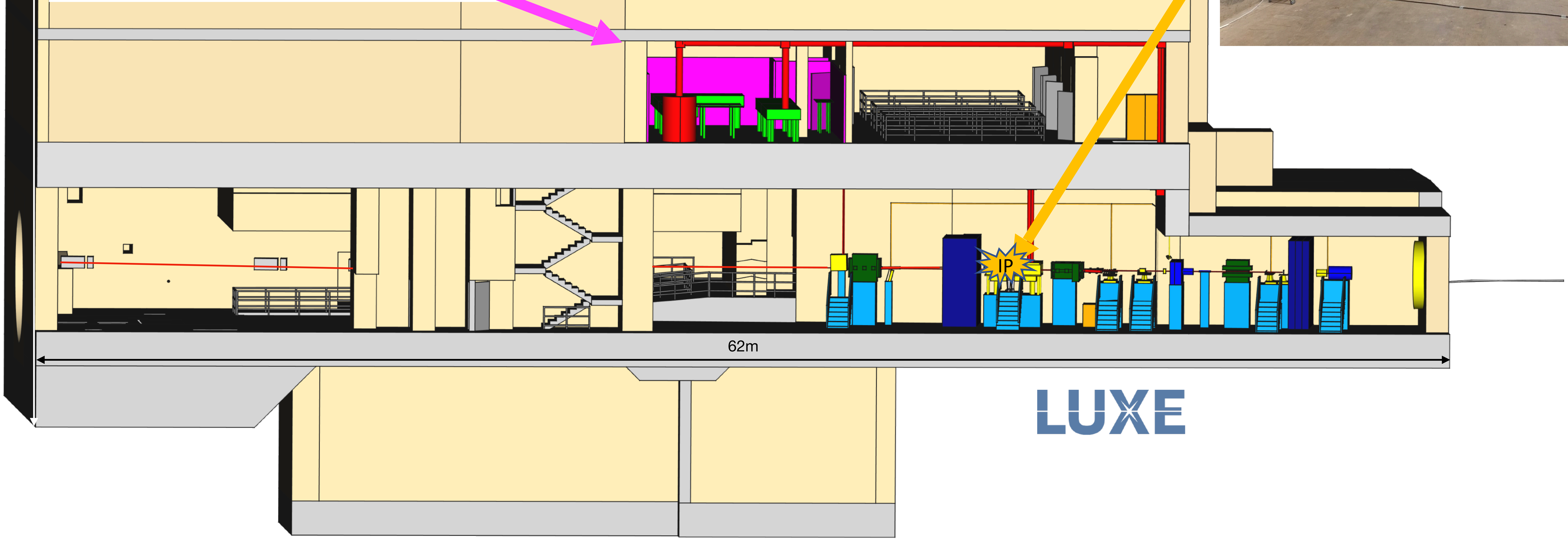


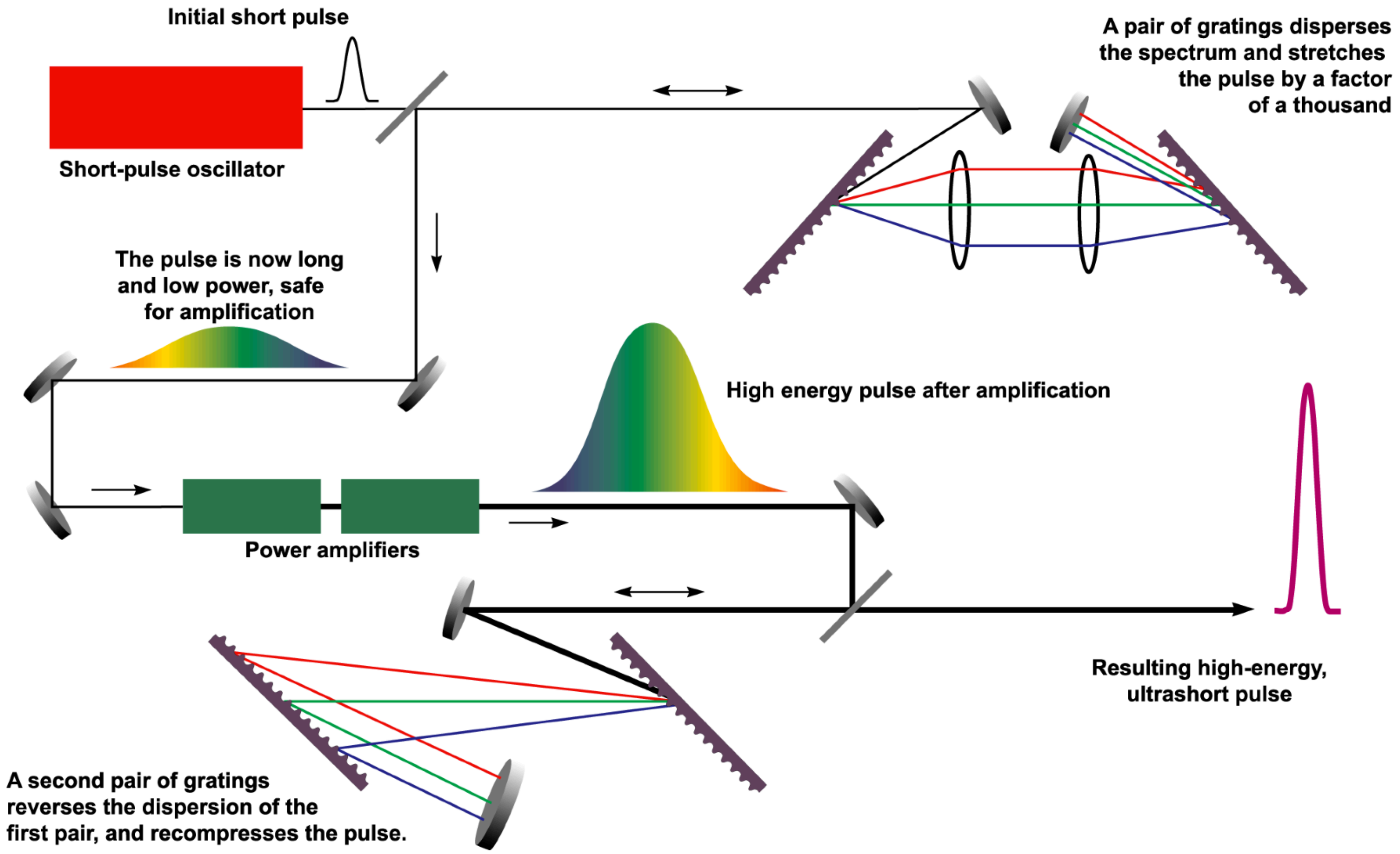
Figure 22. Schematic of the JETI system highlighting major assemblies. Current Installation of JETI-40 at the University of Jena. Front-end is shown in centre and power amplifiers right.

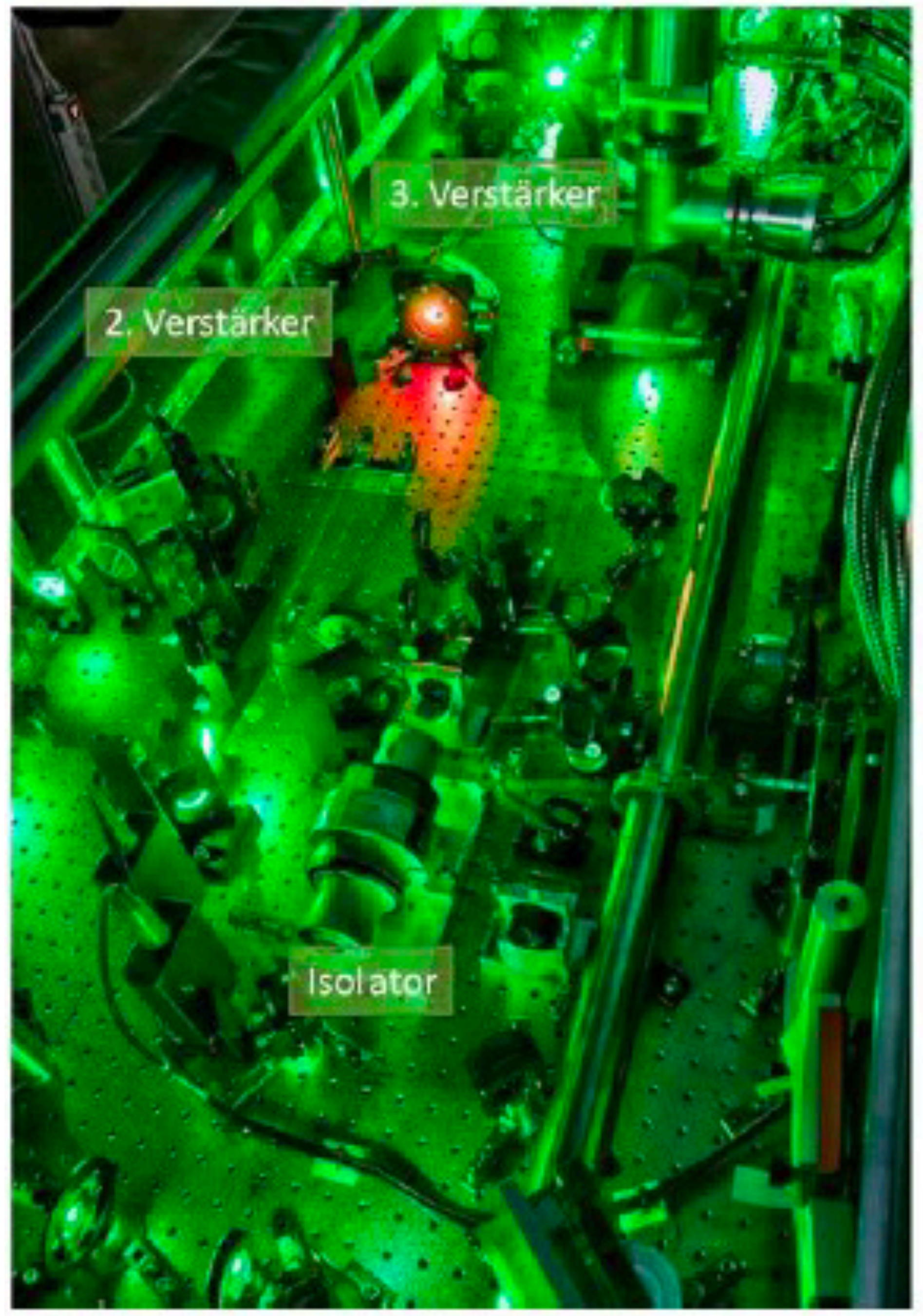


LUXE

LASER

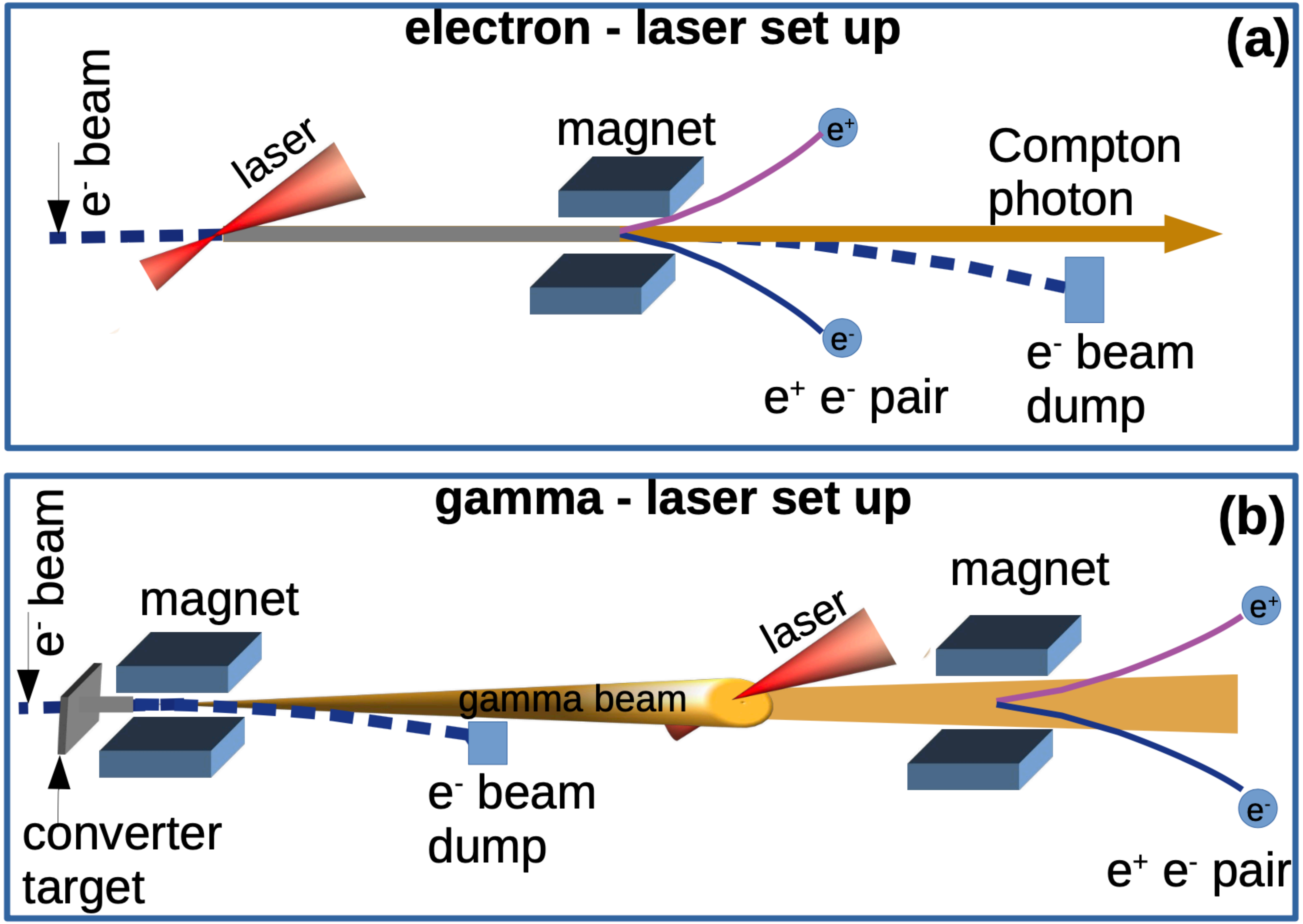
- Chirped Pulse Amplification (CPA) technique
- Ti:Sa laser with 800 nm wavelength (E=1.55 eV).
- Two phases:
  - In phase 0 uses JETI40 (Jena custom 40 TW laser).
  - In phase I will use commercial 350 TW laser.
- Laser parameters:
  - Repetition rate: 1Hz.
  - Pulse length 30 fs
- Laser characterisation quantities: energy, pulse length, spot size
  - $\leq$ 5% uncertainty on Laser intensity, 1% shot-to-shot uncertainty





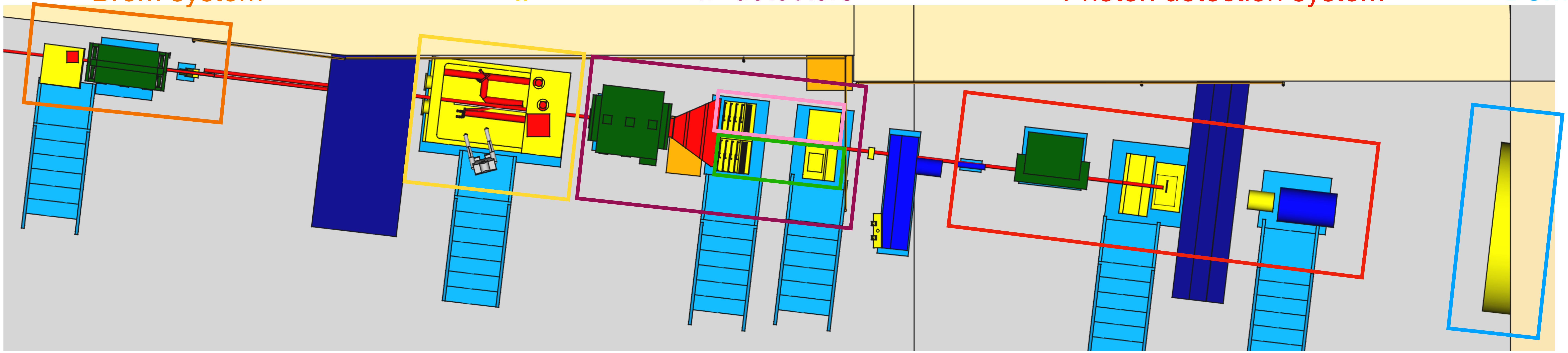
Parameter	Phase 0	Phase 0	Phase I
Laser power	40 TW		350 TW
Laser energy after compression [J]	1.2		10
Percentage of laser in focus [%]	50		
Laser focal spot size w_0 [μm]	>8	>3	>3
Peak intensity [10^{19} W/cm2]	1.9	13.3	120
Peak intensity parameter ξ	3.0	7.9	23.6
Peak quantum parameter Χ E_{beam}=16.5 GeV	0.56	1.5	4.5

DATA TAKING MODES

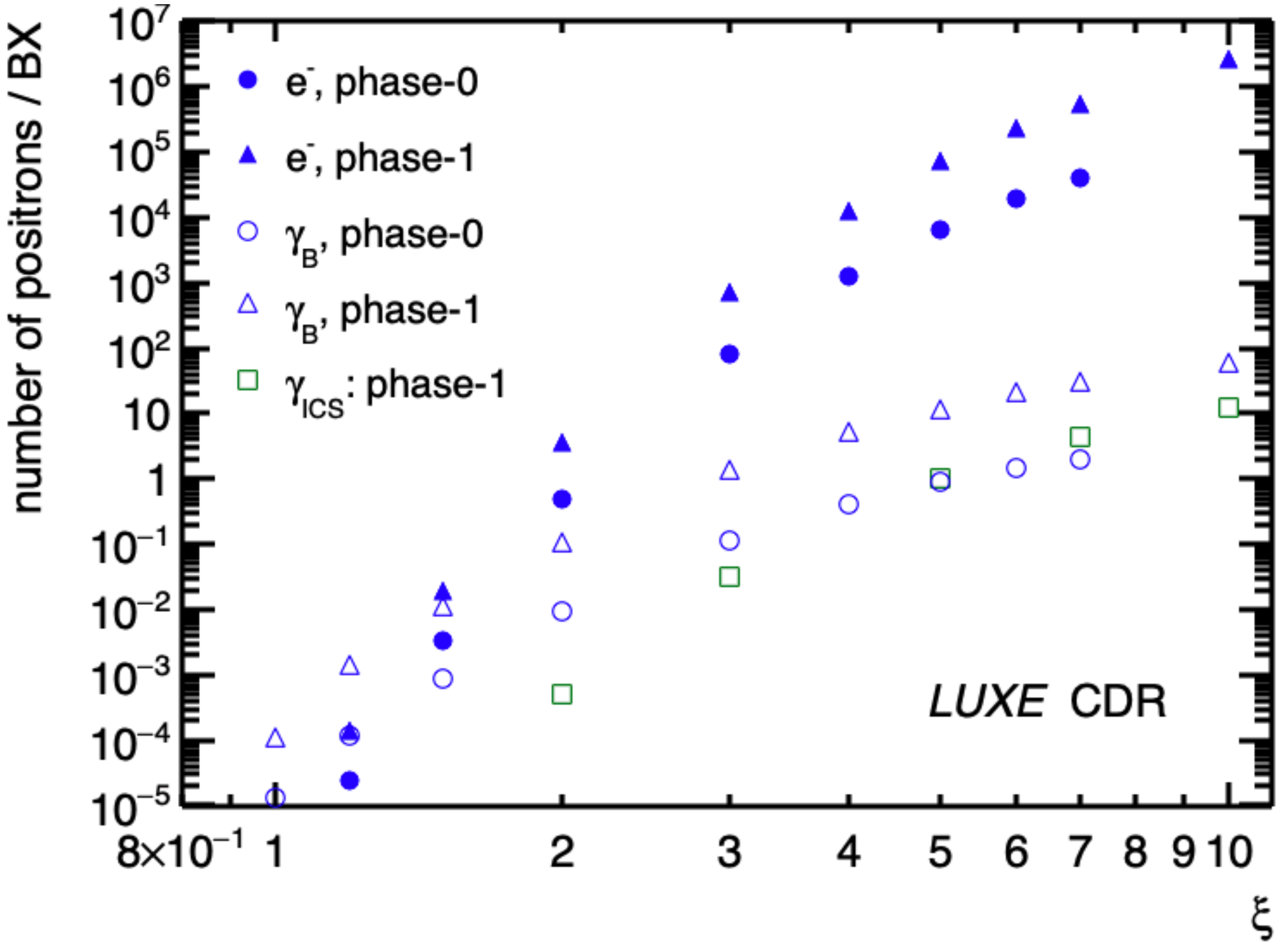


RATES PER BUNCH CROSSING

See O. Borysov talk on Monday
https://indico.desy.de/event/28202/contributions/105760/

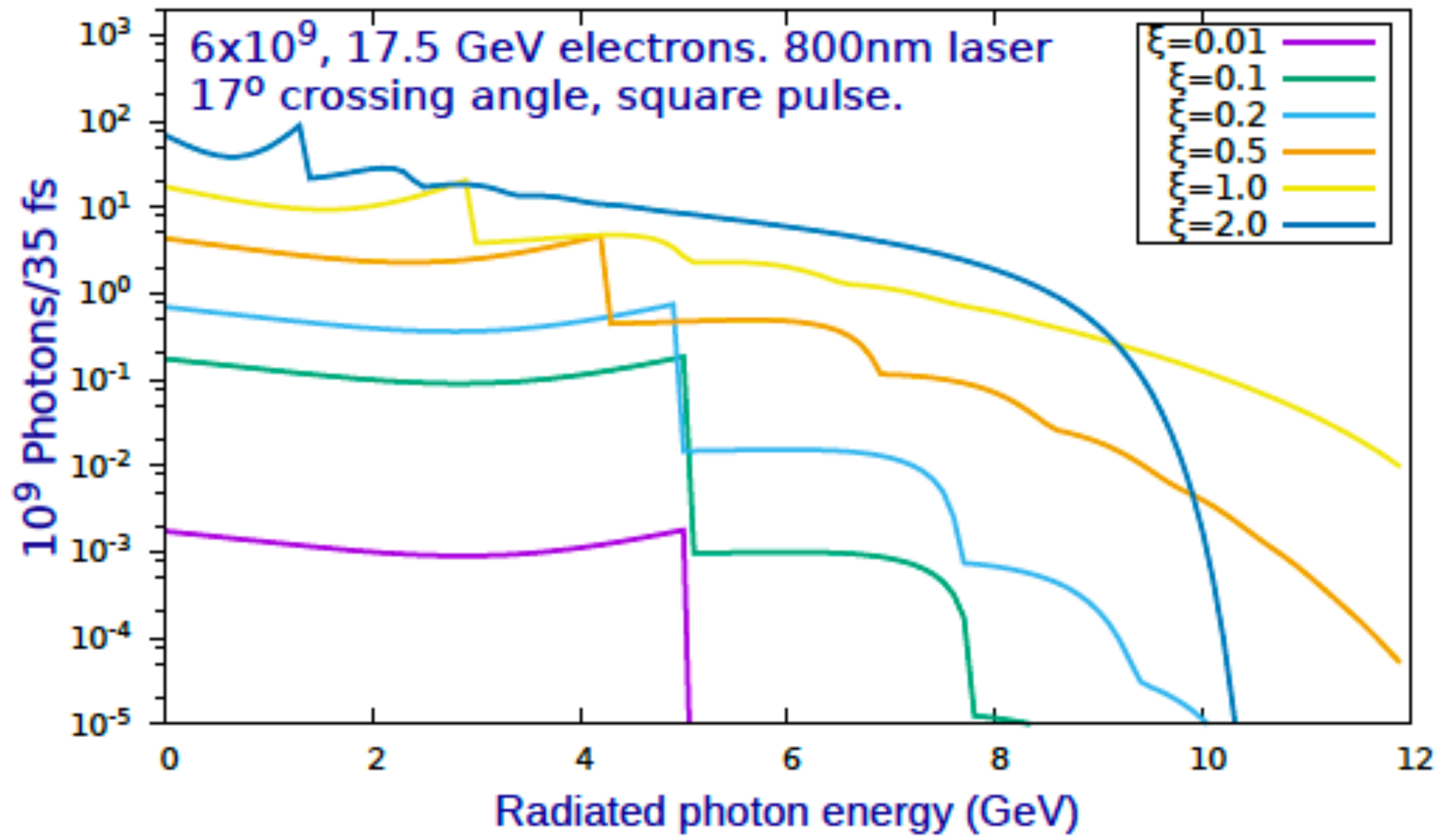


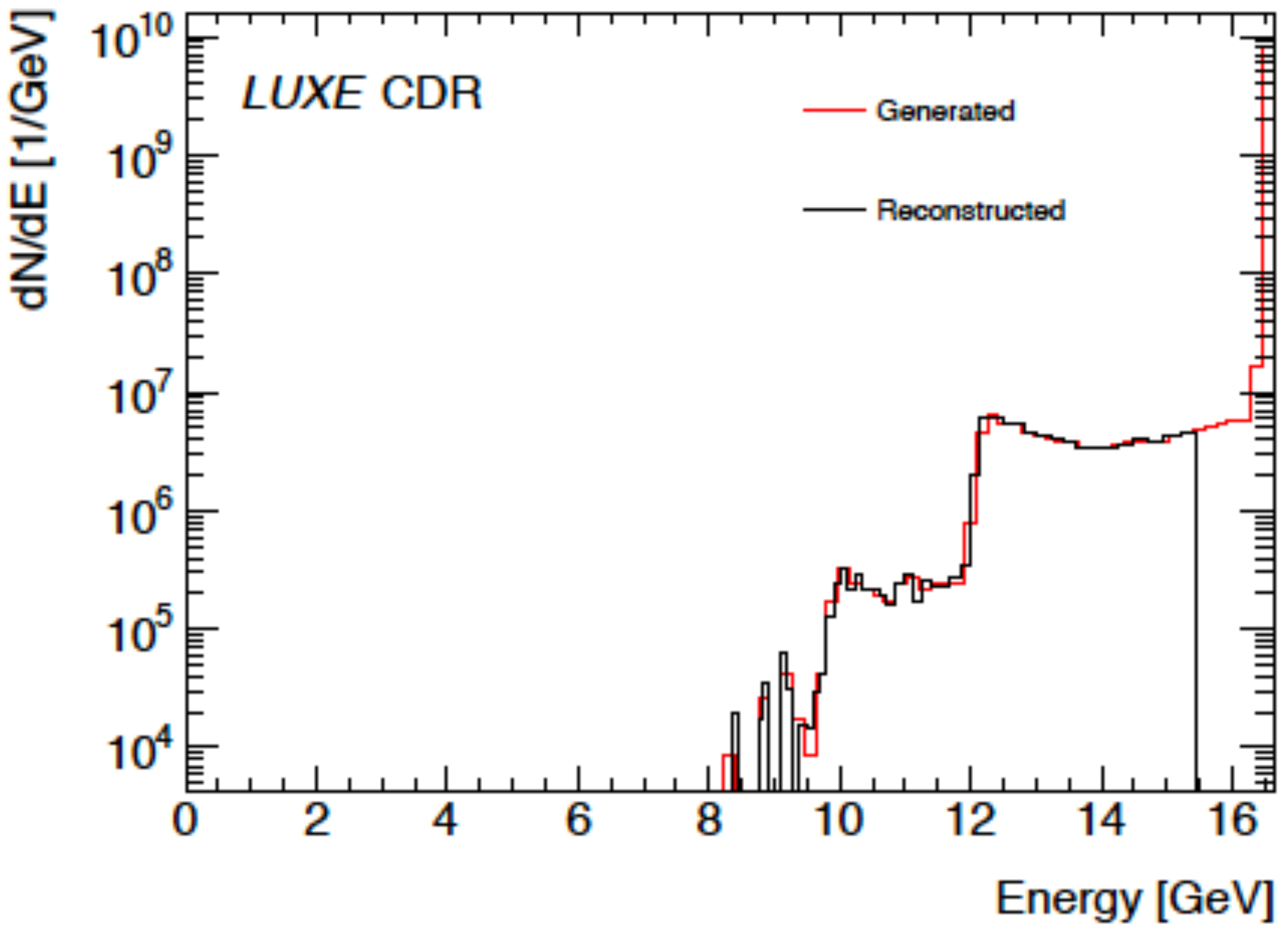
- Electron-laser:
  - Signal pairs created: 10^{-4} to 10^{6}.
  - Background particles flux and detectors used:
    - e^- side: up to 10^9 particles, Cherenkov, and scintillating screen.
    - e^+ side: up to 10^3 particles, calorimeter and tracker.
- Gamma-laser:
  - Signal pairs created: 10^{-5} to 10.
  - Background particles flux and detectors used:
    - e^- side: up to 10 background particles, calorimeter and tracker.
    - e^+ side: up to 10 particles, calorimeter and tracker.
    - Brem target: 10^6 particles, Cherenkov, and scintillating screen.
- In both setups: Photon detection system up to 10^9 photons to detect uses:
  - scintillating screen, beam profiler, backscattering calorimeter.

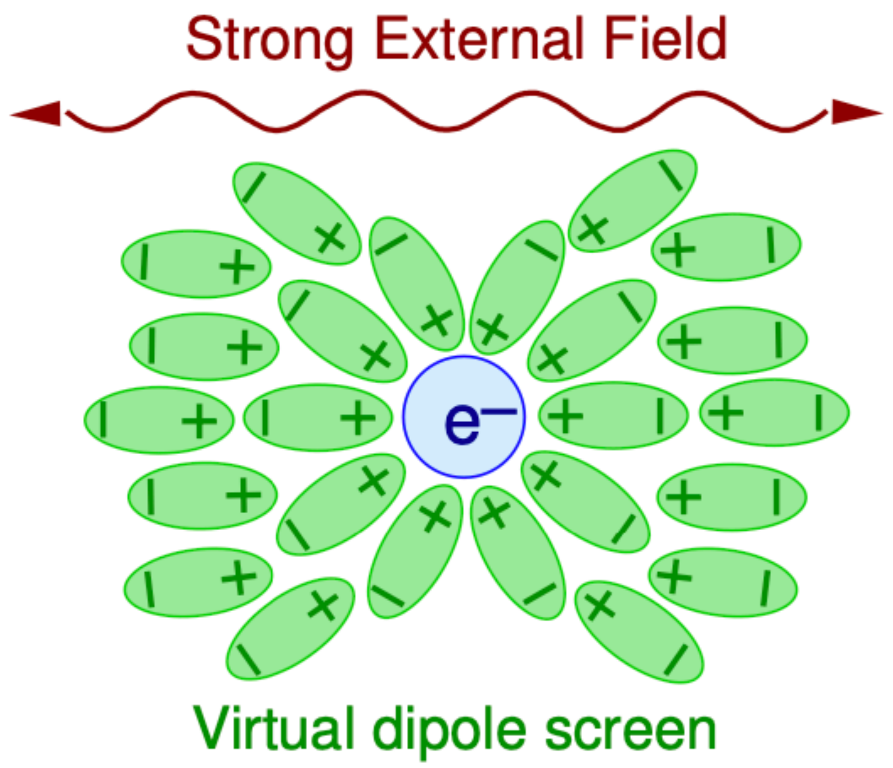


COMPTON EDGE SHIFT

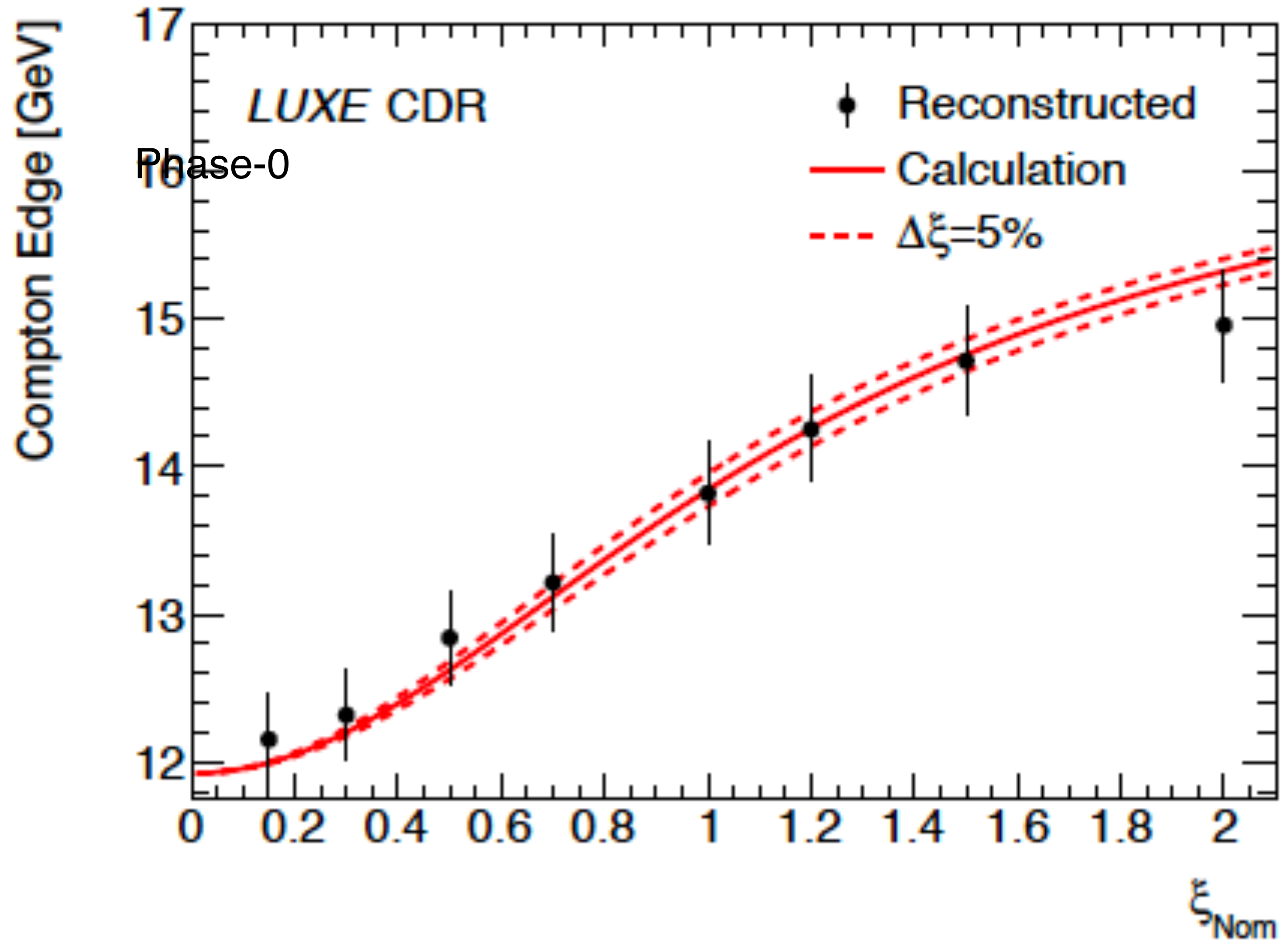
- Need to measure Compton edges, as they will be shifted to lower energies in SFQED!







- Electron energy spectrum to reconstruct Edges using **Finite Impulses Response Filter** (FIR) technique.
- Compare result to theory prediction in phase 0:

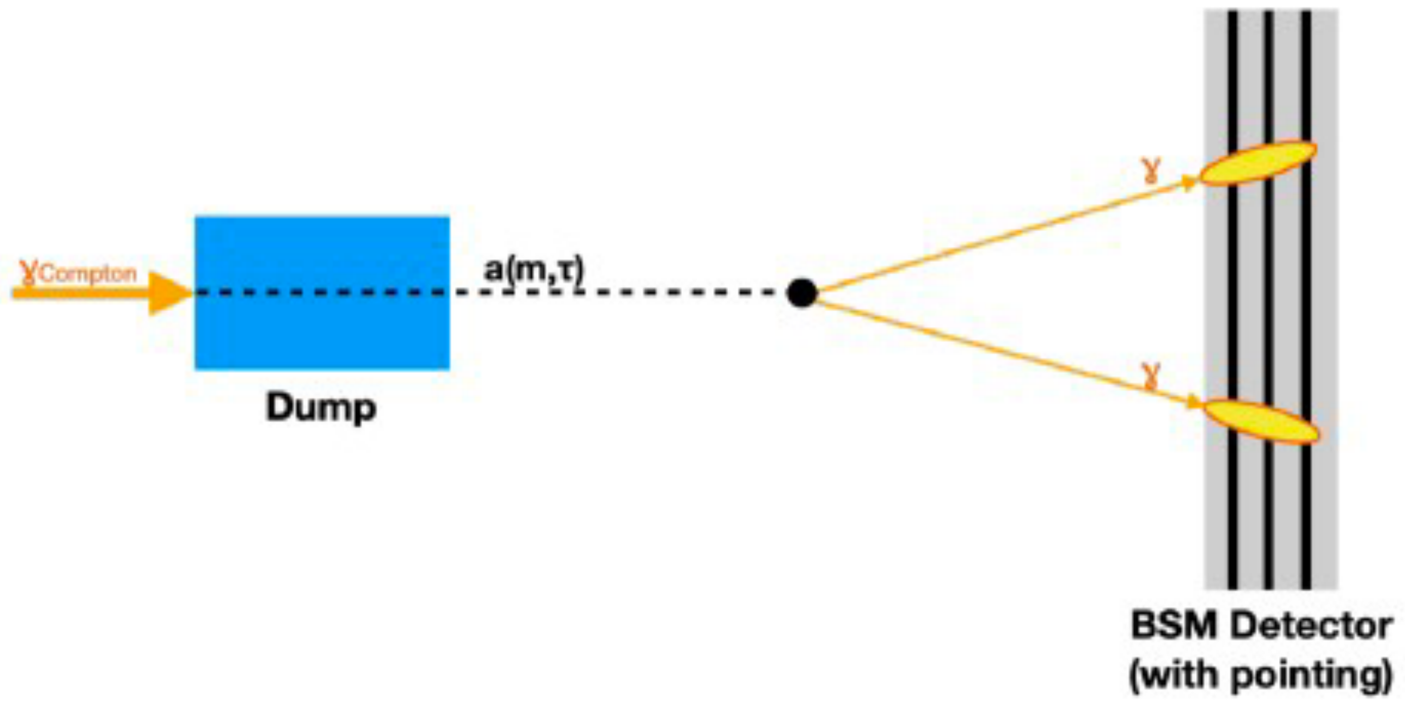


BSM PHYSICS?

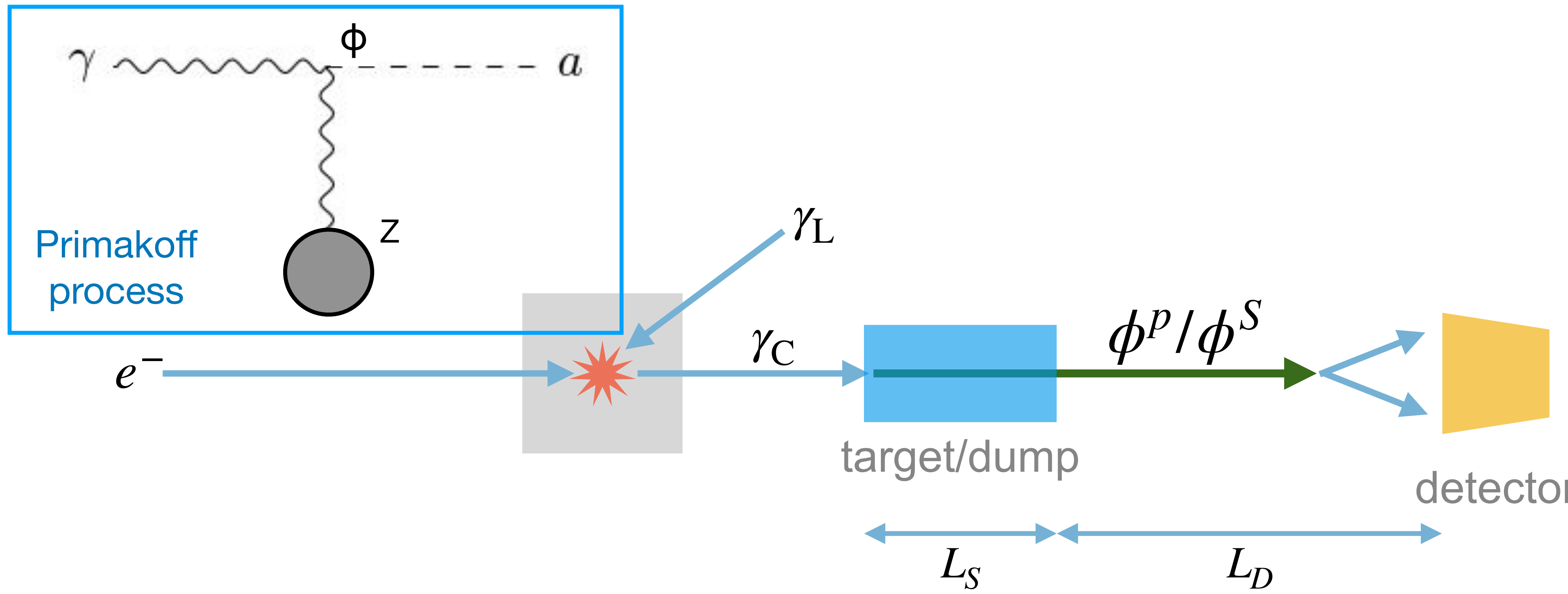
See N. Hod talk on Friday
https://indico.desy.de/event/28202/contributions/105538/

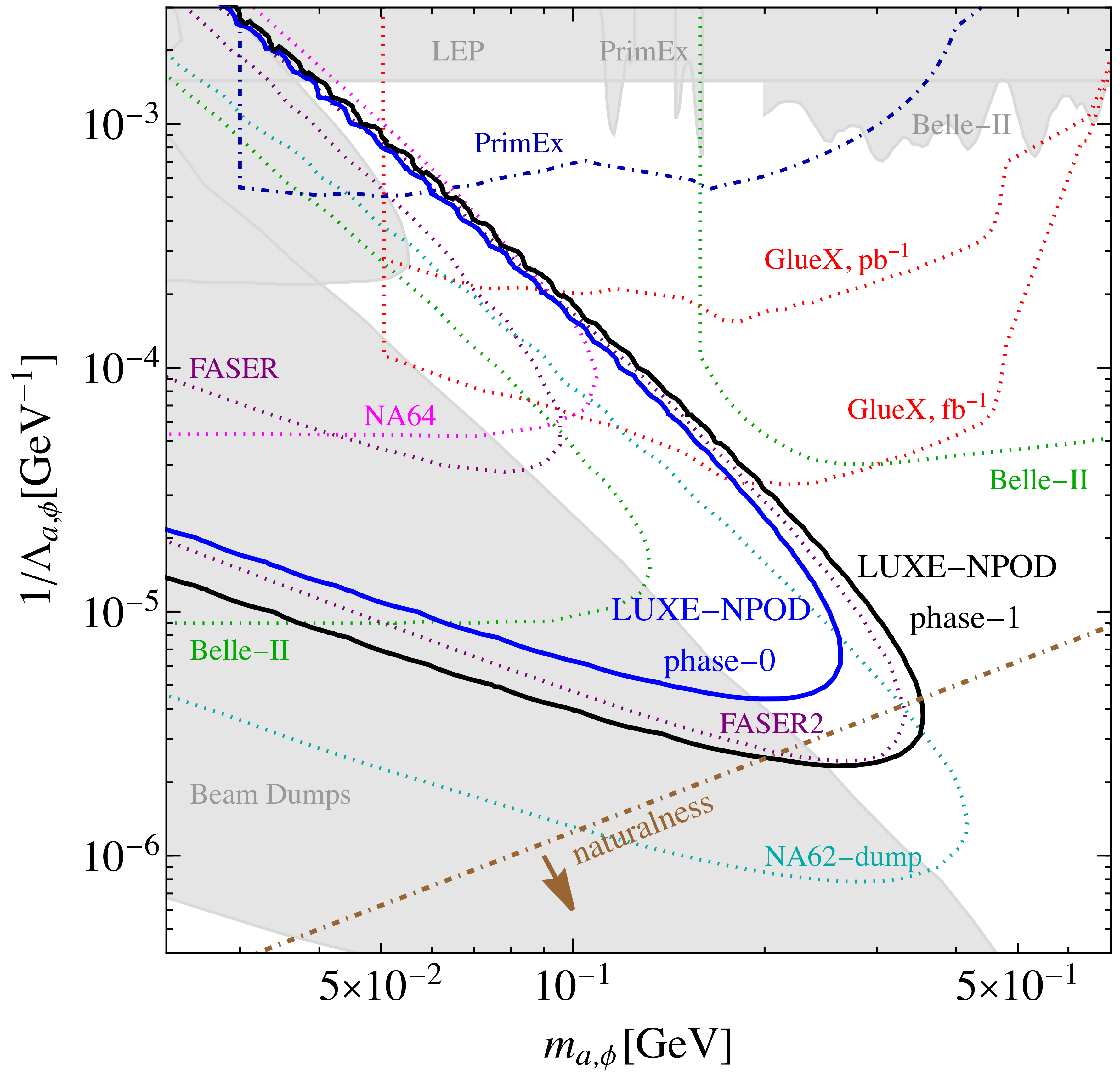
- Explore sensibility to BSM theories.
  - Axion-like particles (ALPs) produced in dump.
  - New neutral particles produced at IP.
  - Milli-charged particles

- For ALPs:
  - sensitive to masses m(a)~100 MeV.
  - decay to photons after some lifetime τ.
  - Place detector behind dump.
  - Could use calorimeter with good pointing resolution to constrain decay point.



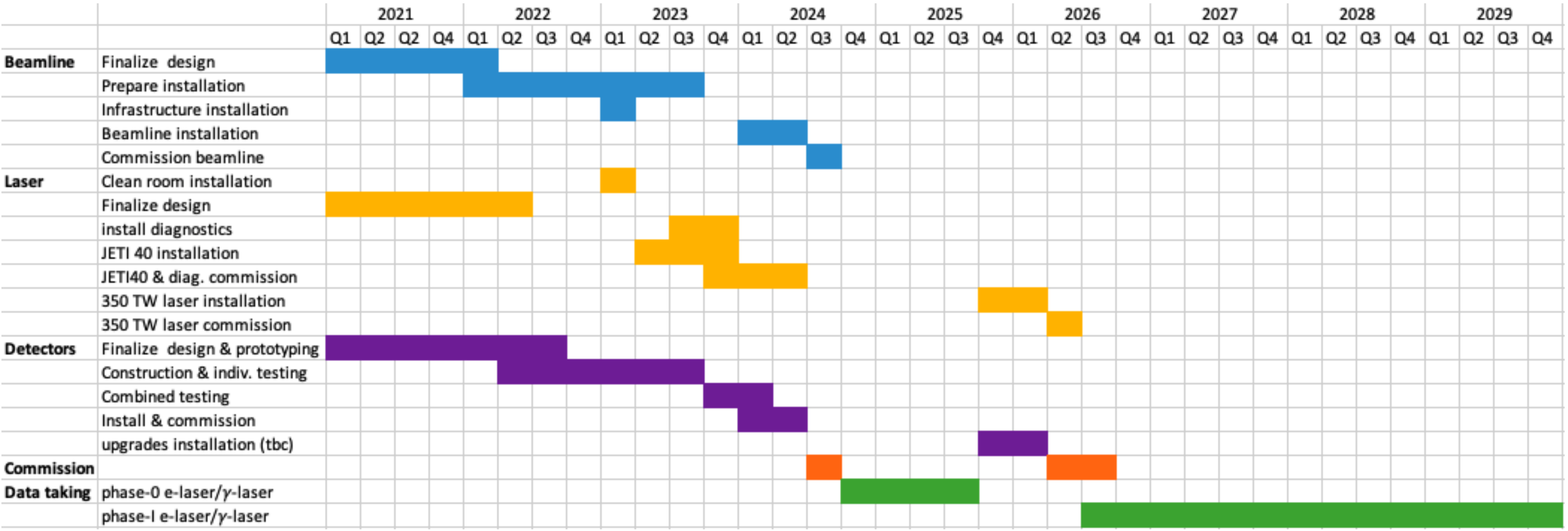
- First sensitivity show very competitive results!
  - After just 1 year of data.



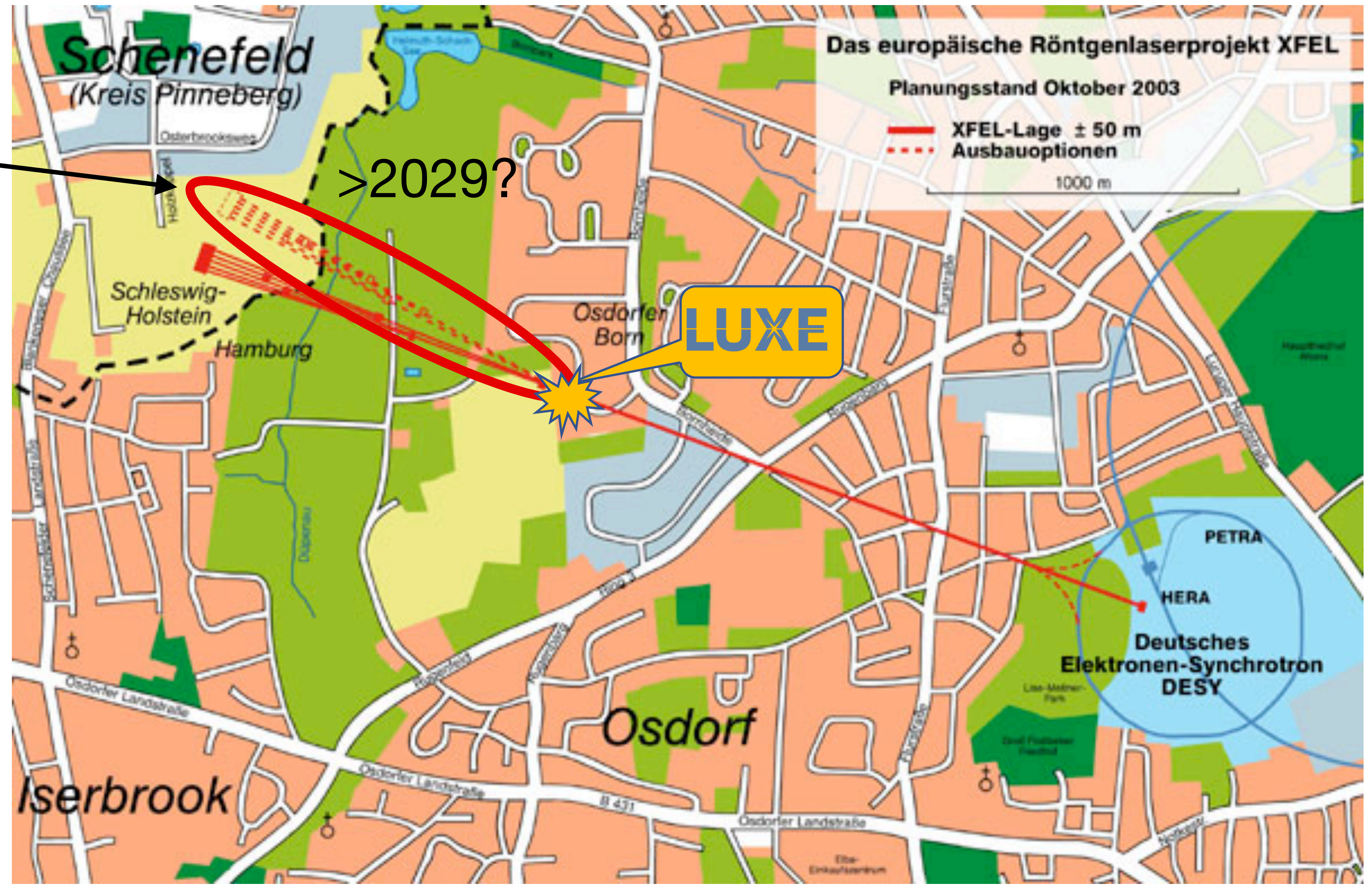


ONE WORD ON THE PLANING

- CDR recently released.
  - Now working toward TDR for 2022.



- Experiment has to be installed in XS1 by 2024.
  - Long shutdown of the XFEL.
  - Only moment where the beam-line can be installed.
  - Data taking to start in 2024.
    - Start with e-laser.
    - γ-laser to start in 2025.
    - Laser upgrade (350 TW) in 2026.
    - Run until XFEL want to construct new fan (2029 for now).

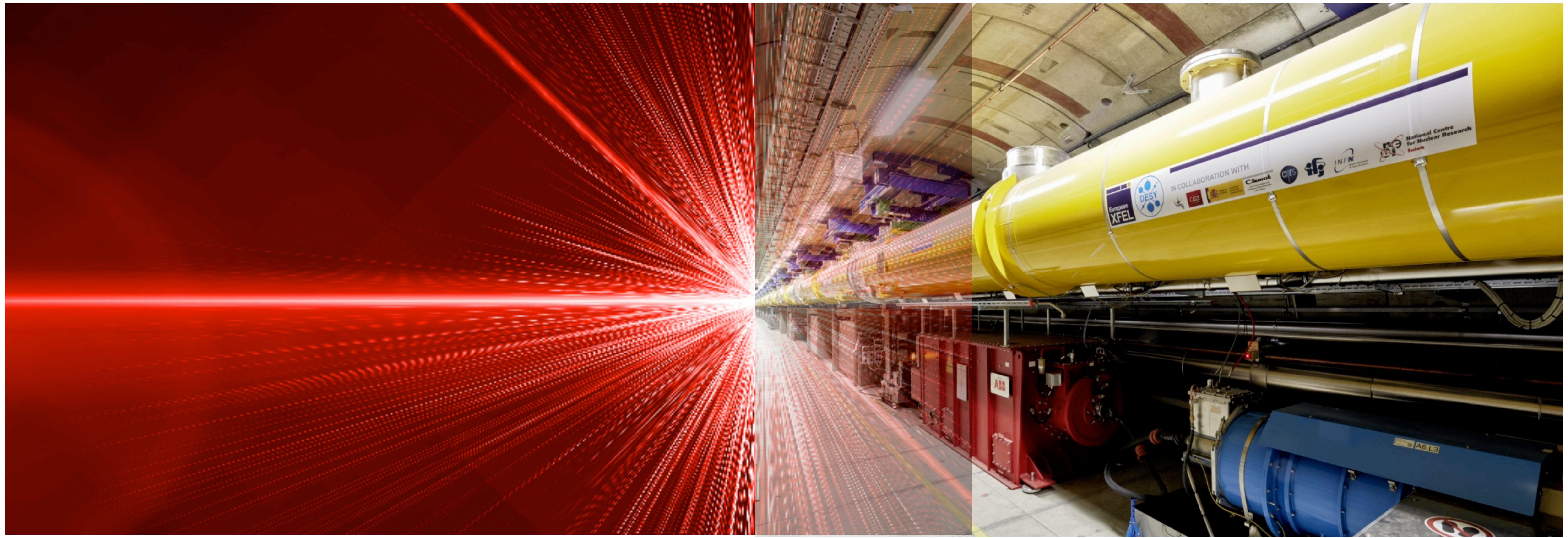


- In parallel of review continue detector R&D, and experiment planification.
  - Plan to perform multiple test-beam campaign in the future.

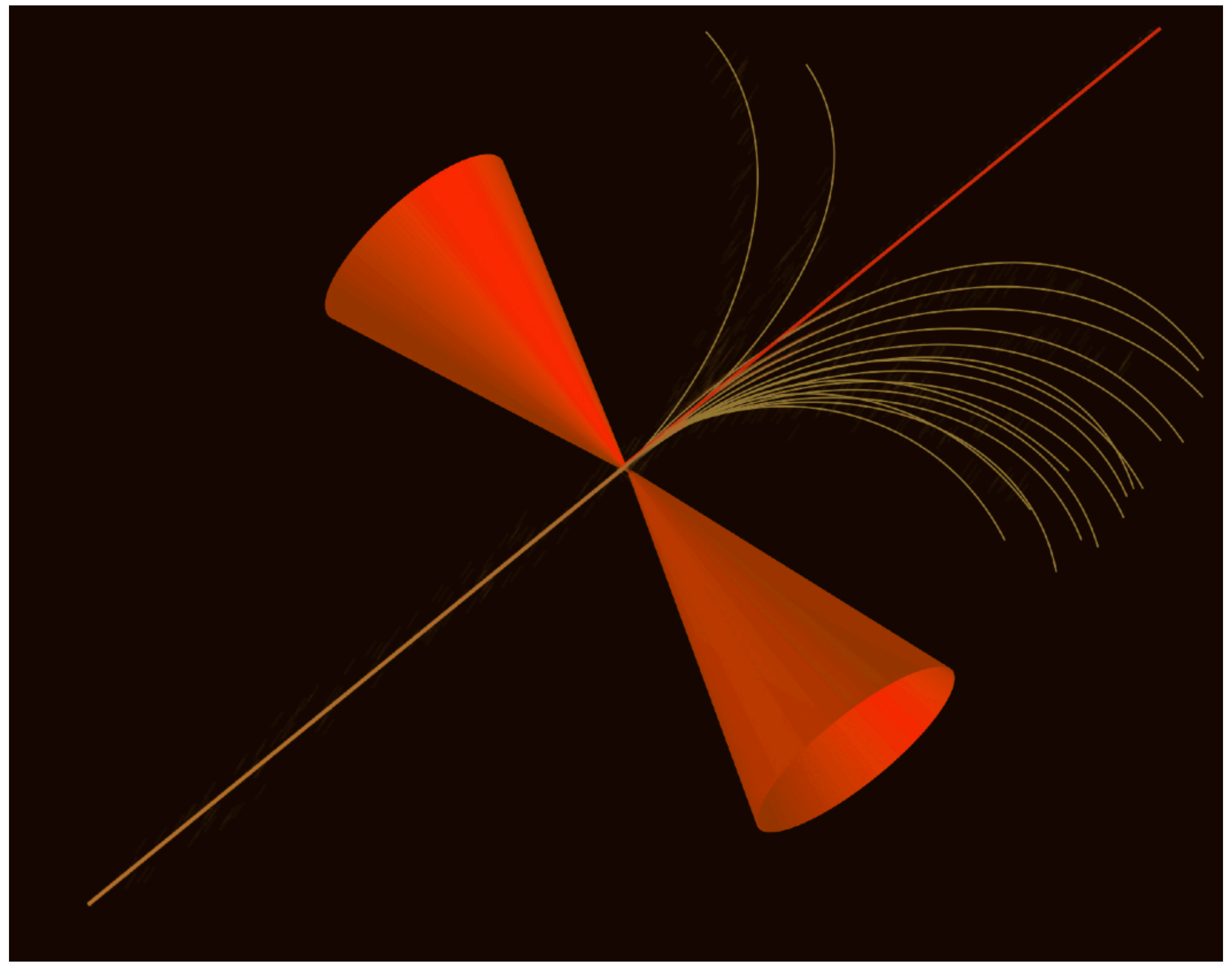
- The LUXE experiment will allow to measure QED in uncharted regime!
  - Might expect some surprises there!

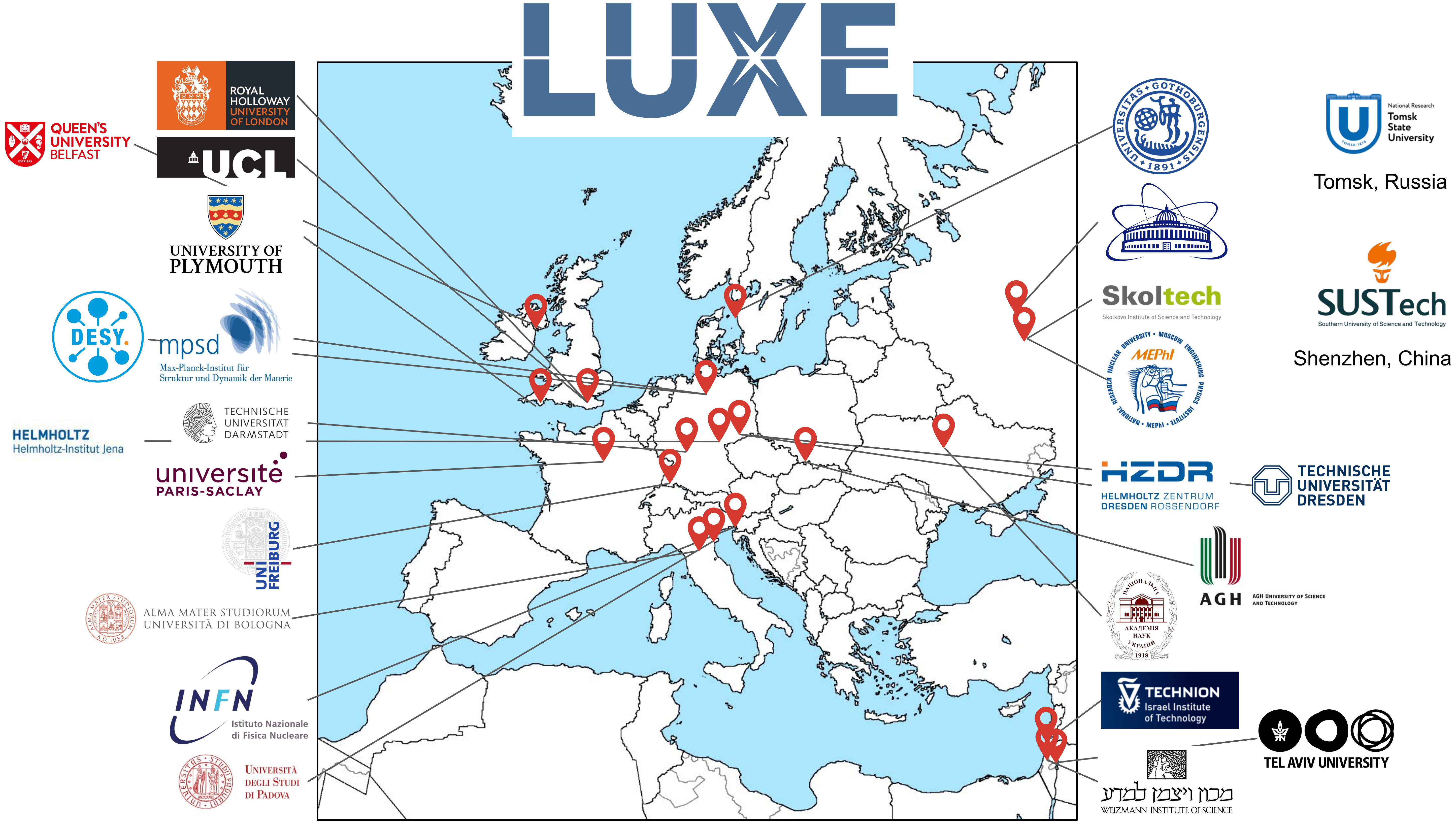
- Synergy experiment between particle physics and Laser physics!
  - Experiment planing to function on established technology to cope with challenging rate to measure!
    - 10^{-2} to 10^{9} per bunch crossing.
  - Innovative development for Laser control system, and Laser diagnostics underway.

- LUXE CDR is now out, working on the TDR for 2022!
    - Still lot of works to do before the experiment can be running in 2024.



THANK YOU FOR YOUR ATTENTION!





Conceptual Design Report for the LUXE Experiment

H. Abramowicz[1], U. Acosta[2,3], M. Altarelli[4], R. Aßmann[5], Z. Bai[6,7], T. Behnke[5], Y. Benhammou[1], T. Blackburn[8], S. Boogert[9], O. Borysov[5], M. Borysova[5,10], R. Brinkmann[5], M. Bruschi[11], F. Burkart[5], K. Büßer[5], N. Cavanagh[12], O. Davidi[6], W. Decking[5], U. Dosselli[13], N. Elkina[3], A. Fedotov[14], M. Firlej[15], T. Fiutowski[15], K. Fleck[12], M. Gostkin[16], C. Grojean[*5], J. Hallford[5,17], H. Harsh[18,19], A. Hartin[17], B. Heinemann[†5,20], T. Heinzl[21], L. Helary[5], M. Hoffmann[5,20], S. Huang[1], X. Huang[5,15,20], M. Idzik[15], A. Ilderton[21], R. Jacobs[5], B. Kämpfer[2,3], B. King[21], H. Lahno[10], A. Levanon[1], A. Levy[1], I. Levy[22], J. List[5], W. Lohmann[‡5], T. Ma[23], A.J. Macleod[21], V. Malka[6], F. Meloni[5], A. Mironov[14], M. Morandin[13], J. Moron[15], E. Negodin[5], G. Perez[6], I. Pomerantz[1], R.Pöschl[24], R. Prasad[5], F. Quéré[25], A. Ringwald[5], C. Rödel[26], S. Rykovanov[27], F. Salgado[18,19], A. Santra[6], G. Sarri[12], A. Sävert[18], A. Sbrizzi[§28], S. Schmitt[5], U. Schramm[2,3], S. Schuwalow[5], D. Seipt[18], L. Shaimerdenova[29], M. Shchedrolosiev[5], M. Skakunov[29], Y. Soreq[23], M. Streeter[12], K. Swientek[15], N. Tal Hod[6], S. Tang[21], T. Teter[18,19], D. Thoden[5], A.I. Titov[16], O. Tolbanov[29], G. Torgrimsson[3], A. Tyazhev[29], M. Wing[5,17], M. Zanetti[13], A. Zarubin[29], K. Zeil[3], M. Zepf[18,19], and A. Zhemchukov[16]

More informations:

- CDR, accepted by European Physics Journal ST: https://arxiv.org/abs/2102.02032
- Detector talk@EPS: https://indico.desy.de/event/28202/contributions/105760/
- BSM talk@EPS: https://indico.desy.de/event/28202/contributions/105538/